Trends in Optical Burst Switching

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ABSTRACT

Optical burst switching (OBS) has been proposed in the late 1990s as a novel photonic network architecture directed towards efficient transport of IP traffic. OBS aims at cost-efficient and dynamic provisioning of sub-wavelength granularity by optimally combining electronics and optics. Optical bursts cut through intermediate nodes, i. e., data stays in the optical domain at all times, while the control information is signaled out-of-band and processed electronically. In contrast to optical packet switching, OBS aggregates and assembles packets electronically into bursts of variable length according to destination and QoS class at the edge of the network.

This paper surveys current trends in OBS and discusses proposed solutions for burst reservation and scheduling, burst assembly, contention resolution and QoS provisioning as well as design and scalability of OBS nodes. Also, it looks at the question of the optimal burst size, which has been around from the very beginning of OBS, based on recent trends and results. On the one hand, burst size and burst characteristics are influenced by client layer traffic and burst assembly scheme. On the other hand burst size and burst characteristics have an impact on network performance and node architectures. Finally, consequences of burst durations in the microsecond and millisecond range are presented and compared.

1. INTRODUCTION AND MOTIVATION

Since its introduction as a new switching paradigm for optical transport networks,[1,2] optical burst switching has received huge attention both from the academic, vendor and even the operator point of view. During the .com boom in the late 1990s, prototypes and even commercial products seemed only a few years ahead. While optical packet switching (OPS) research already had started in the early 1990s but still had to overcome severe technological hurdles, optical burst switching seemed to offer the dynamics and flexibility presumably needed to cope with the exploding Internet traffic with less complex technology than OPS, i. e., with less capital expenditures.

Today, transport network traffic still increases with a hundred percent per year and data has surpassed voice in traffic volume. However, the downturn of the industry has shifted the focus of operators from the introduction of highly innovative network technologies to cost-efficient operation of existing network technologies, i. e., to lowering operational expenditures. This slowdown in network evolution has moved a potential introduction of OBS networks several years into the future. As OBS is still in its infancy and several optical components needed are still immature, this situation can be used to thoroughly analyze and assess all options and to identify the best solutions both for architectures as well as for protocols.

During the past years, definition of optical burst switching networks (Figure 1) has become less clear due to the large number of new proposals. Still, following concepts can be regarded as defining for OBS: (i) client layer data is aggregated and assembled into variable length optical bursts in edge nodes, (ii) control header packets are signaled out-of-band, are processed electronically in core nodes and used to set up the switch matrix before the data bursts arrive, (iii) data bursts are asynchronously switched in core nodes and stay in the optical domain until they reach their destination edge node.

Bandwidth granularity and switching complexity of OBS are in between those of wavelength routing (WR) and OPS networks. With respect to wavelength routing networks, OBS provides more bandwidth flexibility, i. e., it can better adapt to changes in the traffic pattern, but needs faster switching and control technology. Regarding optical packet switching, OBS requires less complex technology as it extensively uses aggregation to

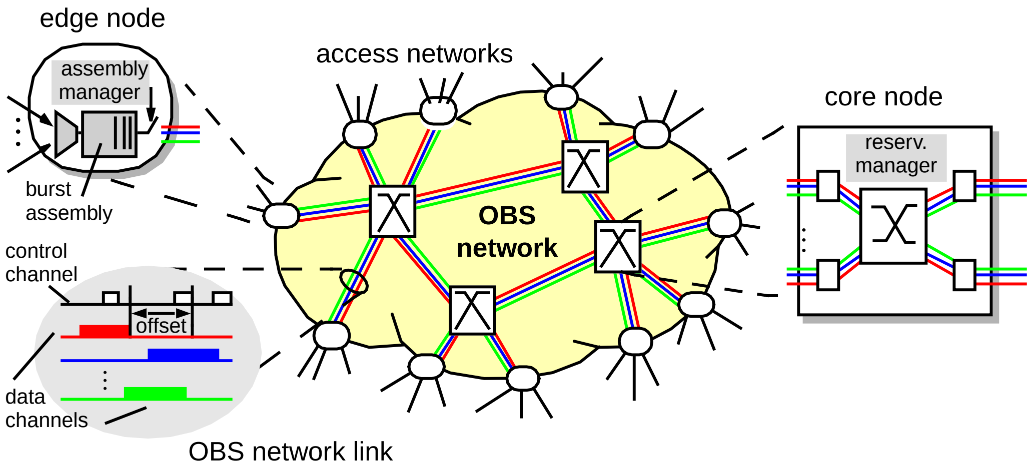

Figure 1. Network scenario for optical burst switching

form larger containers and does not mandate processing of optical inband headers. Also, in contrast to several OPS architectures, there is no need for synchronization in OBS.

Although the fact that OBS lies in between WR and OPS regarding granularity has been clear from the very beginning of OBS, the question in which order of magnitude the optimal burst size is has not been answered eventually. While some research topics in OBS can be treated independent of burst size it is really essential for most solutions concerning performance and realization as will be seen in the following sections. Therefore, this paper analyzes recent trends and results in order to contribute to finding an answer to the question of the optimal burst size.

The remainder of this paper is structured as follows: Sections 2–5 review recent trends and results in OBS research regarding burst reservation and burst scheduling, contention resolution, aggregation and assembly, quality of service (QoS) as well as node design. Finally, Section 7 summarizes this paper and compares consequences of burst sizes in the microsecond and millisecond range.

2. RESOURCE MANAGEMENT

2.1. Burst reservation

Reservation of bursts in the OBS network is one of the key issues regarding performance. Depending on network dimension and granularity, i. e., burst size, either the tell and go (TAG) or the tell and wait (TAW) concept are favorable.[1,3–5] TAW assumes classical end-to-end (virtual) path setup with acknowledgment, which leads to a setup delay for bursts in the ms range in long-haul transport networks. In case intermediate switches are already set during the setup phase the bandwidth wasted can be much higher than the bandwidth actually needed for burst transmission. Resource management in TAW can be either performed centrally as in wavelength-routed OBS (WR-OBS)[6] or by a distributed setup protocol.[4,7]

In TAG, burst transmission is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated immediately when or shortly after the burst has been assembled and the control packet has been sent out. This is also referred to as one-pass reservation. Due to the sub-millisecond burst duration assumed in most work on OBS the TAG concept is usually applied (among others[1,2,5,8–10]). In metropolitan area networks (MAN), distances are short, i. e., setup delay and overhead are also small compared to wide area networks (WAN) and thus TAW obviously performs better than TAG.[11]

If burst transmission in TAG is delayed with respect to the control header, this delay is referred to as offset time and can be reduced in core nodes to compensate processing times. In this case, information on the number of nodes on the path (total expected processing time) has to be considered for determining the offset time. In general, the topic of offset time and its impact on burst scheduling and QoS is one of the most controversially discussed.

Due to the fact that burst reservation has been one of the first topics studied in OBS and the fact that both solutions for (virtual) path setup are well known, e. g., from ATM, relatively few work has been devoted to this topic recently.

2.2. Burst scheduling

While burst reservation considers end-to-end burst transmission, burst scheduling focuses on assigning and managing resources for individual bursts in OBS nodes.

Burst scheduling schemes can be classified based on the duration for which resources are scheduled for a burst.[5] A rather simple approach occupies resources from the time the control packet requests the resource until the resource is explicitly released,[4, 7] e. g., by an in-band terminator. Thus, burst size does not have to be known at the start of burst transmission. The only information that has to be kept record of in core nodes is whether a wavelength is currently available or not. *Reserve-a-limited duration* (RLD) schemes require the sender to signal the start and end of a burst and resources are explicitly reserved until the end of burst transmission. For each resource, the time when it will become idle again is recorded. Horizon[2] and LAUC[9] are RLD schemes. Finally, *Reserve-a-fixed duration* (RFD) schemes consider the exact start and end time of bursts for resource scheduling, i. e., in principle gaps (or voids) between already reserved bursts can be used for newly arriving bursts. JET[12] and LAUC-VF[9] are RFD schemes. Recently, several proposals have been published which optimize resource allocation of RLD and RFD schemes by improving wavelength selection or by minimizing voids (among others[13, 14]).

In case no offset time between control header and data burst is used at all, the three basic scheduling schemes have the same performance. RFD schemes only yield superior performance over RLD schemes in the presence of voids which are generated by scheduling requests with large offset times. Such voids can only be reused if a burst that has a smaller offset time, i. e., requests resources later, and fits into the void. Relevant scenarios regarding voids are OBS approaches which exhibit a large variation in offset times, e. g., due to coarse grain offset reduction in core nodes or due to an additional QoS offset (c. f. Section 5). Also, OBS nodes with FDL buffers, in which FDL and output wavelength are reserved at the same time and can benefit from RFD.[15]

Although offset times are beneficial in compensating processing delays without applying additional resources several problems can be attributed to offsets: Unfairness between bursts which have a different number of nodes to traverse to their destination node, dependence of performance on burst length characteristics[16] and insufficient offset times when deflection routing is applied.[17]

As RFD schemes have to record exact start and end times of all reserved bursts—or alternatively of all existing voids—they have been considered to be too complex for realization in core nodes. However, recently actual implementations of JET schedulers have been presented. One approach targets bursts in the microseconds range and scales up to more than 100 wavelength channels. It is implemented in an FPGA and reserves a burst in approx. 60ns.[18, 19] Another approach manages and searches gaps in a data structure implemented in software and running on a regular workstation and is fast enough for bursts with a duration in the millisecond range.[14]

In order to minimize transmission delay and to limit complexity in the control module of OBS core nodes, most approaches for burst scheduling serve requests strictly on a first-come first-serve basis. However, some more recent proposals use increased offset times and queue requests in order to be able to serve the request queue in a different order, e. g., according to classes of service.[20, 21] Also, window-based algorithms are reported in literature to optimize resource utilization or minimize the penalty of blocking switch architectures.[22] Still, in order to make control modules scalable only a very limited amount of processing in core nodes is feasible.

3. CONTENTION RESOLUTION

Optical burst switching inherently relies on statistical multiplexing in order to achieve good utilization in presence of bursty traffic. As a consequence, temporary overload situations called contention situations occur which could lead to burst loss. For OBS to be a feasible network technology for transport networks, burst loss probability has to be very low, e. g., in the range of 10^{-6}. Thus, efficient contention resolution is required in OBS.

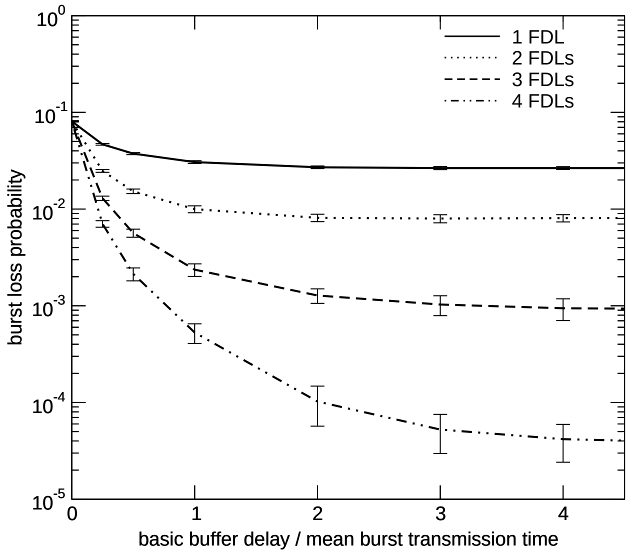

Figure 2. Burst loss probability vs. the delay of the shortest FDL in the buffer

In an all-optical burst switch, a reservation conflict exists if the wavelength on which a burst arrived to he node is blocked on the designated output fiber by a different burst. Such a contention situation can be resolved in one or a combination of the following three domains:

- *Wavelength domain:* By means of a wavelength converter, a burst can be sent on a different wavelength channel to the designated output fiber. Thus, all wavelength channels of an output fiber can be considered a single shared bundle of channels.
- *Time domain:* In an fiber delay line (FDL) buffer, a burst can be delayed until the contention situation is resolved and the wavelength becomes available. In contrast to buffers in the electronic domain, FDLs only provide a fixed delay and data bursts leave an FDL in the same order in which they entered, i. e., they do not have random access functionality.
- *Space domain:* In deflection routing, a burst is sent to a different output fiber of the node and consequently on a different route towards its destination node. Thus, deflection uses the entire network as a shared resource for contention resolution.

Almost all work on OBS assumes contention resolution by *full* wavelength conversion, i. e., a dedicated wavelength converter is provided for each input or output wavelength. For a low to medium load, this provides a low burst loss probability because all wavelength channels of an output fiber can be shared among all bursts directed towards this output fiber.[2,5,16,23–25] For a high load, the number of wavelength channels has to be very large to reach burst loss probabilities in the order of 10^{-6} or less, e. g., 350 wavelength channels are needed to carry a load of 0.8 Erlang per wavelength channel at this loss rate.

Wavelength conversion has also been complemented by providing a number of FDLs in an FDL buffer. It has been shown that even FDL buffers with rather simple functionality and low technological requirements can improve OBS performance significantly.[9,15,23,26] Figure 2 shows how burst loss probability is reduced by increasing the FDL delay of feedback FDL buffers with 1, 2, 3 or 4 FDLs for 16 wavelengths per fiber and FDL and a load per wavelength channel of 0.8 Erlang. In contrast to OPS which does not apply RFD scheduling, buffer and output scheduling in OBS nodes with FDLs is more flexible and more robust regarding the FDL delay as voids can be reused.[15]

When using FDL buffers in OBS nodes, the physical length of the FDL has to be considered. Several physical constraints like attenuation, chromatic dispersion and non-linear effects etc. limit the feasible length of the FDLs.

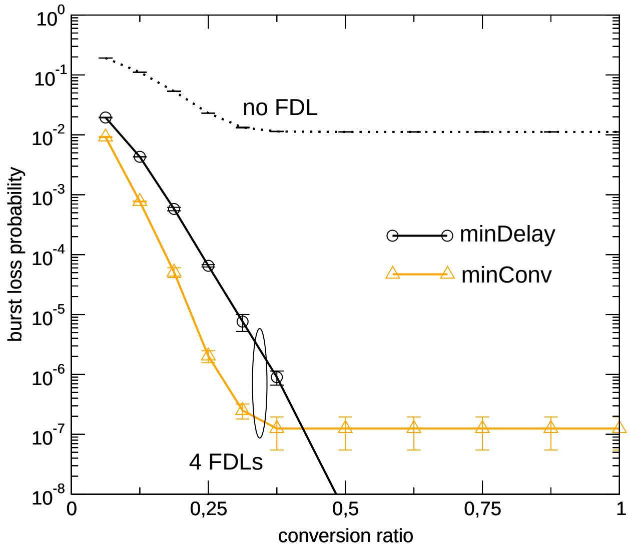

Figure 3. Optimized combination of wavelength conversion and FDL buffers

Even if the FDLs are dispersion compensated if needed, the maximum length of an FDL is limited by the power budget. Assuming that in maximum a single erbium doped fiber amplifier (EDFA) is used per FDL, all FDLs used for contention resolution have to be shorter than a typical EDFA span of 80 km which limits the maximum FDL delay to $266\mu s$ ($c = 2 \cdot 10^8 m/s$). Previous work showed (Figure 2) that FDL delays should be in the order of a few mean burst durations in order to be efficient.[23, 26] In an FDL buffer with 4 FDLs, e.g., a delay of 8 mean burst durations for the longest FDL is a good choice. From the $266\mu s$ it can be derived that in order for this FDL buffer to be feasible the mean burst length has to be in the order of 10 kbyte, 41 kbyte and 166 kbyte for 2.5, 10 and 40 Gbps respectively. Thus, combining performance and technology arguments, mean burst lengths in the order of Mbytes cannot be realistically stored in FDL buffers.

Deflection routing has also been analyzed in the context of OBS for irregular mesh networks.[17, 27, 28] In general, the path a deflected burst takes through the network should be kept as short as possible in order to minimize resource consumption. In OBS schemes which apply offset times, the problem of *insufficient offset times* has to be avoided, i. e., it has to be ensured that there always be a large enough offset between control packet and data burst even if extra nodes are traversed. Thus, it is proposed to use FDL buffers to increase offset times in intermediate nodes prior to deflection.[17]

By intelligent combination of different contention resolution strategies cost and performance of OBS nodes can be optimized. As wavelength converters are technologically complex and expensive,[29] the concept of *partial* wavelength conversion, i. e., only a limited number of wavelength converters is available in a pool, has also been investigated with a focus on the optimized combination with FDL buffers.[30] It is shown that depending on the number of converters and the complexity of the FDL buffer a different order for probing both resources should be applied. Figure 3 depicts the burst loss probability versus the relative number of converters in the pool for a node with 8 input and output fibers, 8 wavelengths per fiber and FDL and 2 or 4 FDLs in the buffer as well as for a load of 40%. First, it can be seen that application of an FDL buffer has a significantly reduced burst loss probability compared to the bufferless case. Also, for a small conversion ratio, i. e., number of converters in the pool, a strategy which minimizes converter usage by preferring buffering over conversion can yield lower losses than a strategy that minimizes delay by preferring conversion over buffering.

Burst segmentation or composite burst switching is an approach for contention resolution which is solely based on burst scheduling: It tries to minimize the data volume discarded by not dropping an entire burst but only dropping the part of a bursts which actually conflicts with another burst[10, 31]

4. AGGREGATION AND ASSEMBLY

Traffic aggregation and burst assembly offers an additional degree of freedom but also requires an additional network component compared to OPS. Bursts are either assembled based on time, i. e., a timer is set to limit the waiting time of the oldest packet in an assembly queue, or based on size, i. e., minimum or maximum burst size criteria, or based on hybrid schemes considering both time and size.[32–34] Although burst length distribution has no impact on performance in pure loss systems (assuming Poisson arrivals), it becomes essential for RFD reservation schemes with offsets, e. g., JET with QoS offsets.[16]

Burst assembly can also perform admission control functions. It checks whether a certain traffic class complies to the profile agreed on and marks bursts with out-of-profile traffic accordingly.[33] Thus, core nodes can decide which bursts should be discarded preferably in contention situations without keeping per class state.

As TCP is the predominant transport layer protocol of the Internet, the impact of burst assembly delay on TCP performance has been studied.[35] It is shown that the timeout value for time-based assembly has to be carefully chosen in order not to interfer with TCP timeout calculations which cause reduced goodput. In order to synchronize assembly with TCP's congestion control mechanism an adaptive assembly algorithm is also proposed.

Initially, aggregation and burst assembly in OBS were mostly considered a mean to reduce the complexity of the optical layer, e. g., by application of slower switching technologies. However, the idea to reduce the detrimental effects of bursty and self-similar Internet traffic by using burst assembly to shape traffic appeared soon. The claim that burst assembly could reduce traffic self-similarity[36] was disproved by analysis and simulation of both synthetic traffic and traffic traces.[37–39] Still, burst assembly can smooth traffic on short time-scales, i. e., reduce its variability, which leads to a performance improvement compared to unaggregated packet traffic like in OPS.[38–40] Here, longer assembly times lead to improved smoothing. Also, it has been shown that burst assembly of Internet traffic modeled as Fractional Gaussian Noise (FGN) yields a lower burst loss probability than Poisson traffic, i. e., analysis based on Poisson traffic provides an upper bound regarding FGN Internet traffic.[38]

5. QUALITY OF SERVICE

One of the central ideas of IP-over-WDM is to allocate functionality where it can be best implemented and to minimize redundancy in functionality. As the IP layer does not inherently support QoS, the optical layer could implemenent QoS schemes and provide this service to the IP layer. In order to provide service differentiation directly in OBS several approaches have been proposed. Extending a classification in[33] approaches for providing QoS are classified in the following:

- *Additional QoS offset*: Offset-based schemes rely on the fact that a greater offset time translates into an earlier reservation, and thus into a higher probability of successful reservation. While the total blocking probability remains constant for RFD burst scheduling, high priority bursts which are assigned an additional QoS offset can have significantly reduced blocking.[23] Analysis showed that the additional QoS offsets have to be in the order of a few mean burst durations. However, offset-based schemes have the drawback that burst loss probability of the high priority class is very sensitive to burst length characteristics of the low priority class.[16] Also, offset-based QoS leads to problems if FDL buffers are applied.[26]

- *Preemption*: In preemption schemes, high priority bursts can preempt bursts of lower priority in case of a reservation conflict. An extension to this approach limits preemption to out-of-profile bursts.[41] In general, preemption of bursts has the disadvantage that resources in downstream nodes are either wasted or that these nodes have to be informed accordingly which increases signaling load.

  Combining burst segmentation and preemption, the priority of a burst decides whether the tail of an already reserved burst is dropped, i. e., the burst is partially preempted, or whether the head part of the newly arriving burst is dropped.[42] A new approach for preemption-based QoS with burst segmentation is to put high priority packets at the head of a burst and low priority packets at the tail of a burst. In this scheme, the tail of bursts are dropped in case of contention which then mostly concernes low priority bursts.[32]

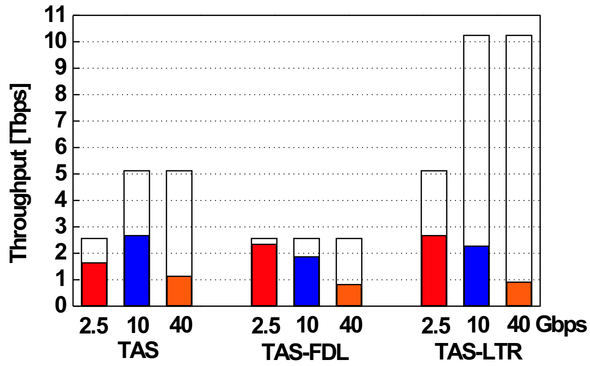

Figure 4. Results of a scalability analysis of TAS nodes, taken from[46]

- *Intentional dropping*: Similar to schedulers in the electronic domain which provide proportional service differentiation by intentionally dropping packets in order to maintain a certain loss probability, some approaches provide service differentiation by actively dropping bursts.[33, 43]
- *(Re)scheduling of control packets*: In case burst control packets are not strictly scheduled on a first-come first-serve basis but according to their QoS class service differentiation can be provided.[20] However, this causes additional and non-deterministic processing delay for low priority burst control packets and requires more complex reservation control modules.
- *Resource reservation*: These schemes do not grant all bursts access to all resources, i. e., they do not perform *complete sharing* but reserve some resources, e. g., for high priority bursts. *Static partitioning*, *partial sharing* or *trunk reservation* are well-known concepts for resource reservation which can provide different degrees of isolation and performance.[33, 44]

Although no clear trend can be formulated regarding concepts for QoS provisioning in OBS, stability, robustness and ease of implementation will be key decision criteria. In this context, resource reservation schemes will play an important role.

6. NODE DESIGN AND SCALABILITY

Architectures for highly dynamic photonic switches are based on different concepts than their electronic counterparts. This is due to the still comparably basic functionality of photonic components which implies several technological and physical constraints. During the past 10 years, considerable work has been put into design of optical cross-connects and optical packet switches (among others[45]) as well as into the improvement of photonic components like semiconductor optical amplifiers (SOA), array waveguide gratings (AWG) and tunable wavelength converters (TWC). Now, OBS node design can greatly benefit from this rich experience although the paradigm of asynchronous switching of variable length bursts requires adaptations into most designs.

In order to have negligible switching overhead the switching time has to be much smaller than the average burst size. Although several switching technologies are known only few have reached a level of maturity to be considered for OBS nodes.[47] Matrices based on micro-electromechanical systems (MEMS) have the potential to scale to large sizes but have switching times in the ms range and are thus hardly applicable for OBS—probably not even for WR-OBS. Broadcast-and-select architectures applying SOA gates as well as AWG architectures employing fast TWCs for switching provide sub-microsecond switching times and are therefore candidates for realizations of OBS nodes. Unfortunately, the coarser granularity of OBS compared to OPS cannot be exploited here and similar switching technologies have to be used.

	Burst duration	
	microseconds	milliseconds
Burst reservation	only TAG	TAG, possibly TAW
Burst scheduling (load on control module)	complex (high)	less complex (low)
Buffering in FDLs	feasible	unlikely
Burst assembly: - Smoothing - Impact on TCP	 some little/no	 significant possible
Quality of service: - offset-based	 small additional delays	 extensive additional delays
Node design requirements	similar to OPS	more relaxed

Table 1. Comparison of OBS with microsecond and millisecond burst duration

Tune-and-select (TAS) is a broadcast-and-select architecture which has been adapted for OBS. An integrated evaluation of technology (signal degradation due to noise and crosstalk) and performance showed that TAS nodes scale to throughput values in the terabit per second range under dynamic traffic load depending on the bitrate of the wavelength channels.[46, 47] Figure 4 depicts maximum throughput (static traffic) and effective throughput (Poisson traffic, shaded areas) of an OBS node with 8 input and output fibers and 2.5, 10 and 40 Gbps bitrate. Apart from the TAS base architecture (left), an extension employing one dedicated FDL per output fiber (center) and a variation with only limited tuning range wavelength converters (right) are included. While the maximum throughput is defined by the maximum number of wavelengths for which this node can be built at a certain bitrate the effective throughput is defined to yield a burst loss rate of 10^{-6}. It can be seen that effective throughput can be much lower than the maximum throughput depending on the architecture and the bitrate.

As integrated electronic multi-chassis core routers also target the terabit per second range[48] the comparison between such electronic IP routers and OBS nodes has to consider cost of switch matrices and switch ports. As SOAs and TWCs are not commercially available in large numbers, i. e., prices are still very high, the cost of an OBS switch cannot be estimated realistically. However, even if component prices declined significantly, the large number of components needed for a switch matrix would still make an OBS switch a rather expensive network element.

7. CONCLUSION

This paper surveys recent research and trends in optical burst switching with respect to resource management, contention resolution, burst assembly, QoS and node design. Several topics discussed in the paper are closely related to the task of finding a range for the burst size which is advantageous for resource management, contention resolution, traffic smoothing by burst assembly and node design. Currently, two main trends regarding burst size can be identified: The first trend is to keep OBS as flexible and dynamic as possible which leads to an average burst duration of few tens of microseconds. The second trend is to aggregate a large amount of traffic which leads to an average burst duration of a few milliseconds.[6, 14] Table 1 compares both trends based on conclusions of research work surveyed in this paper.

During the past years, research on OBS on the one hand has provided a large number of proposals for architectures and algorithms and new approaches for performance analysis. On the other hand, these activities have created a much clearer view on the overall benefits and shortcomings of this new switching paradigm. Still, one of the key questions regarding both OBS and OPS has not been answered yet: the question of how dynamic a transport network carrying highly aggregated traffic streams really has to be.

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