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Optical Burst Transport Network (OBTN) — A Novel Architecture for Efficient Transport of Optical Burst Data over Lambda Grids

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***Abstract*— This paper presents a novel network architecture, called Optical Burst Transport Network (OBTN), which can efficiently transport burst data over a virtual topology and reduce the port count of optical burst nodes.**

In OBTN nodes, bursts from attached optical feeder networks, e. g., metro networks, are multiplexed and transported to their egress OBTN node in one of two ways: *preferably* on direct end-to-end lightpaths set up between OBTN nodes or *alternately* on a relatively small number of hop-by-hop overflow burst wavelengths assigned to specific links which are shared among traffic flows. In contrast to *hybrid* network architectures which partition network resources completely and classify traffic at the edge for burst or circuit transport to isolate traffic classes, our OBTN approach integrates both resource types, i. e., circuit and burst wavelengths. It minimizes transit traffic in intermediate nodes and reduces node sizes while providing an overall very low burst-loss probability due to optimized contention resolution.

First, we outline an emerging optical network scenario. Then, we introduce the OBTN network and node architectures, and show the impact of key design parameters. Finally, we compare OBTN with optical burst switching (OBS) and an approach using optical edge traffic aggregation switches, called burst over circuit switching (BoCS), regarding performance, required network resources, and node complexity.

I. Introduction

Today, dynamic optical networks may be introduced realized by the Automatically Switched Optical Network (ASON) and Generalized Multiprotocol Label Switching (GMPLS) architectures, popularly referred to as *Lambda Grid*. Employing protocol-transparent wavelength switching, these networks can transport arbitrary client services and thus offload client layers by optically bypassing transit traffic at intermediate nodes.

Highly dynamic optical networks such as optical burst switching (OBS) [21] and optical packet switching (OPS) [22] allow fine-grain statistical multiplexing directly in the optical domain. An emerging application of such networks is envisioned in optical metro networks where traffic is less aggregated and also more bursty. When several such optical metro networks are attached to a core network node, efficient and seamless transport of burst data has to be provided across the core network. As traffic demands between individual metro networks across the core network might not reach full wavelength granularity—thereby leading to inefficient use of lightpaths between metro networks—a natural extension of OBS/OPS in the metro domain would be their application for burst transport in the core network. Although concepts presented in this paper are not restricted to this network scenario, we use it for illustration purposes in the following.

So far, research on OBS/OPS has concentrated on all-OBS network scenarios over physical topologies [11] or on basic virtual topologies but without considering contention resolution arguments [4], [5]. Transit traffic has to be switched at all intermediate nodes, which yields a high number of costly burst switch ports and may touch technological limits [3].

In contrast, the alternative concept of optical switches as traffic aggregators only at the edge of the network [18] multiplexes bursts/packets into end-to-end lightpaths. In this approach, which we refer to as *burst over circuit switching* (BoCS) here, nodes are interconnected in a fully (or densely) meshed topology thereby avoiding transit traffic.

In both concepts, link resources can be provisioned by the underlying Lambda Grid forming virtual topologies. While Figure 1(b) shows the *OBS virtual topology* corresponding to an example physical topology in Figure 1(a), the BoCS full-meshed virtual topology is depicted in Figure 1(c).

Topology design and link dimensioning directly impact both network performance and node size, and there are counteracting arguments to be considered. In OBS, transport resources are assigned to relatively few links and are shared by all traffic streams. While this requires additional burst switch ports for transit traffic, it yields a high statistical multiplexing gain. BoCS corresponds to the other extreme where few resources are assigned to a larger number of links which are dedicated to certain traffic streams. While no transit traffic has to be switched in the nodes, which reduces the number of burst switch ports significantly, the smaller capacity per link (e. g., in wavelengths) yields a much lower statistical multiplexing gain. In general, a low (high) statistical multiplexing gain translates into a high (low) overprovisioning factor to meet a QoS objective, e. g., a certain burst-loss probability.

Based on the above observations, we propose OBTN which targets an optimized combination of the OBS and the BoCS concepts to support efficient contention resolution. It prefer-

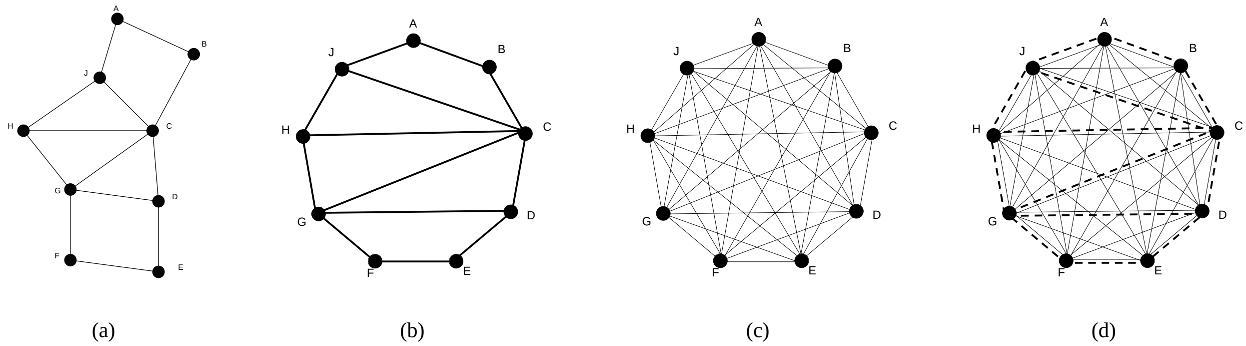

Fig. 1. Burst layer topologies: (a) physical topology, (b) OBS virtual topology, (c) BoCS virtual topology, and (d) OBTN virtual topology.

ably transports bursts over end-to-end lightpaths between core nodes to accommodate the majority of burst traffic but also uses additional shared hop-by-hop links to exploit statistical multiplexing in the optical domain. OBTN's design parameters can be used to tune the required network capacity and node size. Next-generation multi-service transport networks have to be able to offer high quality network services to upper layers, e. g., IP, in order for them to be able to guarantee a packet loss rate below 10^{-3} end-to-end across an entire public IP network reference path [14]. For the burst transport network, the focus lies thus on very low ingress-egress burst loss probabilities, e. g., 10^{-5}.

In this paper, OBS or OPS both refer to architectures in which data containers are switched in the optical domain, while signaling can be either out-of-band or inband with a possible separation of data and control in time. Assembly is performed at the edge of optical metro networks, there is no end-to-end reservation, and fiber delay line (FDL) buffers can be applied. Here, we will use OBS to refer to both concepts.

This paper is structured as follows. Section II introduces the OBTN architecture and architectural aspects. Section III describes our dimensioning and modeling approach. Section IV presents results of performance and node size studies. Finally, Section V summarizes the paper and discusses future work.

II. OBTN Architecture

This section introduces OBTN which employs a network and node design approach accounting for network resource efficiency as well as node complexity.

A. Network and node architecture

In the OBTN virtual network topology, nodes are interconnected by end-to-end lightpaths in a dense or fully-meshed virtual topology based on traffic demands in order to carry most of the traffic. Although these end-to-end lightpaths carry optical bursts we term them *circuit links* as they bypass intermediate OBTN nodes and are similar in operation to the BoCS approach. In addition to circuit links, hop-by-hop wavelengths are allocated to the relatively small number of links of the original OBS topology which are completely shared and can be used by bursts in case of contention in the circuit links. We term them *burst links*. Circuit and burst links can be considered as primary and overflow groups, respectively, in a classical switching system.

Figure 1(d) illustrates the OBTN virtual topology as an overlay of the topologies in Figures 1(b) and 1(c). Note that most OBTN node pairs are only connected by circuit links (solid) while some nodes are connected by circuit and burst links (dashed) in which case both resources can be administered together or separately based on policy.

Figure 2 shows an OBTN node which switches bursts originating from the attached metro networks into circuit or burst links. Also, they handle transit traffic entering on burst links. In order to achieve high network resource efficiency, both wavelength conversion and an FDL buffer are employed. Studies on node realization and an integrated performance and technology evaluation [3], [10] are work in progress.

FDL buffers lack random-access functionality and are not effective in resolving contention alone, but in combination with wavelength converters even very simple shared FDL buffers can drastically lower burst-loss probability [9], [11].

B. Discussion of architectural options

The combination of end-to-end circuit links and shared hop-by-hop burst links introduces several new degrees of freedom and architectural consequences which are discussed below.

Transport Mode: The decision on whether a burst is transmitted over the circuit link or over a path of burst links can be either made end-to-end or locally at each node.

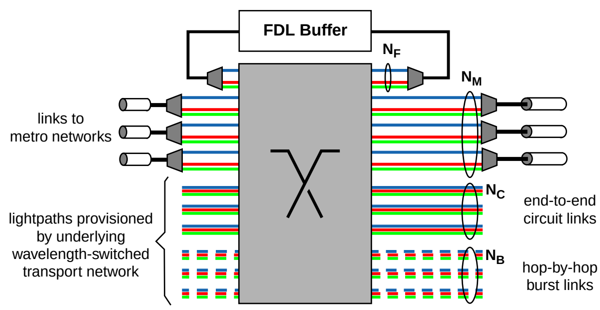

Fig. 2. Node architecture and dimensioning.

Routing: In OBTN routing can be classified as alternative with the circuit link as the primary route and a path of burst and cirucit links as the alternate route. As dimensioning of the burst links should reflect routing [12], we for now only consider shortest-path routing without additional deflection options.

Hunting Modes: Hunting modes describe the order in which available resources for burst transmission are searched in the nodes. The key dimensions are circuit link vs. burst link and transmission without or with using an FDL. Also, hunting can be sequential, integrated, or QoS-class-based. As traffic should be sent primarily over the direct circuit link, there are two main options for sequential hunting: (i) try circuit and burst link first without using the buffer; if this fails, use the buffer, or (ii) try the circuit link first without, and then with, the buffer; only if this fails, use the burst link without, and then with, the buffer. Performance evaluations showed that option (i) is beneficial as it better exploits the contention resolution options. Thus, we only present results for this option here.

Transport and hunting modes, as well as routing, could all apply adaptive decision algorithms.

Burst Control Information: Control information in OBS is usually signalled out-of-band, and first proposals assumed a separate control wavelength on each link. While this approach is efficient for links with many data wavelengths, different schemes should be adopted for links with only few wavelengths. Alternative out-of-band signaling schemes such as sub-carrier modulation (SCM) [16] or even alternative inband schemes [4] should be applied.

QoS and Survivability: Absolute or relative QoS differentiation should be realized on top of the best effort transport platform to achieve a more modular and extentable QoS framework, e. g., [7], [19]. Survivability of OBTN networks could be either realized in the burst layer [23] or by the underlying wavelength-switched service layer.

Grow-As-You-Go: OBTN does not require hundreds of wavelengths per link to achieve acceptable QoS. It specifically supports a *grow-as-you-go* evolution of OBS networks by first upgrading shared hop-by-hop burst links for smaller demand increases; later, when traffic increases qualify for end-to-end transport, OBTN offloads traffic to end-to-end circuit links. Also, an initial BoCS network [18] can be improved by adding few shared burst links on specific links to improve efficiency.

Challenge #1 – Burst Reordering: Regarding the possibility of burst reordering, delay variations due to large differences in propagation delay between bursts using end-to-end links and bursts using hop-by-hop links can be avoided by constraint-based routing end-to-end lightpaths in the physical topology. Delay variation introduced by FDLs and switching in intermediate nodes is negligibly small compared to the inter-arrival time of bursts belonging to the same end-to-end traffic stream, i. e., it should not be the cause of reordering.

Challenge #2 – Implications of Physical Infrastructure: The physical infrastructure, e. g., amplifiers, has to support burst-mode transmission [8] for burst transport in lightpaths.

C. Related Work

So far, virtual topology design for OBS has only been mentioned as a principal concept [5], and it has been applied in order to limit the maximum shortest path length [4]. These works do not capture the impact of virtual topology dimensioning on contention resolution in the burst layer. In contrast, OBTN is optimized towards effective contention resolution to provide an overall very low burst-loss probability while minimizing transit traffic and reducing node sizes.

Hybrid OBS/OCS network architectures aim at isolating traffic classes and providing differentiated transport services to client layers [6], [17], [20]. Thus, they partition network resources completely and classify traffic flows at the electro/optical interface of the edge router for OBS or OCS transport. Since these approaches assume that traffic is already highly aggregated at the E/O interface and qualifies at least for wavelength granularity, they are not applicable for transport of smaller burst data streams at the edge of metro networks.

The hybrid architecture described in [1] uses a specialized technology to only drop best-effort traffic to a packet switch matrix in OPS nodes while premium traffic bypasses a node by using a lightpath. The approach proposed in [2] aims at balancing network utilization by inserting specially marked IP packets in gaps of otherwise dedicated lightpaths. This approach does not consider optical switching and requires network state information of the IP and the WDM layers.

III. OBTN Dimensioning and Modeling

This section introduces key OBTN design parameters and the dimensioning of circuit and burst links as well as burst matrix ports in a unified manner for OBTN, OBS and BoCS. For illustration purposes and due to space restrictions, we limit this presentation to the case with uniform traffic demands but the extension to non-uniform demands is straightforward. Finally, the model used for performance evaluation is described.

A. Node and Link Dimensioning

In the network scenario outlined above, we assume that the traffic demand between all metro networks of any two arbitrary core networks nodes i and j is given by $A_{i,j}$ and that there are c core nodes in the network. Thus, the sum of all traffic a core node collects from the metro networks attached and sends to the other $c-1$ core nodes is $A = (c-1)A_{i,j}$.

To meet a certain QoS objective, a total transport capacity of $A_{i,j}\alpha$ has to be provisioned for each traffic demand $A_{i,j}$ along its path. We refer to α as the overprovisioning factor, $\alpha > 1$. This approach matches an operator's task of planning network resources based on traffic demands.

We divide this total capacity into a share β which is assigned to hop-by-hop burst links and a share of $1-\beta$ which is assigned to end-to-end circuit links. Since circuit links are provisioned as end-to-end lightpaths, their respective capacity $w_c = A_{i,j}\alpha(1-\beta)$ has to match or be rounded to an integer value. For burst links, resources are pooled among several nodes and thus their capacity per node pair does not have to be an integer value. For the network scenario used for

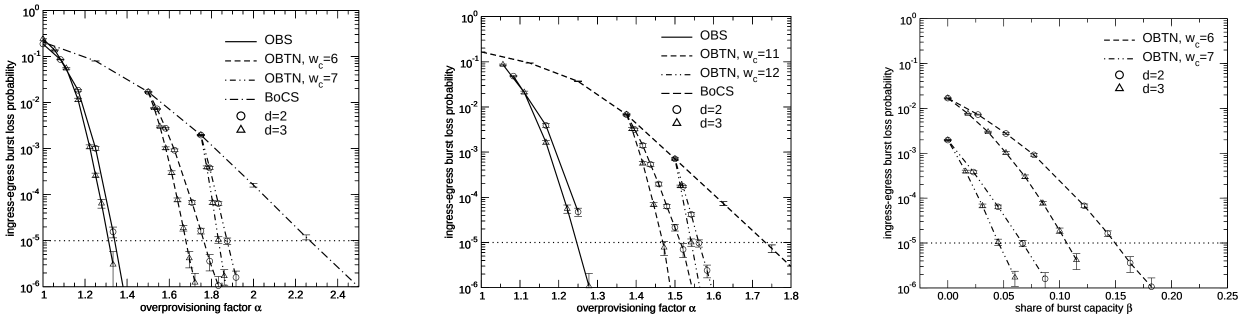

Fig. 3. Global overprovisioning factor α for (a) $A = 4$ Erlang and (b) $A = 8$ Erlang as well as (c) share of burst capacity β for $A = 4$ Erlang

performance evaluation, several combinations of α and β could be found which met the QoS objective, so we do not consider this to be a major restriction.

The ports of the OBTN node (Figure 2) can be distinguished in the following four categories for which we provide principal dimensioning rules:

- N_M ports connect each node to the metro networks attached. Assuming an average metro network utilization of ρ, their number can be estimated to be $N_M = A/\rho$.
- N_C ports are required for the end-to-end circuit links to all other core nodes which results in $N_C = A\ \alpha\ (1-\beta)$.
- For the N_B ports of the hop-by-hop burst links, we also have to take transit traffic into account, which from a network perspective, depends linearly on the average hop distance d of the *burst link* topology. Thus, N_B can be approximated by $N_B = A\alpha\beta d$.
- As the number of buffer ports N_F depends more on the architecture of the buffer and less on the traffic demands, we consider N_F to be an independent parameter.

The total number of ports is the sum of N_M, N_C, N_B and N_F. Note that dimensioning for OBS and BoCS is included in this representation for values of β being 1 or 0, respectively.

B. Performance Model

In order to allow for a comprehensive performance evaluation of OBTN using simulation and a fair comparison with OBS and BoCS we developed a unified performance model. A single node model captures all network effects such as transit traffic and FDL buffer sharing among different streams. For OBTN, the demand and characteristics of transit overflow traffic which depends on link dimensioning, hunting mode, and FDL buffer design are considered in detail by feeding back a delayed trace of respective streams leaving the node.

Ingress-egress performance values for the core network are derived by applying the well-known stream analysis [13], which yields a very good approximation for low burst-loss probabilities, to an effective path representation in which the different path lengths are weighted by their actual usage share collected in the simulation. Fundamental results for a wide range of networks can be obtained as size and physical topology of the core network are abstracted by mean hop distance d and average node degree.

IV. Performance Evaluation

In this section, we present results of simulation studies using the dimensioning approach and model presented in Section III. In our illustrative example, a node exchanges traffic with 9 other core nodes. In OBTN and BoCS, this node is connected to all other nodes by circuit links with w_c lightpaths each. For OBTN and OBS, three of the 9 core nodes are direct neighbors in the physical topology, i. e., also connected by shared links. Two of the 6 others are connected to each them, respectively. Circuit and burst link resources are administered separately.

Two scenarios for the traffic demands $A_{i,j}$ exchanged between core node pairs are used: a low traffic scenario with 4 Erlang and a high traffic scenario with 8 Erlang (1 Erlang is the equivalent of one wavelength channel here). Also, a smaller network with $d = 2$ and a larger network with $d = 3$ as average hop distance are used.

Bursts are generated following a Poisson process [15] and burst length is assumed to be exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $h = 10\,\mu s$ for 10 Gbps line rate. Full wavelength conversion capability is assumed in all core nodes. The FDL buffer contains a single FDL with delay $2h = 20\,\mu s$ and there are 32 wavelengths in this FDL. The OBTN transport mode is chosen such that decision on circuit or burst transport is performed locally.

The key performance metric used is ingress-egress burst-loss probability. Ingress-egress delay is not considered as the propagation delay in core networks (typically ms) is much higher than intra node delays and thus dominates.

A. Principal OBTN Behavior and Parameters

Figure 3 provides a unified evaluation of all three architectures, and it quantifies the trade-off between capacity on circuit links and capacity on burst links outlined in the qualitative discussion in Section I. Figures 3(a) and 3(b) depict the impact of the overprovisioning factor α on ingress-egress burst-loss probability for the two traffic scenarios. It can be seen that OBS requires a smaller overprovisioning factor α compared to OBTN and BoCS to reach a burst-loss probability of 10^{-5} due to its higher statistical multiplexing gain. The better performance of OBTN compared to BoCS results from the few shared resources on burst links provided for overflow.

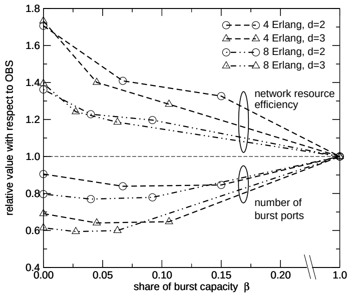

Fig. 4. Relative network resource efficiency and number of burst ports.

In OBS and OBTN, burst-loss probability is slightly lower for larger networks ($d = 3$) as burst links have absolutely more resources yielding a better multiplexing gain. In BoCS, mean hop distance has no impact due to the full-mesh topology.

Note that, for OBTN, the burst capacity share β increases implicitly with α along curves with constant w_c. Curves for different values of w_c reach the 10^{-5} requirement for different values of α and β. Thus, Figure 3(c) shows the impact of the share of burst capacity β for the low traffic scenario. Here, α increases along curves of constant w_c for increasing β. It can be seen that the loss objective can be reached with values of β between 4% and 15%, and that networks with a larger hop distance can again achieve lower losses for the same β value.

B. Comparison of Node and Network Resources

This section compares OBS ($\beta = 1$), BoCS ($\beta = 0$), and OBTN with respect to network resource efficiency and number of burst ports to quantify the trade-off outlined in Section I. Network resource efficiency is expressed by the respective values of α for a burst-loss probability of 10^{-5}. Number of burst ports is calculated according to the model in Section III with a value of $\rho = 0.5$. Numbers are normalized to OBS.

Looking at network efficiency in Figure 4, it can be seen that OBTN encounters a penalty compared to OBS of 20–40%, but is clearly more efficient than BoCS. The curves are grouped by traffic demands which decide on the amount of resource sharing while the network size has only minor impact here.

Regarding the number of burst ports in Figure 4, we can see that OBTN performs equally well or even slightly better than BoCS and that it can save between 20–40% of ports compared to OBS. Here, curves are grouped by mean hop distance which decides the amount of transit traffic. Note that this reduction is realized considering all the add/drop ports for the metro networks, and not only the core network ports. For reference, bufferless OBS requires 20–40% additional network resources and approx. 30% more burst ports than OBS with an FDL.

This integrated view for a given QoS objective, shows that OBTN can effectively reduce the number of burst ports compared to OBS. In a Lambda Grid network scenario, in which bandwidth is commonly considered a commodity and node equipment the major cost driver, this approach thus constitutes an effective solution to reduce cost.

V. Conclusion

This paper introduced OBTN, an architecture for efficient transport of optical burst data optimized towards minimizing transit traffic and reducing node sizes while providing an overall very low burst-loss probability. Compared to OBS, the number of ports in the burst matrix can be reduced by 20–40% with a penalty in network resource utilization of 20–40% depending on traffic demands and network size. This unified comparison of a pure OBS network, OBTN and a network with traffic aggregation only at the edge quantifies for the first time the impact of contention resolution on virtual topology dimensioning and node size in OBS/OPS networks.

Future work will consider the impact on physical node design, extend performance evaluations towards non-uniform traffic demands, other traffic models, and buffer architectures.

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