Optical Burst Switching—the Network Perspective

Christoph M. Gauger

Institute of Communication Networks and Computer Engineering (IKR)
University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany
E-mail: gauger@ikr.uni-stuttgart.de

ABSTRACT

This paper motivates the combination of optical burst switching (OBS) networks with wavelength-routed networks which provide a virtual topology. Opportunities for advanced network design, support for important future transport network scenarios, and resilience as well as capacity adaptation functionality are among its key benefits.

The paper discusses principal trade-offs, both qualitatively and quantitatively, regarding virtual topologies and statistical multiplexing in order to derive guidelines for resource efficient topology design. Then, the OBTN architecture is described, which can efficiently transport burst data over a virtual topology of lightpaths and can reduce the port count of optical burst-switched nodes. Finally, the OBTN dimensioning process is outlined and results of a unified performance and cost comparison are presented.

1. INTRODUCTION

Optical burst switching (OBS)[1] and optical packet switching (OPS)[2] attracted interest as highly dynamic optical network architectures capable of statistical multiplexing directly in the optical domain. Although a broad scope of research is reported in literature, network design considerations so far have mostly concentrated on isolated, green-field scenarios.

Today, dynamic optical networks, popularly referred to as *Lambda Grid*, are introduced based on the Automatically Switched Optical Network (ASON) and Generalized Multiprotocol Label Switching (GMPLS) architectures. They will likely remain an integral part of future transport networks because of their scalability and manageability benefits. Transparent wavelength-routed networks offer multiservice integration as they transport and switch arbitrary client services in the same infrastructure. Also, virtual topologies of lightpaths enable network designers to bypass expensive client layer nodes, e. g., IP routers, and offload transit traffic to the more cost-efficient optical layer.

Integration of OBS and wavelength-routed networks has been embraced in hybrid optical networking concepts,[3,4] which select one of the network technologies depending on service or traffic requirements. In contrast, virtual topologies as a client-server combination as depicted in Figure 1a did not play a major role, yet. Still, they should be considered due to following reasons:

- OBS architectures can migrate into wavelength-routed transport networks as traffic aggregators at the edge of the core network.[5,6] In this scenario, lightpaths in the underlying wavelength-routed network interconnect these aggregation nodes forming a virtual topology.
- Typical transport network topologies have mean hop distances ranging from 2 to 3.5,[7] i. e., transit traffic amounts to 50–70 % of all traffic in the network. Intermediate OBS nodes have to switch this transit traffic which requires a high number of costly burst switch ports and can cause physical node scalability problems.[8] Here, virtual topologies create new design opportunities, by offloading transit traffic to underlying lambda grids.
- Finally, a lambda grid can offer functions for resilience and for capacity adaptation on higher time-scales to the OBS layer.

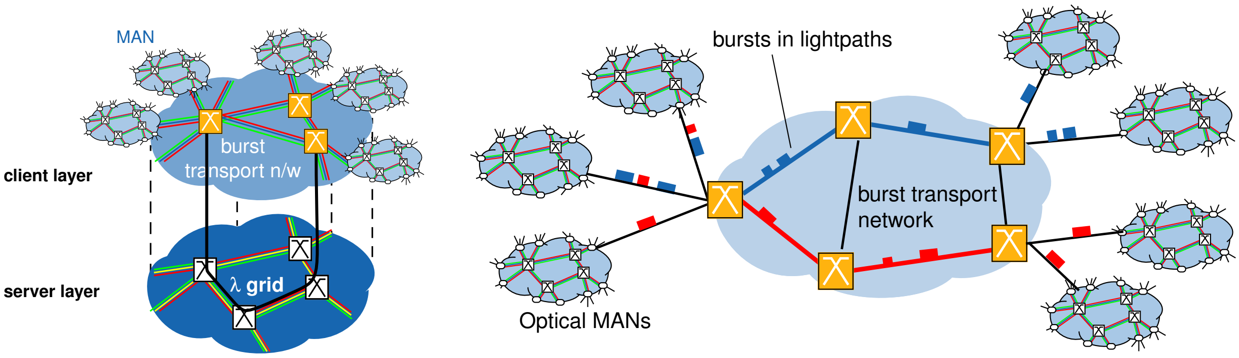


Figure 1. Transport network scenario: (a) burst transport and a wavelength-routed network layers and (b) interconnection of burst-switched optical MANs using lightpaths

Section 2 describes an important burst transport network scenario while Section 3 analyzes design trade-offs for virtual topologies in OBS. Then, Section 4 outlines the Optical Burst Transport Network (OBTN), a burst-switched architecture employing a virtual topology to balance node complexity and network efficiency, in more detail. Finally, dimensioning of OBTN networks and representative performance evaluation results are presented in Section 4 and Section 5. This paper extends an earlier version[9] by the detailed OBTN description, the dimensioning guidelines, and the comprehensive performance evaluation.

2. NETWORK SCENARIO FOR BURST TRANSPORT

Commonly, interconnection of huge core routers in transport networks is proposed as the main application scenario for OBS. However, highly aggregate traffic flows in such routers are less bursty and an only limited capacity improvement may not justify the transition from circuit-switched to burst-switched transport network architectures.

In future OBS scenarios, optical networking could reach farther out toward the user than in current networks. Instead of repeated aggregation and consolidation of bursty data traffic in the electronic domain, it could be assembled and handed over to the optical domain earlier, e. g., as in references[10, 11] at the edge of the MAN. Then, traffic at the ingress to the optical network would be less aggregate and more bursty, and would thus better suit the ideas of burst transport.

As OBS core nodes would mainly aggregate/disaggregate optical burst traffic originating in MANs at the edge of the transport network, bursts would not have to be switched in all intermediate transport nodes. Instead, optical bursts with the same OBS aggregation/disaggregation nodes could be switched together through the transport network in a direct lightpath[5, 6] as also illustrated in Figure 1b. In the following, we refer to such an approach, in which no traffic is switched in core nodes at all as *burst-over-circuit-switching* (BoCS).

Summarizing, the interconnection of OBS switches in this network scenario constitutes a major application case for virtual topologies in OBS.

3. TOPOLOGY DESIGN AND STATISTICAL MULTIPLEXING

In the design and analysis of OBS architectures, network efficiency and node complexity—*cost of transport* and *cost of switching*—always have to be considered together.[12, 13] On the one hand, the still limited functionality and mostly *analogue* nature of agile optical systems[12] indicate that their implementation cost will remain high for some years to come. On the other hand, the cost of transport will decrease due to the huge available bandwidth of optical networks. Accounting for both trends, switching will continue to dominate the cost of optical networks in general and of OBS networks in particular. Therefore, the number of interfaces of OBS nodes, which are an important indicator of their realization complexity, is critical and should be minimized at first place even at the cost of additional network capacity.

In order to comprehensively understand all effects of virtual topology design as well as fundamental potentials and limits the following two sub-sections present qualitative and quantitative arguments respectively.

3.1. Qualitative Arguments

In networks with dynamic traffic, topology design is not a straightforward task as it involves conflicting arguments regarding statistical multiplexing gain and node size.

- On a typical physical topology like in regular OBS (Figure 3b), traffic streams share all transport resources which are assigned to relatively few links. While this requires additional switch ports for transit traffic, it yields a high statistical multiplexing gain on all links.
- A very densely or fully-meshed virtual topology like in BoCS (Figure 3c) corresponds to the other extreme*. On the one hand, nodes do not switch any or hardly any transit traffic, which reduces the number of switch ports significantly. On the other hand, as more links comprise fewer capacity each, traffic streams can only share less resources, which yields a much lower statistical multiplexing gain.

In network dimensioning, a lower statistical multiplexing gain translates into a higher overprovisioning factor for link and switch resources to meet a QoS objective, e. g., a certain burst-loss probability, and vice versa. The positive effect of reduced transit traffic and the negative effect of higher necessary overprovisioning both decide on the number of switch ports. Consequently, virtual topologies for highly dynamic networks like OBS have to balance these effects to find optimal solutions.

Existing work on virtual topologies for OBS focuses on reducing the number of contention situations and the control processing overhead in intermediate nodes. In reference[16] this is achieved by minimizing the maximum shortest path length. However, it does not capture any of the conflicting effects.

3.2. Quantitative Arguments

In order to quantify the potentials and limits of virtual topology design, we look at basic relations of node and network dimensioning for the two extreme cases of a physical and a full-mesh topology. We restrict the discussion to the number of (sending) OBS trunk interfaces and the number of wavelength hops in the fiber infrastructure. We neglect rounding effects and assume that the number of add/drop interfaces does not differ.

The product of total traffic demand A in the network, the mean overprovisioning factor α, and the mean hop distance per bit d in the OBS layer determines the number of trunk interfaces as $\alpha \cdot d \cdot A$. The virtual topology characterizes both, the overprovisioning factor and the mean hop distance. While the mean hop distance per bit usually is slightly lower than the mean shortest path length in typical physical network topologies,[17] it equals 1 in the full-mesh topology. Based on the qualitative discussion above we conclude that the overprovisioning factor α_{p} for a physical topology is lower than α_{fm} for a full-mesh topology. Thus, we can directly see that the total number of trunk interfaces for the full-mesh virtual topology ($\alpha_{\mathrm{fm}} \cdot A$) is smaller than for the physical topology ($\alpha_{\mathrm{p}} \cdot d \cdot A$) if $\alpha_{\mathrm{fm}}/\alpha_{\mathrm{p}} < d$. Consequently, densely-meshed virtual topologies have to achieve a low α_{fm} and a low ratio $\alpha_{\mathrm{fm}}/\alpha_{\mathrm{p}}$ to yield gains in the number of switch ports. Advanced contention resolution strategies should thus be applied in these cases. Also, the larger a network is in terms of mean hop distance, the greater the benefits are that could be realized.

To study network resources, we derive the number of wavelength hops in the physical fiber infrastructure from the number of trunk interfaces. For the physical topology case, each trunk interface corresponds to one wavelength hop. In the full-mesh topology, a virtual topology link can span several hops in the underlying physical topology. Thus, the number of trunk interfaces is multiplied by the mean length of virtual topology links, which approximately corresponds to the mean hop distance per bit d. Comparing the virtual topologies, the number of wavelength hops in the physical infrastructure is always higher for the full-mesh topology ($\alpha_{\mathrm{fm}} \cdot d \cdot A$) than

*Note that full-mesh interconnection patterns are not as uncommon as they seem. For instance, they frequently occur in dynamic multi-layer networks (IP over WDM, SDH/SONET over WDM).[14,15]

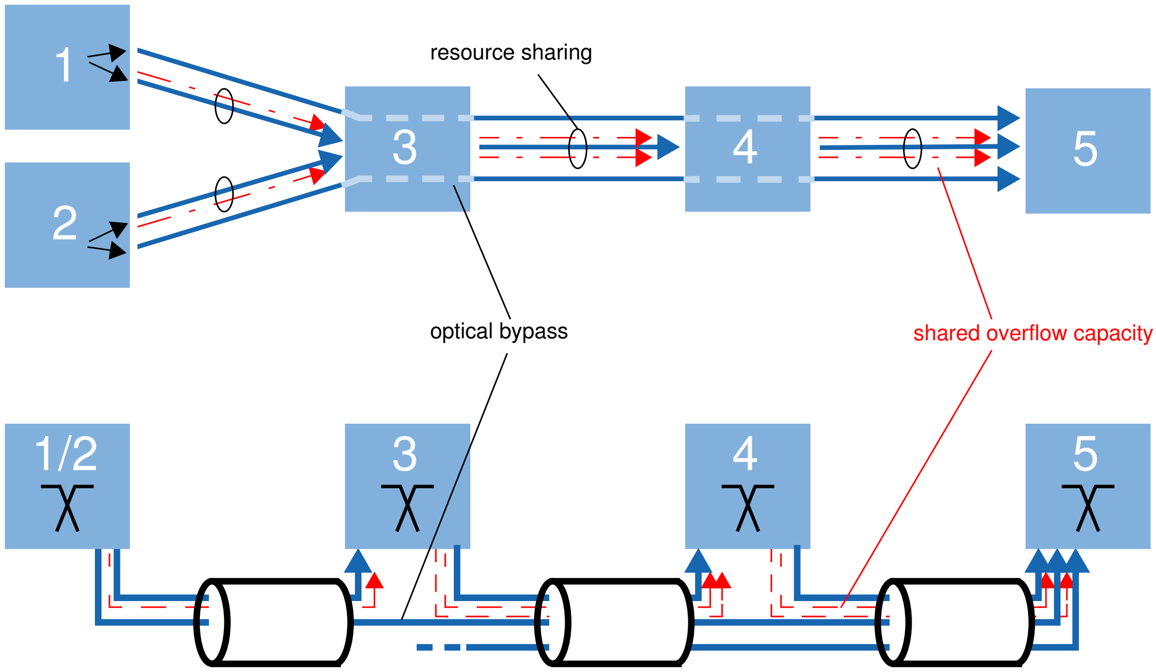


Figure 2. Example OBTN network segment with 5 nodes for OBTN with traffic demands $A_{1,3}$,$A_{2,3}$,$A_{1,5}$,$A_{2,5}$,$A_{3,4}$, $A_{4,5}$

for the physical topology case ($\alpha_{\mathrm{p}} \cdot d \cdot A$) as $\alpha_{\mathrm{p}} < \alpha_{\mathrm{fm}}$. Again, a densely-meshed topology has to be engineered to achieve a small ratio of overprovisioning factors $\alpha_{\mathrm{fm}}/\alpha_{\mathrm{p}}$. However, our previous discussion also emphasized that reducing the number of node interfaces has precedence over the number of wavelength hops.

This discussion of extreme scenarios exhibits the principal trade-offs and bound the margins for improvement in intermediate scenarios. Reference[18] presents a unified performance comparison of OBS and BoCS including systematic traffic and network size studies.

4. THE OPTICAL BURST TRANSPORT ARCHITECTURE (OBTN)

This section outlines the Optical Burst Transport Network (OBTN)[18] architecture which targets the network scenario outlined in Section 3. OBTN defines a virtual topology design together with contention resolution strategies in order to reduce the number of OBS switch ports and to keep a high network efficiency at the same time.

First, OBTN applies a virtual topology, in which OBTN nodes are interconnected by direct lightpaths in a dense virtual topology the interconnection pattern of which is defined by traffic demands or operational criteria. Second, as statistical multiplexing on a large number of network links with small capacity each can be inefficient alone, OBTN comprises two additional complementing concepts: (i) bursts are allowed to use an alternate path in case of contention on the direct lightpaths and (ii) a small amount of shared overflow capacity is allocated to links used by the alternate paths.

In OBS, alternate routing—commonly referred to as deflection routing—leads high delay variation, significant burst reordering, and finally negative effects on the performance of upper layers, e. g., TCP.[19] However, in OBTN alternate routes and shared overflow capacity are allocated such that all bursts follow the same links in the physical topology although they are on different virtual topology links. This is achieved by assigning alternate routes and shared overflow capacity to the links of the virtual topology which connect neighbors in the physical topology. At the same time, this avoids burst reordering and increases the efficiency of shared overflow capacity.

Figure 2 explains this OBTN resource allocation for a network segment with 5 nodes. In this example, burst layer traffic demands $A_{i,j}$ exist from nodes 1 and 2 to nodes 3 and 5 as well as from node 3 to node 4 and from node 4 to node 5. The figure depicts the (virtual) topology of the burst layer (top) as well as the interconnection of nodes by lightpaths in the physical fiber infrastructure (bottom). Note that for the physical fiber infrastructure, only one of the nodes 1 and 2 is drawn and in the lightpath layer cross-connects are not shown to improve clarity.

In the presented example, OBTN employs direct lightpaths, which are represented as arrows, for all traffic demands. The direct lightpaths for the multihop demands from nodes 1 and 2 to node 5 bypass the intermediate burst-switched nodes 3 and 4 and follow the links of the physical fiber topology. In case of congestion in nodes 1 or 2, an alternate route via nodes 3 and 4 can be taken. The figure illustrates how OBTN allocates a small amount of overflow capacity (dashed arrows) for the multihop demands to all burst layer links, which are traversed by alternate routes in case of contention in nodes 1 and 2 respectively. This overflow capacity can be rather small if it is shared among all bursts on the respective burst layer link as shown. Figure 2 (bottom) also demonstrates that the direct lightpaths for multihop traffic and the alternate path on burst layer links with additional shared overflow capacity follow the same route in the physical fiber infrastructure. Thus, bursts in direct lightpaths and in the alternate paths experience the exact same propagation delay.

Figure 3d shows an example OBTN virtual topology for a Pan-European core network[7] as an overlay of a full-mesh lightpath topology and the shared overflow capacity on the links of the physical topology. Although OBTN is not limited to this case, a full-mesh lightpath topology is assumed for the presented evaluation studies. Note that the capacity of most virtual topology links is dimensioned to carry the traffic demand between the respective OBTN node pair (thin in Figure 3d) while the capacity of virtual topology links between neighbor nodes in the physical topology also comprises additional shared overflow capacity (thick).

4.1. Realization Consequences

In order to achieve high network resource efficiency despite the reduced statistical multiplexing gain per network link both wavelength conversion and a simple shared FDL buffer are employed in OBTN nodes. However, as FDL buffers cannot be integrated, require additional fiber amplifiers and also contribute to the number of switch ports, their complexity in terms of FDL and wavelength count, as well as their delay should be kept to the necessary minimum.[12]

A virtual topology with a large number of links but with fewer wavelength channels per link renders out-of-band signaling of burst control headers on a dedicated wavelength per link inefficient. However, alternative out-of-band signaling schemes[20] or even alternative inband schemes[16] are presented in literature and should be applied instead.

Although bursts are transported inside the lightpaths, the physical network infrastructure has to support burst-mode transmission as in OBS, e. g., fiber amplifiers have to be robust against power fluctuations using fast power control.[21, 22] Also, in case advanced out-of-band signaling schemes like sub-carrier modulation are applied, the infrastructure should be transparent with respect to those signals.

4.2. OBTN dimensioning

This section introduces key OBTN parameters and a static dimensioning approach of node and network resources. The presented approach will also allow a unified description of OBS, BoCS, and OBTN in order to evaluate their QoS performance for the same number of burst switch ports and wavelength hops.

In the following OBTN dimensioning process, resources for direct lightpaths and for shared overflow capacity are treated separately. The parameter β, $0 \leq \beta \leq 1$, denotes the share of overflow capacity allocated in the network while $(1-\beta)$ defines the share of network resources allocated to direct lightpaths. This description also comprises the OBS architecture ($\beta = 1$) and, if a full-mesh topology of direct lightpaths is assumed in OBTN, the BoCS architecture ($\beta = 0$).

1. Dimensioning starts from the traffic demand matrix which contains values of offered traffic (in Gbps or Erlang) with a total sum of A.

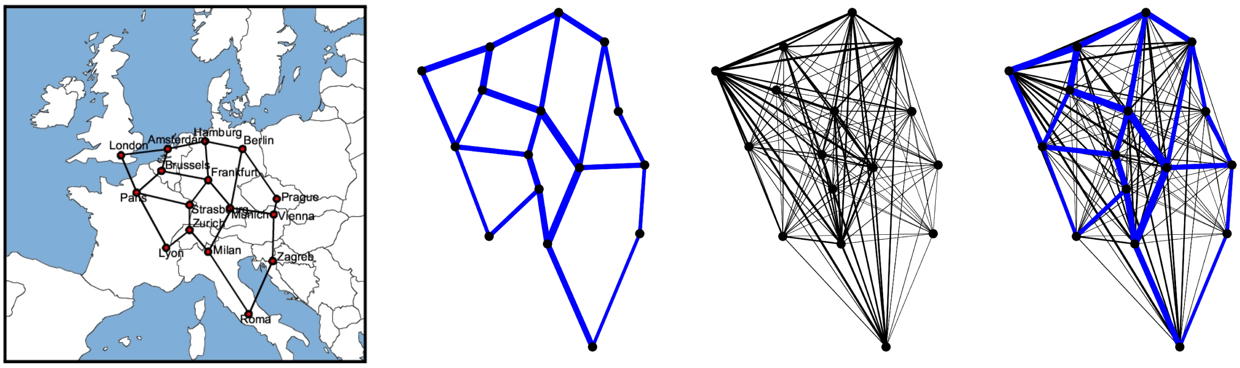


Figure 3. Burst layer topologies: (a) European reference network topology (b) OBS virtual topology (c) BoCS virtual topology, and (d) OBTN virtual topology (line width not drawn to scale).

2. As in Section 3.2, the total amount of network resources is modeled by a global overprovisioning factor α, as $A \cdot \alpha \cdot d$.

3. These resources are split into two pools for shared overflow capacity, $A \cdot \alpha \cdot d \cdot \beta$, and for direct lightpaths, $A \cdot \alpha \cdot d \cdot (1 - \beta)$.

4. From these resources, the number of trunk ports is computed respectively. For the shared overflow capacity, each wavelength hop corresponds to one trunk port. In contrast, for the direct lightpaths, the total number of trunk interfaces is obtained as $A \cdot \alpha \cdot (1 - \beta)$ after division by the mean length of virtual links d

5. These two pools of trunk ports are allocated to the nodes such that the traffic routed on the respective topologies experiences the same QoS on each link.[23,24]

6. The number of trunk ports per link is rounded to an integral number using an algorithm which keeps the overall capacity unchanged. From this allocation of trunk interfaces, the allocation of network resources follows by routing the links of the burst-layer topology onto the lambda grid.

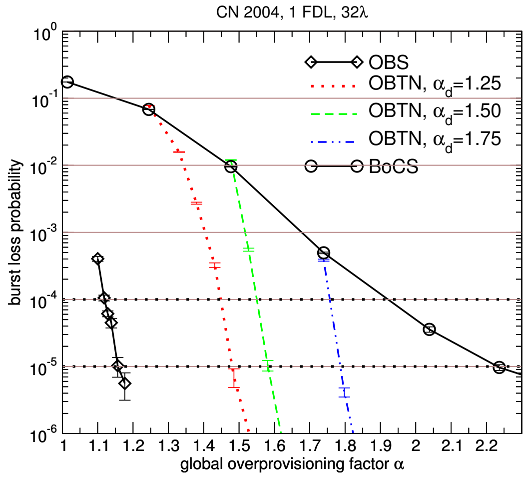
7. Finally, the node and network resources for direct lightpaths and shared overflow capacity are combined by adding up values for corresponding links. Note that because of the specific assignment of the overflow resources only links of the physical topology appear in both dimensioning.

5. PERFORMANCE EVALUATION

In this section, we compare the effect of (virtual) topologies and different contention resolution strategies on QoS performance. We study a Pan-European reference network (core network, CN) defined in the projects COST266/LION.[7,25] In this physical topology with 16 nodes and 23 links (Figure 3a), the mean shortest path spans 2.64 hops. The traffic matrix contains the traffic demands for the year 2004 with a total of 960 Gbps and a mean hop distance per transported bit of 2.43. In average, node pairs exchange 4 Erlang of traffic assuming the bitrate of 2.5 Gbps per wavelength channel. A systematic study of the effects of traffic demands and network topology on OBTN performance and the architecture comparison is published in reference.[18]

Bursts are generated following a Poisson process and burst length is assumed to be exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $40\,\mu s$. Full wavelength conversion capability is assumed in all core nodes. The FDL buffer contains a single FDL with delay $80\,\mu s$ and there are 32 wavelengths in this FDL.

Burst-loss probability serves as the key QoS performance metric. As propagation delay dominates in core networks—typically ms and thus much higher than node-internal delays—we do not analyze transfer delay here.



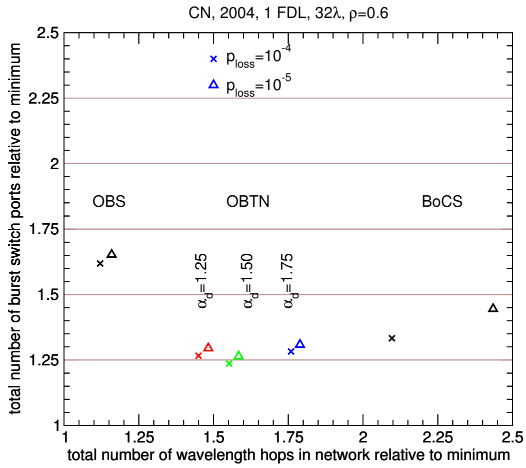


Figure 4. Effect of overprovisioning factor and share of overflow capacity on burst-loss probability (left); integrated architecture comparison of node complexity and network efficiency for two QoS values (right)

5.1. Principal OBTN Behavior

Figure 4 (left) evaluates all three architectures in a unified way and quantifies the effect of the overprovisioning factor α on burst-loss probability for OBS, BoCS, and OBTN. For the latter, three values of α_d are plotted which denotes the overprovisioning factor of the lightpath capacity only. Along curves of constant α_d, β increases from $\beta = 0$ on with increasing overprovisioning factor α.

Because of its higher statistical multiplexing gain, OBS requires a smaller overprovisioning factor α compared to OBTN and BoCS to reach a given burst-loss probability, e. g., 10^{-4} or 10^{-5}. The better performance of OBTN compared to BoCS results from the few shared overflow resources and the possibility of alternate routing. Not shown here are results which show that BoCS would only benefit from alternate routing for very high overprovisioning factors.

The complete picture, however, is only obtained when comparing network and node resources.

5.2. Comparison of Network and Node Resources

This section compares OBS ($\beta = 1$), BoCS ($\beta = 0$), and OBTN ($0 < \beta < 1$) with respect to network resource efficiency (number of wavelength hops in the underlying fiber infrastructure) and number of burst ports to quantify the trade-off outlined in Section 3.

Network resource efficiency is expressed by the ratio of the α values of the respective architectures for a burst-loss probability of 10^{-5}. The total number of burst ports is calculated based on the resource model in reference.[18] The model includes trunk ports, FDL ports, and add/drop ports, for which a utilization of 60 % is assumed. All numbers are normalized to the case of OBS.

Looking at network efficiency in Figure 5 (left), it can be seen that suitable OBTN parameterizations encounter a penalty compared to OBS of 25–40 %, but are clearly more efficient than BoCS which requires approx. 130 % more network resources than OBS. Regarding the number of burst ports in Figure 5(right), we can see that OBTN performs better than BoCS and that it can save up to 40 % of trunk ports and approx. 20 % of total ports (incl. FDL and add/drop ports). For reference, comparable studies showed that bufferless OBS requires 20–40 % additional network resources and approx. 30 % more burst ports than OBS with an FDL. Figure Figure 5 (right) also include the minimum number of ports for BoCS if all traffic was transported with the optimal overprovisioning factor $\alpha = 1$.

Finally, evaluations presented in Figure 4 (right) quantify the trade-off between number of burst-switched ports and the number of wavelength hops for all architectures in one graph. Node and network complexity are

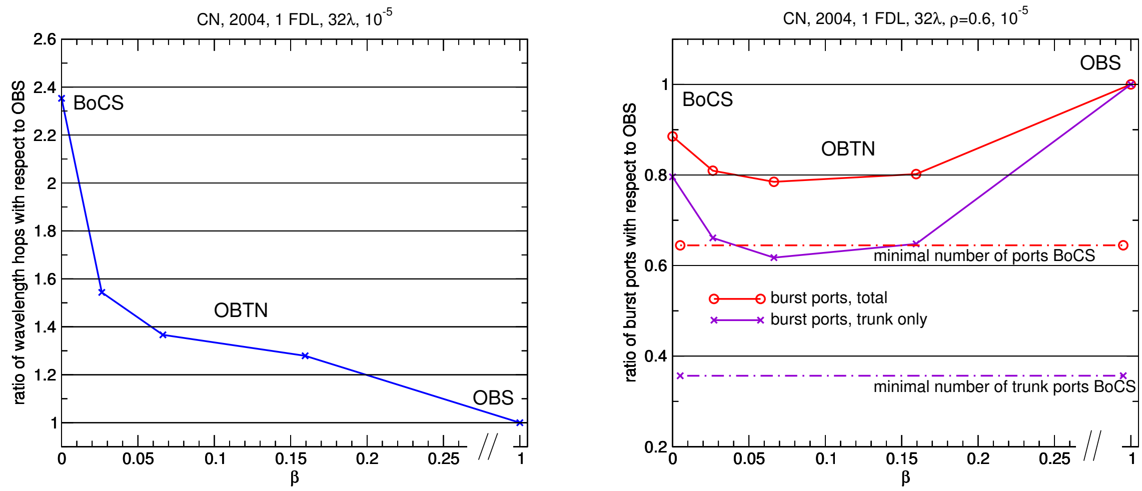


Figure 5. Comparison of node and network resources for OBS ($\beta = 1$), BoCS ($\beta = 0$), and OBTN($0 < \beta < 1$)

both derived for burst loss probabilities in the network of 10^{-4} and 10^{-5}. All values are normalized to the respective minima for OBS, i. e., $d \cdot A$, following the notation in Section 3.2. For OBTN, the three different dimensioning combinations of direct lightpaths and shared overflow capacity are included.

Figure 4 (right) clearly shows, that, on the one hand, OBS requires the highest number of burst ports due to the high transit traffic, while, on the other hand, it also requires the smallest number of wavelength hops due to the high statistical multiplexing gain. BoCS which does not switch any transit traffic, requires less burst-switched ports, however, at the cost of a significantly increased number of wavelength hops. Finally, OBTN successfully and very insensitive to the QoS level balances the required number of ports and wavelength hops

Applying the cost relations for Lambda Grid scenarios outlined in Section 3, in which bandwidth is considered a commodity and node equipment the major cost driver, OBTN constitutes an effective solution to reduce cost.

6. CONCLUSION

This paper presented application scenarios for virtual topologies in the context of OBS. It discussed key trade-offs with respect to statistical multiplexing and network size and derived consequences for network design. It is shown that network architectures with efficient contention resolution can be expected to benefit from densely-meshed virtual topologies in terms of the number of burst-switched interfaces. Finally, the OBTN architecture and dimensioning approach is described and representative performance studies are reported for a reference network scenario. The presented results show that OBTN can effectively reduce the number of burst switch ports and thus the overall network cost.

Future work should extend research on optimized combinations of wavelength-routed and burst-switched networks to migrate toward and efficiently implement OBS networks.

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