COST 266, WG2

Technical Committee Telecommunications

COST **266, workgroup 2**

Advanced Infrastructure for Photonic Networks

Optical Packet and Burst switching

Report

Preface

This report contains EPS (Encapsulated Post Script) figures, and should therefore be printed on a postscript printer or viewed in a Ghostscript viewer (available free).

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8.1 Introduction

8.1.1 Definition and Motivation of OBS

Optical Burst Switching has been proposed as a new switching paradigm [6] for optical networks and has emerged as a candidate for the optical transport layer of the next generation Internet. Bandwidth and quality of service (QoS) requirements of future Internet services, e.g., voice-over-IP (VoIP) or distributed multimedia applications, as well as the currently exploding number of high-speed Internet access lines motivate a scenario in which optical transport capacity can be provisioned on the time-scale of IP-layer dynamics. In OBS networks (Figure 1), these dynamics can be supported by edge nodes that aggregate traffic and assemble it into variable length optical bursts as well as core nodes that switch these bursts in optics.

OBS is a fast circuit switching technique (FCS) that provides a granularity in between wavelengths and packets but neither mandates the use of optical header processing nor optical buffering, i.e., it requires less complex technology than optical packet switching. A key characteristic is the hybrid approach, in which control information is signaled out of band and processed electronically while data stay in the optical domain at all times. Another key concept of OBS is one-pass reservation, i.e., transmission of a burst is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated as soon as the burst has been assembled.

Efficient contention resolution in core nodes is essential in order to achieve a low burst blocking probability despite one-pass reservation strategy and statistical multiplexing. Contention resolution can be performed in the time domain, wavelength domain or space domain. In this report, FDL buffers as well as shared wavelength converter pools are investigated. Less complex FDL buffer architectures than the ones proposed in the context of OPS [7] can be deployed in order to reduce the loss probability of OBS nodes and are shown to improve performance significantly [4, 17, 26]. So far, all proposals and investigations assumed contention resolution by *full* wavelength conversion. This has been shown to provide low loss probabilities because all wavelength channels of an output line can be shared among all bursts directed towards this output line [17, 22, 14, 13, 20]. As wavelength converters are technologically complex and expensive, their usage should be minimized without significant degradation of performance in an OBS core node. Therefore, performance of an OBS node which employs only *partial* wavelength conversion, i.e., wavelength converters are only

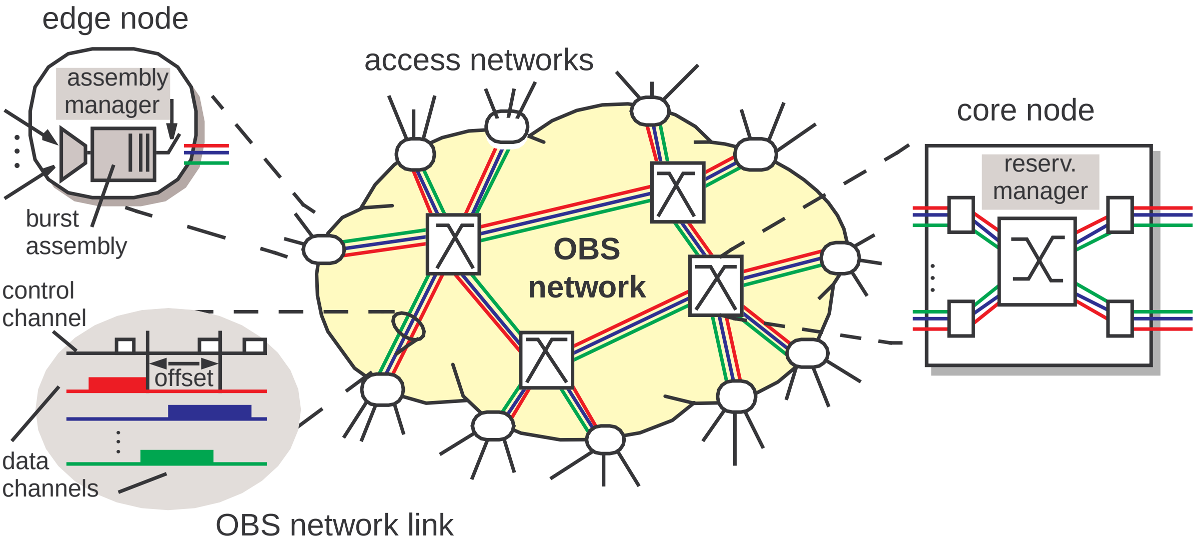

Figure 1: Network scenario for optical burst switching

available for a limited number of bursts at a time, is studied. In this scenario, tunable wavelength converters (TWC) are shared in a converter pool and can be assigned to a wavelength channel in case of contention. Partial wavelength conversion has been investigated for bufferless optical packet switches under the assumption that all packets have identical length [17, 21] and in the context of optical cross-connects for wavelength routed optical networks [11, 12]. It is reported that depending on node dimensioning, traffic model and converter assignment strategy a substantial number of converters can be saved. However, performance of partial wavelength conversion has not been evaluated under self-similar traffic and in combination with simple FDL buffers which are both interesting topics.

8.1.2 JET Reservation Strategy

As depicted in Figure 1, burst transmission works as follows: IP packets are assembled to data bursts [13] in an OBS edge node. Before transmitting a burst, a reservation request (control packet) is sent on a dedicated channel, e.g. on a separate wavelength. After a basic offset and without waiting for acknowledgement of successful reservations, the data burst is released into the network. This basic offset has to be large enough to electronically process the control packet and set up the switching matrix in core nodes on the path. When a data burst arrives in a core node the switching matrix has been already set up, i.e. the burst is kept in the optical domain.

Different mechanisms have been proposed for reservation of wavelengths as well as FDL's for burst transmission. In [14] and [4] we give a detailed overview, classification, and performance comparison of the most important proposals. In JET [18] which is called *void filling* in [26], predetermined start and end times of each burst transmission are considered for reservation. This allows both efficient utilization of resources and service differentiation. The latter is achieved by assigning an additional quality of service (QoS) offset to a high priority burst which leads to a higher probability of successful reservation which is illustrated in Figure 2 for a scenario with three wavelengths. The low priority burst cannot be served as all wavelengths are already occupied during its transmission time whereas the high priority burst can be served on an available wavelength due to its much larger offset. However, as larger offsets cause additional fixed delay this offset has to be chosen carefully [3].

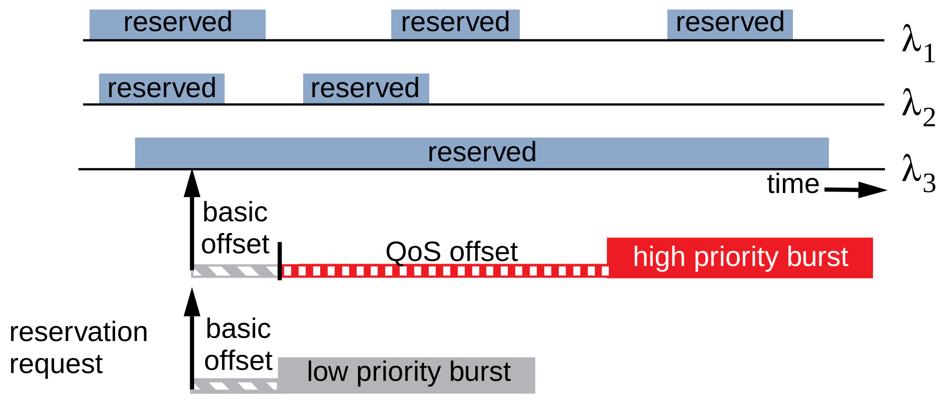

Figure 2: Reservation scenario for bursts of different classes

8.1.3 Overview of Investigations

Section 2 discusses options and key design parameters for contention resolution in OBS nodes which employ wavelength converters and simple FDL buffers. Also, FDL buffer architectures, buffer reservation strategies and converter pool architectures which are investigated section 4 are introduced. Section 3 describes the traffic models and simulation scenario used for the performance evaluation. Section 4.1 focuses on the dimensioning of FDL buffers while section 4.2 investigates converter pools for OBS. Finally, section 4.3 finally concentrates on the combination of FDL buffers and converter pools.

8.2 Contention Resolution

8.2.1 Options for Contention Resolution

In an all-optical burst switch, incoming bursts should primarily be sent on the same wavelength to their designated output line. In case of a reservation conflict, i.e., the wavelength on this output line is already reserved, one or a combination of the following three major options for contention resolution can be applied.

- *Wavelength domain:* By means of wavelength conversion, a burst can be sent on a different wavelength channel of the designated output line.

- *Time domain:* By applying an FDL buffer, a burst can be delayed until the contention situation is resolved. In contrast to buffers in the electronic domain, FDL's only provide a fixed delay and data leave the FDL in the same order in which they entered.

- *Space domain:* In deflection routing, a burst is sent to a different output line of the node and consequently on a different route towards its destination node. Space domain can be exploited differently in case several fibers are attached to an output line. In this case, a burst can also be transmitted on a different fiber of the designated output line without wavelength conversion.

In contrast to using a wavelength converter, an FDL buffer or a different parallel fiber deflection routing does not resolve contention locally in a single node but reroutes over-load traffic to neighboring nodes. Therefore, it depends heavily on network topology and routing strategy. Investigations comparing the efficiency of different contention resolution strategies

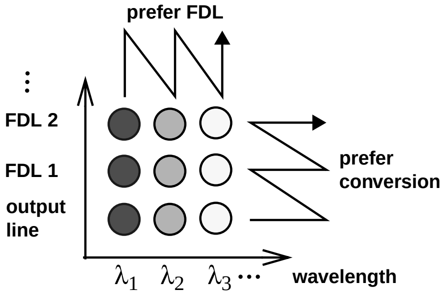

Figure 3: Usage strategies for wavelength converters and FDL's.

have shown that it results in only limited improvement [22]. Deflection routing is not considered in this report.

8.2.2 Key Design and Dimensioning Parameters

Performance of contention resolution in an OBS node is influenced by several parameters. Following list provides an overview of the key design parameters and introduces strategies for the combination of FDL buffers and wavelength conversion.

- *Node functionality:* This relates to the availability and architecture of wavelength converters and FDL buffers in the node. Nodes can provide no, full or partial wavelength conversion. In the latter case, converters are organized in a converter pool and can be used in case of a reservation conflict. Converters can be either placed at the input or at the output of the switch. A node can employ no buffers at all or FDL buffers of different complexity and architecture, e. g., feedback or feed-forward structure. FDL buffers can be shared per input line or per output line respectively or be shared per node.

- Node functionality is closely related to the physical realization of the node, e. g., some node architectures trade-off wavelength conversion by the number of gates in the switch matrix and vice versa [8, 21]. Therefore, in order to assess fundamental contention resolution strategies in OBS nodes from a performance point of view, an abstract node model is chosen.

- *Dimensioning and physical constraints:* In case of conversion, dimensioning relates to the number of converters in a converter pool. Wavelength converters can either convert from any input wavelength to any output wavelength or can only convert within a limited conversion range [22]. FDL buffers are characterized by the number and individual delays of the FDL's in the buffer as well as by the number of wavelengths per FDL.

- *Usage strategy:* If wavelength conversion and FDL buffers are applied in combination an additional degree of freedom exists. The arrows in Figure 3 illustrate the order in which the two strategies seek reservation. In the *prefer conversion* strategy wavelength converters are applied preferably and only if they cannot resolve the conflict FDL buffers are used. In the *prefer FDL* strategy FDL buffers are applied preferably and only if they cannot resolve the conflict wavelength converters are used. While the former strategy extensively uses wavelength converters the latter can be expected to save converters.

- *Reservation strategy:* In case a burst uses a wavelength converter or an FDL buffer for contention resolution these resources also have to be reserved. Several strategies which

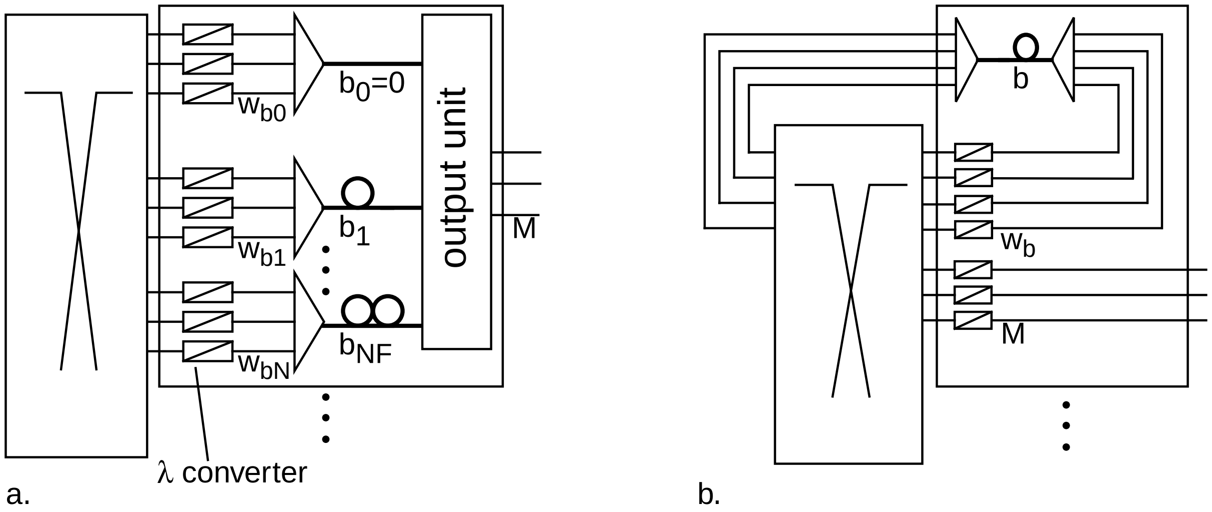

Figure 4: Architecture for a.) feed-forward FDL buffer and b.) feedback FDL buffer

have been proposed for output channel reservation can be applied [14]. Regarding FDL buffers, an additional degree of freedom exists during the reservation process. The output channel for the time when the burst will leave the FDL buffer can be either reserved before entering the FDL or when leaving the FDL.

Apart from the architecture, functionality and dimensioning of converters and FDL buffers, node dimensioning as well as traffic behavior have a significant impact on performance. Concerning node dimensioning, the number of input and output lines as well as the number of wavelength channels per output line are key parameters. Regarding traffic, the offered load, the arrival process of bursts as well as the distribution of burst lengths have to be considered.

8.2.3 Fiber Delay Line Buffers

8.2.3.1 FDL Buffer Architectures

Buffer architectures can be categorized into feed-forward (FF) and feedback (FB) architectures as well as into single-stage and multi-stage structures [7]. In FF buffers data are delayed while forwarded towards the output of the node whereas in FB buffers data are delayed while being fed back to an earlier stage of the node. In single-stage buffers, the delay is realized by a set of fixed-length FDL’s while in multi-stage buffers the delay is determined by a cascade of FDL and switch pairs. The capacity of FDL buffers can be increased by using WDM in the FDL’s.

In OBS switches, FDL buffers can be applied as output, input or recirculation buffers and can either be dedicated to a single port or be shared. Figure 4a shows an FF output buffer and Figure 4b a recirculation buffer for one output of an OBS switch. Both are dedicated, single-stage and employ WDM. The FF buffer has a direct line, i.e. delay $b_0=0$, with w_{b0} wavelengths and N_F FDL’s with delays b_i and w_{bi} wavelengths, $i=1,2,...,N_F$. The function of the output unit in Figure 4a depends on the reservation strategies introduced below. The FB buffer comprises a single FDL of delay b and allows a maximum of Q recirculations. There are w_L wavelengths on the output fiber and w_b in the FDL. In FB buffers, a burst can only reenter the buffer on the same wavelength if its length is shorter than b. In case of full wavelength conversion, as assumed here, b does not limit the burst length.

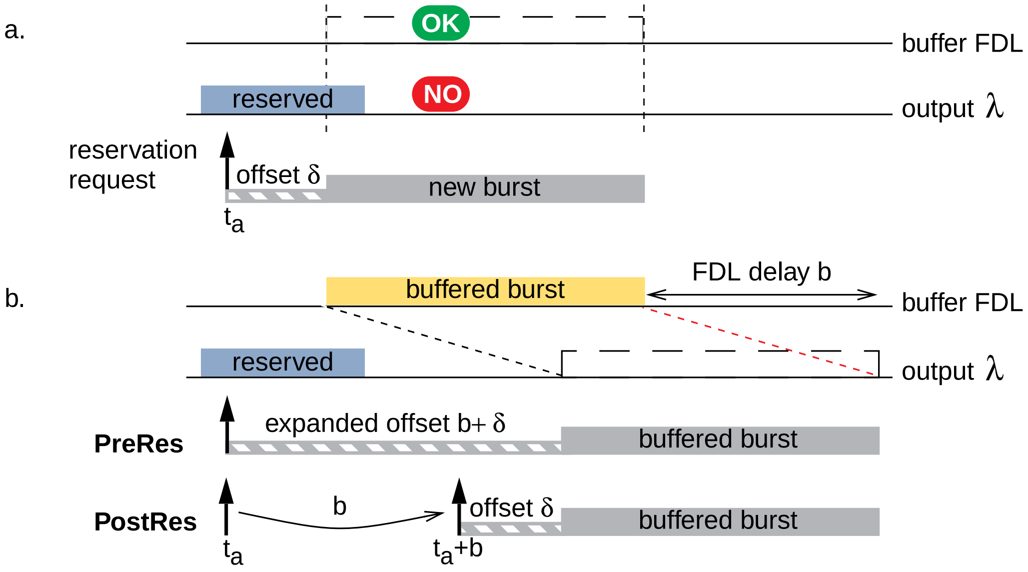

Figure 5: a.) Burst blocking event and b.) buffer strategies PreRes and PostRes

For each wavelength in a buffer FDL there is an input port to the buffer. The total number of buffer input ports, n_p, equals $\sum_i w_{bi}$ in case of FF buffers and w_b in case of FB buffers. The total number of buffer input ports corresponds to the number of additional switch ports needed per output fiber to support an FDL buffer. This directly translates into cost as it determines size of switching matrix or demultiplexer elements as well as number of wavelength converters. For a given total number of buffer ports, assigning these ports to the N_F FDL's of an FF buffer, i.e. determining all individual w_{bi}, is an additional degree of freedom.

Another option in case of FF buffer optimization is choosing individual FDL delays b_i such that burst loss probability is minimized. However, in this paper we only consider FF buffers with linearly increasing FDL delays, i.e. $b_i=i \cdot b$ for $i=1,2,...,N_F$.

From a technological point of view, attenuation in FF and FB buffers can be compensated by amplifiers dedicated to and exactly tuned to the attenuation of the FDL delay b_i. In FB buffers, bursts going through the FDL repeatedly accumulate noise, which limits the possible number of recirculations.

8.2.3.2 Buffer Reservation Strategies

If a burst cannot make a reservation on an output wavelength in an OBS node with FDL buffers (Figure 4a and 4b) it seeks reservation of a buffer FDL instead. For a system with one output wavelength and one buffer FDL, Figure 5a depicts the arrival of a reservation request at time t_a and of the corresponding burst separated by an offset δ. The new burst is blocked from direct transmission by an already reserved burst. However, as a buffer is available during the transmission time of the new burst it can be buffered in the FDL. There are different options for the order and exact time of the FDL and output channel reservation. Figure 5b illustrates two possible scenarios in which the new burst buffered in Figure 5a seeks reservation for the time when it leaves the buffer after FDL delay b.

So far, the following reservation strategy has been proposed and evaluated [17, 26, 15]: At time t_a, i.e. when the reservation request of a burst is blocked for the first time, both the shortest available FDL and an output channel are reserved using JET. If either no output channel or no FDL is available for the burst, the burst is discarded. As the output is reserved prior to entering the buffer we call this *PreRes*. By requesting a wavelength reservation at time t_a, i.e. with an expanded offset $b+\delta$ prior to the burst transmission (Figure 5b), this request is prioritized over unbuffered bursts. Hereby, buffered and unbuffered bursts take up the role of high and low priority bursts in offset-based QoS [18], respectively. The differences are that partitioning into two classes is dynamic based on the current contention situation and that the expanded offset is only effective in this node if the control packet is sent to the next node δ before the burst. From this similarity, we deduce two potential shortcomings: (i) Offset-based prioritization leads to a higher loss rate of long low priority bursts [14] which in PreRes translates into a higher probability for long bursts to be blocked and sent to the buffer or even to be lost. (ii) In a scenario with QoS classes and FDL buffers using PreRes, prioritization of buffered bursts can interfere with QoS classes as the same mechanism is applied in both cases.

In [4], we proposed and evaluated a different mechanism for reservation of buffer and output channels: If a burst is blocked at time t_a the shortest available FDL is reserved using JET but no output is reserved at that time. Only at t_a+b, i.e. after the burst has entered the FDL and δ before the burst leaves the buffer, an output reservation is requested. As can be seen from Figure 5b, the offset δ of the burst stays unaltered for the buffered burst, i.e. it has no priority over newly arriving bursts. We call this mechanism *PostRes* as output reservation takes place after the burst entered the FDL. In PostRes, all blocked bursts are buffered if buffer space is available. Those unable to reserve an output channel when they leave the FDL are either sent back to the buffer and delayed in case of FB buffers or discarded in case of FF buffers.

The output unit in Figure 4a consists of wavelength converters as well as of a combiner in case of PreRes and components for selecting bursts which can be transmitted in case of PostRes.

8.2.3.3 Port Assignment Strategies

The impact of the total number of buffer ports, n_p, of an FF buffer is investigated under the assumption that all FDL’s are assigned an equal number of ports $w_{bi}=w_b=n_p/N_F$. The latter assumption raises two questions: (i) Is this assignment strategy optimal? (ii) How should a given number of ports, n_p, be assigned to N_F FDL’s if n_p is not divisible by N_F? Regarding the first question, assigning an equal number of ports to each FDL might be beneficial as reentry times of blocked bursts are spread more uniformly over time. However, assigning more ports to shorter FDL’s may be advantageous as simulation results show that the mean FDL occupation is higher for the shorter FDL’s in a multi-FDL FF buffer. This is due to the fact, that PreRes seeks reservation on the shortest FDL first and only if no reservation is possible it probes the next longer FDL.

8.2.4 Wavelength Conversion

Performance of converter pools for OBS nodes is evaluated by simulation studies that are based on an abstract node model. This model is depicted in Figure 6 for an OBS node with a converter pool and an optional FDL buffer. The node has a non-blocking switching matrix, N single fiber input and output lines and M wavelength channels per fiber. The converter pool comprises N_C tunable wavelength converters which can be shared among all wavelength channels of this node and which can convert over the entire range of wavelengths. In order to

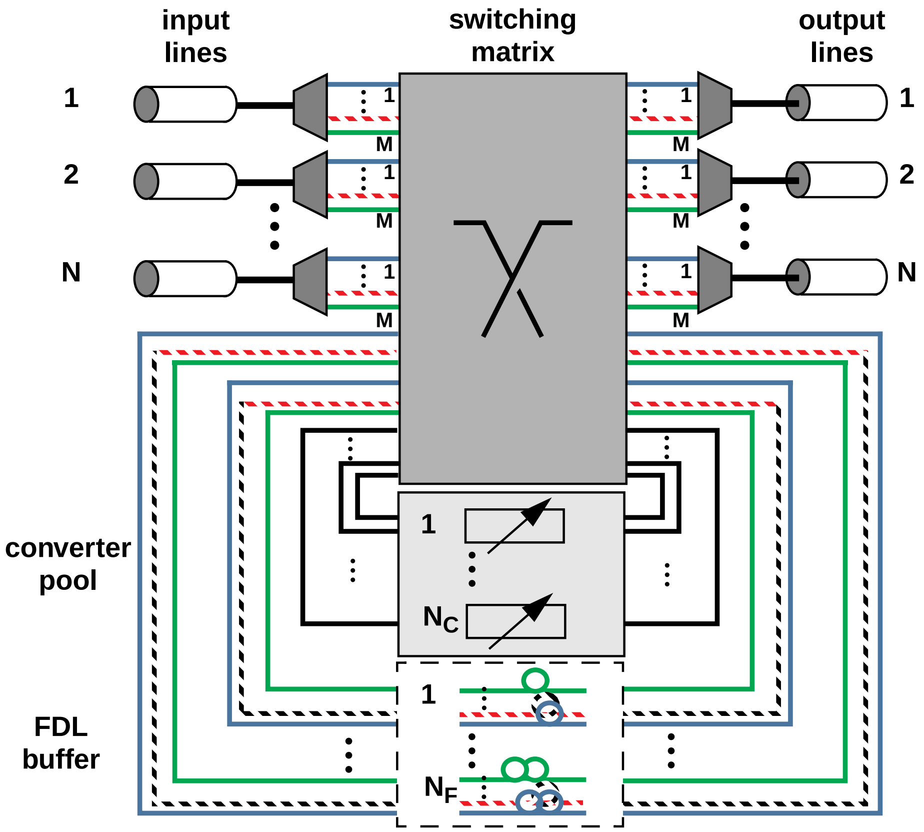

Figure 6: Model of an OBS node with shared converter pool and optional feedback FDL buffer

compare performance of nodes with different dimensioning, the figure *conversion ratio*, r_c, is introduced: It is defined as the ratio of converters in the pool, N_C, and the total number of *output* wavelength channels that share this converter pool, $r_c=N_C/(N \cdot M)$. In case of FDL buffers are employed together with converter pools, the FDL feedback buffer has N_F fiber delay lines with basic delay b and linearly increasing FDL delays, i.e., FDL i has delay ib, $i=1,...,N_F$. FDL's employ WDM with M wavelength channels per FDL. No further architectural details of the optical switching matrix, the converter pool or the FDL buffer have been included in the model, because they can be very different for specific node realizations. Wavelength channels on an output line and in an FDL as well as converters are reserved according to the just-enough-time (JET) reservation strategy [18, 26]. It considers the exact predetermined start and end times of each burst for reservation, which allows most efficient utilization of resources.

8.2.5 Combination of FDL Buffer and Converter Pool

In case an FDL buffer is applied, resources for buffering the burst in the FDL, for later transmission on the output line and potentially for wavelength conversion have to be reserved in a coordinated way. Here, it is assumed that a burst uses the same wavelength in the FDL buffer and on the output line, i.e., a potential wavelength conversion has to take place before buffering. Also, all resources are reserved at the same time, which was characterized as *PreRes* policy above.

8.3 Modeling and Performance Evaluation Approach

8.3.1.1 Traffic Model

For the studies in this paper, two models for the arrival process of bursts are applied. In the first model, bursts arrive according to a Poisson process. The second model is a *self-similar* traffic model and motivated by the rapid growth and dominance of Internet traffic which has been shown to exhibit self-similar behavior. In the future, when rather static traffic management functionality provided by ATM or SDH today is no longer used but IP is transported directly over WDM with only a thin adaptation layer in between, dynamics and long-range dependent characteristics of Internet traffic [16] will eventually reach the optical layer. As illustrated in Figure 1, traffic originates from a large number of sources in metro and access networks. Superposition of a large number of ON/OFF sources with heavy-tailed ON or OFF phases has been proposed as a model for long-range dependent network traffic [25]. An M/Pareto traffic model is obtained for an infinite number of sources with Pareto distributed ON phases [23]. In an OBS edge node, incoming traffic is aggregated in the electronic domain and bursts are assembled dynamically, e.g., based on size or time strategies [2]. Large traffic volumes directed to the same egress edge node will form trains of bursts. In the context of OBS, the M/Pareto model is used to generate trains of optical bursts with mean train interarrival time $E\,[T_A]$. The number of optical bursts, X_B, in a train of bursts follows a Pareto distribution with mean $E\,[X_B]$ and Hurst parameter, H. During a train of bursts, optical bursts are generated with constant interarrival times, d, i.e. the burst arrival rate is $1/d$. Instead of $E\,[T_A]$ and d, the model can be characterized by the mean burst arrival rate $m=E\,[X_B]\,/E\,[T_A]$ and the ratio of mean burst arrival rate and burst arrival rate during a train of bursts: $\beta=m\cdot d$.

8.3.1.2 Simulation Scenario

For an isolated OBS node, performance evaluation has been performed by discrete event simulation of the model described above. The tool is realized in C++ and based on a simulation library [9] that provides support for simulation control, traffic generation as well as statistical evaluation. In the simulation, bursts are generated according to either a Poisson or a self-similar model as discussed in the previous section. Burst length is assumed to be negative-exponentially distributed for the Poisson model and constant for the self-similar model with mean 100 *kbits* which leads to a mean transmission time h=10 µ*s* on a 10 *Gbps* ine. The impact of different transmission time distributions with respect to offset-based QoS is described in [3]. The term *load* refers to offered load per wavelength.

Destination of bursts is uniformly distributed over all N output lines. Also, selection of the wavelength on which a burst arrives to the node follows a uniform distribution. Eight wavelength channels per output line or per FDL are used except for Figures 18 and 19 in which there are 16 wavelengths per output line. JET is used for wavelength and FDL buffer reservation. Except for Figure 8, all bursts belong to the same class.

For a dedicated output buffer comprising either a single FDL FF, a multi-FDL FF buffer or an FB buffer (Figure 4) and employing either PreRes or PostRes reservation strategy, we evaluate the impact of key design parameters on performance. In all simulations of the FDL buffer a load of 0.8 per output wavelength is assumed. This combination of relatively high load and only few wavelengths yields rather high losses. However, this allows us to study the principal behavior of an OBS node in a situation in which FDL buffers are essential.

The burst loss probability is used as the key performance metric but transfer time and technological constraints and cost are also discussed. Unless stated differently, graphs obtained for the Poisson arrival process include 95%-confidence intervals based on the batch simulation method. However, as fundamental assumptions for the analysis of confidence intervals do not hold for long-range dependent traffic graphs for the self-similar arrival process show no confidence intervals. In this case, a larger number of bursts has been simulated.

8.3.2 Results of Performance Evaluation

8.3.3 Fiber Delay Line Buffers

8.3.3.1 Single FDL Feed-Forward Buffer

In order to explain the fundamental differences between PreRes and PostRes, we first look at their performance for a single FDL FF buffer without capacity restrictions. Figure 7 shows the burst loss probability for both strategies at load 0.6 and 0.8 over the FDL delay b normalized by the mean burst transmission time h. It can be seen that even a single FDL of length $b=3h$ (which corresponds to 6 km of fiber) can lower burst loss probability, P_{loss}, efficiently. For all FDL delays, PreRes outperforms PostRes, whereas the difference is greater for load 0.6. Curves flatten for larger b, which shows, that the positive effect of an FDL is limited to the resolution of temporary congestion. As PreRes prioritizes the reservation request of a buffered burst over the one of a newly arriving burst, buffered bursts only compete with long bursts already reserved as well as with requests of other buffered bursts. Again, this is similar to the JET reservation process with offset-based QoS. However, our analysis from [14] for the burst loss probability of two QoS classes is not applicable here as the partitioning into two classes is not static but dynamic based on the current contention situation. Still, this interpretation tells us that the competition with long active bursts decreases with increasing delay, b, which leads to smaller losses.

For PostRes, a lower boundary can be obtained by modeling the initial arrival and the arrival from the buffer as independent and taking into account the load of buffered bursts (repeated call attempt model). Comparing the curves of this lower boundary and PostRes shows that an FDL of limited delay cannot achieve the same performance as a system in which buffers provide arbitrary and almost unlimited delay as assumed for the boundary.

Although PreRes only stores bursts which will be transmitted later it sends more bursts through the buffer than PostRes which stores all blocked bursts based on availability. This can be explained by the fact that during a contention situation in PreRes, blocked bursts enter the buffer and reserve the output in advance, which leads to a fragmentation of the output channel. Newly arriving bursts can only reserve an output directly if they fit into a gap formed by active bursts and reservations of buffered bursts [4]. The fact that a substantial share of all bursts is sent through the buffer in PreRes leads to an increased mean transfer time compared to PostRes. As FDL delay is in the order of burst transmission times, i.e. a few microseconds based on above described assumptions, FDL delay can be neglected compared to propagation delays.

As the offset-based QoS differentiation and PreRes contention resolution strategy are based on similar mechanisms an undesired interaction has to be avoided by carefully choosing the respective parameters. Therefore, we study the impact of FDL buffer delay in an OBS node

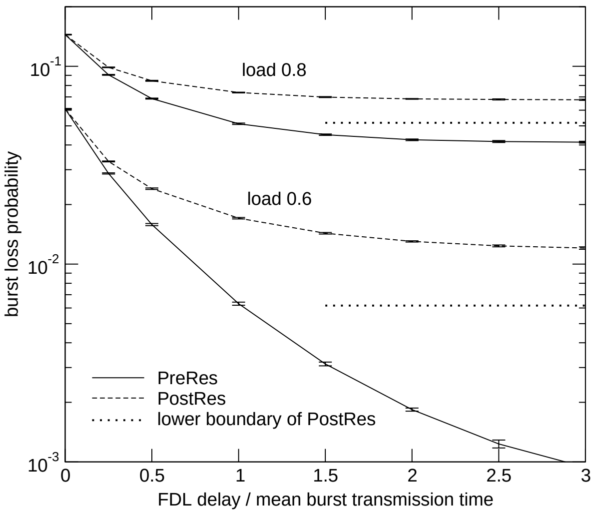

Figure 7: Loss over FDL delay for single FDL feed-forward buffer

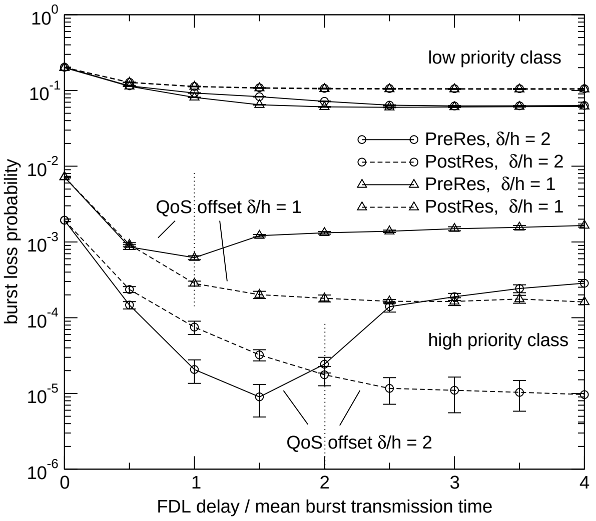

Figure 8: Loss of high priority class over FDL delay (δ/h=1 and (δ/h=2)

with a single FDL and two service classes. The high priority class has a share of 30%. Figure 8 depicts the burst loss probability over the FDL delay for a QoS offset of one respectively two mean burst transmission times at load 0.8. As already mentioned above, it can be seen that for PreRes an FDL that is longer than the QoS offset leads to a reduced isolation between the classes. Furthermore, most of the improvement due to buffering disappears for the high priority class if QoS offset and FDL delay are chosen improperly. Thus, in PreRes, QoS offset and FDL delay have to be adapted such that the QoS offset is always greater than the FDL delay in order to avoid an inefficient use of the system. However, this results in either large QoS offsets, which yield longer delays for all high priority traffic, or restrictions in maximum buffer delay and thus restrictions in the choice of possible buffer architectures.

In contrast, QoS offset and maximum FDL delay can be chosen independently for the PostRes mechanism. Hence, it is possible to have long FDL's (multi-FDL buffers) in order to overcome contention and at the same time have a small QoS offset. For the scenarios in Figure 8, PostRes yields an even better loss probability of the high priority class than PreRes for long FDL's (at the cost of slightly higher losses of the low priority class). In the following, we concentrate on a scenario with a single service class. However, the former results for two service classes have to be considered and principal relations also apply if more complex buffers are used with two service classes.

8.3.3.2 Impact of Architecture and FDL Delay

Burst loss probability can be further reduced by FDL buffer architectures which provide more diversity with respect to FDL delay, i.e.with respect to reentry times. For PostRes, an output channel is only reserved when the burst leaves the buffer. If this output channel reservation is blocked, the burst could be sent back to an FDL and seek reservation later in case of an FB buffer but would be lost in case of an FF buffer. Also, as PostRes always selects the shortest available FDL multi-FDL FF buffers cannot be used efficiently. In contrast, as PreRes reserves an FDL and an output channel before entering the buffer it cannot exploit the greater flexibility of FB buffers. Therefore, we restrict our investigation to FF buffers with N_F=1,2,3,4 FDL's and linearly increasing delay $b_i = i \cdot b$ (i=1,...,N_F) employing PreRes and to FB buffers with FDL delay b and maximum number of recirculations Q=1,2,3,4 employing PostRes.

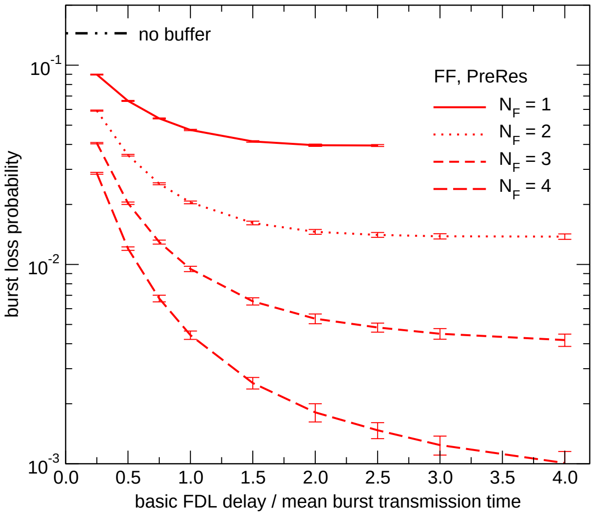

Figure 9: Loss over FDL delay in case of an FF buffer with N_F = 1, 2, 3, 4

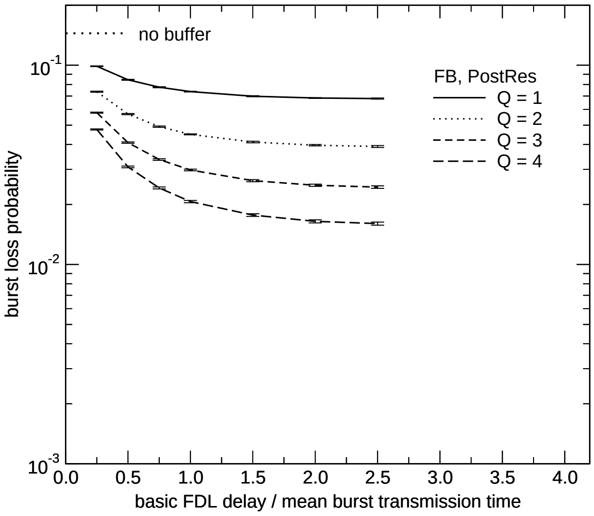

Figure 10: Loss over FDL delay in case of an FB buffer with Q = 1, 2, 3, 4

Figure 9 and Figure 10 depict the burst loss probability P_{loss} over the basic FDL delay b. In both scenarios, the number of wavelengths per FDL is chosen to be no restricting factor. These figures illustrate the impact of FDL delay as well as of number of FDL's, N_F, and maximum number of recirculations, Q. In case of the FF buffer with PreRes, it can be seen that introducing more FDL's, i.e. increasing N_F, leads to significantly reduced P_{loss}. In case of FB buffers with PostRes, increasing the maximum number of recirculations, Q, also leads to a lower P_{loss} but the improvement is smaller compared to FF buffers.

In both scenarios, this improvement comes at the cost of increased transfer times—even for constant b—as several bursts are buffered in longer FDL's. However, increasing N_F in FF buffers means additional FDL's including switch ports and amplifier equipment while increasing Q in FB buffers means few additional switch ports but increased requirements with respect to power and noise budget. In the next section, we study these trade-offs with respect to the number of switch ports as we do not consider the total length of FDL fiber the restricting cost factor.

In case of FF buffers with PreRes and FB buffers with PostRes, burst loss probability always decreases for increasing FDL delays b until a boundary is reached. At load of 0.8, in case of FF buffers with N_F=1 and N_F=2 curves flatten from approximately b=2h on while for N_F>2 this boundary is reached only for higher values of b. In case of FB buffers and all values of Q the boundary is reached at approximately b=2h. In case of lower loads, it can be concluded from Figure 7 that a boundary is only reached for higher values of the base delay.

Summarizing, choosing the basic delay b in the range of a few mean burst transmission times yields significantly improved performance while the fiber delay of the longest fiber in the FF buffer is still in a feasible range. The latter conclusion is valid for burst transmission times up to a few 10's of microseconds as assumed here, however, burst transmission times of milliseconds would lead to infeasibly long FDL's.

In the following, a base delay b=2h is assumed as it provides an optimal or close to optimal P_{loss} for most architectures considered.

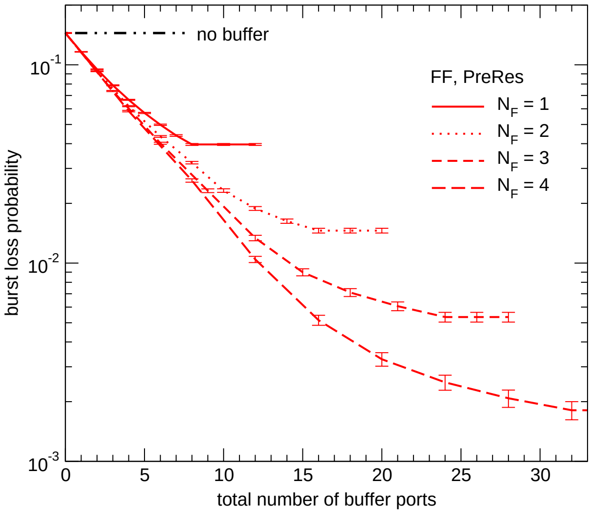

Figure 11: Loss over total number of ports for FF buffers, $N_F = 1, 2, 3, 4$

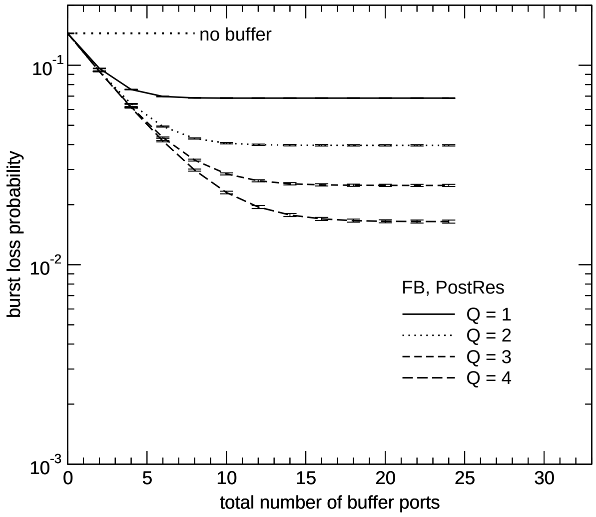

Figure 12: Loss over total number of ports for FB buffers, $Q = 1, 2, 3, 4$

8.3.3.3 Impact of Total Number of FDL Buffer Ports

So far, the number of wavelengths in an FDL which corresponds to the number of bursts which can be stored simultaneously on the same FDL as well as to the number of switch ports assigned to an FDL has not been limited. As the size of the switching matrix is a key design parameter, we study the impact of the total number of buffer ports, n_p, on P_{loss} for an output with w_L=8 wavelengths. In case of an FF buffer we assume for now that each FDL is assigned an equal number of ports $w_{bi}=w_b$, i=1,2,...,N_F, which results in $n_p=N_F \cdot w_b$ ports.

Figure 11 and Figure 12 depict P_{loss} over the total number of buffer ports, n_p, for the FF buffer with PreRes and N_F=1,2,3,4 as well as for the FB buffer with PostRes and Q=1,2,3,4. For all buffer architectures, P_{loss} decreases with increasing n_p—in case of the FF buffer until a bend at $n_p=N_F \cdot w_L$ is reached and in case of the FB buffer until a lower boundary is reached for $n_p<Q \cdot w_L$ ports. Due to the economies of scale relatively fewer ports are needed when increasing Q for reaching the lower boundary. The bend in case of FF with PreRes can be explained by looking at an individual buffer FDL: buffering more than w_L bursts at the same time in the same FDL cannot lead to a lower P_{loss} as only a maximum of w_L bursts can leave the buffer at the same time and be sent to the output channels, i.e. only $w_b \leq w_L$ is a reasonable dimensioning for an individual FDL. This holds true for each FDL in an FF buffer, which leads to the bends at $n_p=N_F \cdot w_L$.

For the FF buffer and a given number of buffer ports, n_p, having a greater number of FDL’s, N_F, with a smaller w_b yields better loss performance than fewer FDL’s with a larger w_b. However, the latter can be achieved at a lower cost. As the difference is slight for small n_p and more distinct for larger n_p a small number of FDL’s is beneficial if only a small total number of ports, n_p, is available in order to minimize cost.

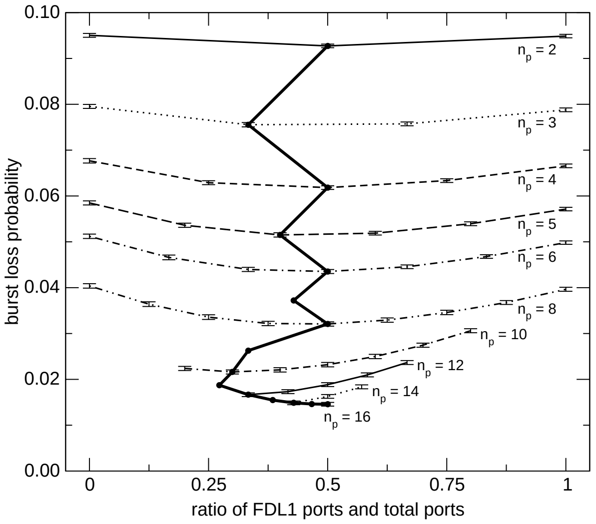

Figure 13: Comparison of combinations of w_b and w_{b2} for constant n_p

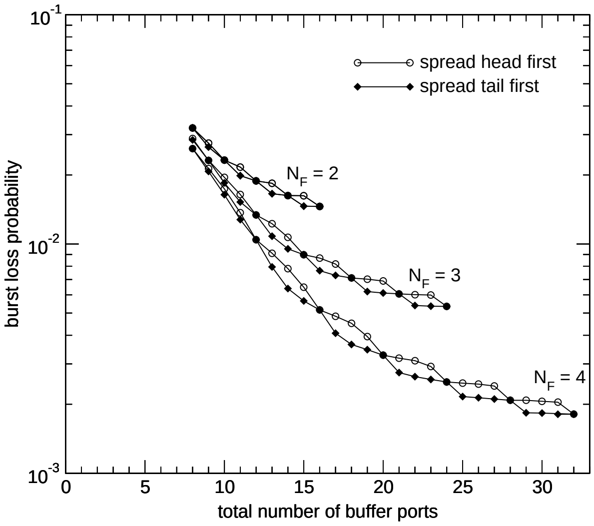

Figure 14: Comparison of spead *algorithms*

Comparing a single FDL FF buffer and an FB buffer with Q=1,2,… under the assumption of an equal number of ports, n_p, is especially interesting as both scenarios are based on an identical FDL buffer. From Figure 11 and Figure 12 it can be seen that Q>2 recirculations in the FB buffer are needed in order to achieve a lower P_{loss} than the single FDL FF buffer. This is independent of n_p, however, the difference is marginal for very small n_p but increases significantly for larger n_p. From the technological point of view a key difference of both scenarios is that in an FB buffer bursts traverse a greater number of switching and amplifier elements and therefore accumulate noise. Thus, if only few ports are available an FF buffer is more desirable due to the reduced complexity.

8.3.3.4 Impact of Port Assignment in FF Buffers

In order to find strategies for assignment of FDL ports, we first evaluate the loss probability for all possible port assignments in a two FDL FF buffer with a constant total number of buffer ports n_p. Each combination of ports for FDL 1 and FDL 2, (w_{b1}, w_{b2}), can be characterized by the ratio w_{b1}/n_p of ports assigned to the shorter FDL w_{b1} and the total number of ports n_p=w_{b1}+w_{b2}. In Figure 13, P_{loss} is depicted on a linear axis over this ratio w_{b1}/n_p for several values of n_p ranging from 2 to 16. As described in the previous section, assigning more than eight ports to any of the FDL’s is not reasonable and is thus not considered here. The fat line in Figure 13 connects the minima of all curves of constant n_p, even for those curves that have been left out in order to improve clarity of the graph.

For only a few ports, n_p, the curves are rather flat, symmetric with respect to w_{b1}/n_p and have their minimum either if half of the ports are assigned to the shorter FDL and half to the longer FDL, or in case of an odd n_p if the longer FDL is assigned one more port. For a greater port count, n_p, the curves are no longer symmetric and minima are taken if the longer FDL is assigned the maximum port count of 8 and the shorter FDL is assigned all remaining ports. From the boundary found in Figure 9 for increasing FDL delay as well as from the fact that P_{loss} is almost identical for the combinations (w_{b1}=8, w_{b2}=0) and (w_{b1}=0, w_{b2}=8) it can be concluded that the different FDL delays are not the main origin of variations of P_{loss} over w_{b1}/n_p but the different distribution of burst reentry times is. This is also supported by

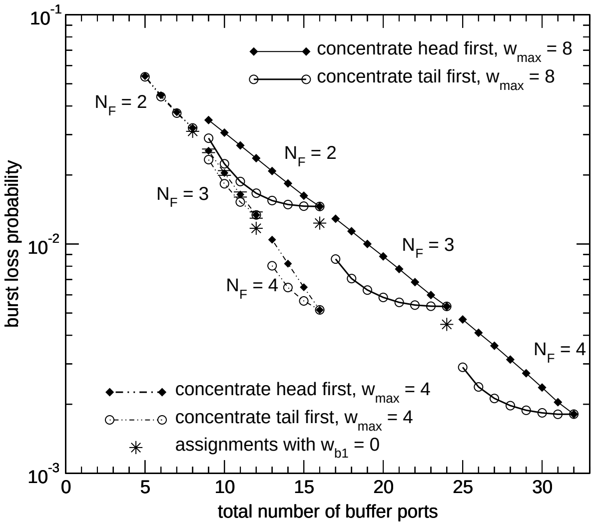

Figure 15: Comparison of concentrate algortithms

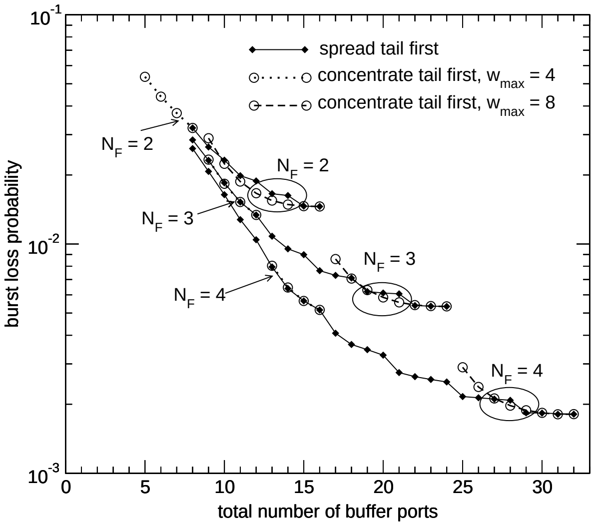

Figure 16: Comparison of spread and concentrate algorithms

simulations for $b=4h$ which showed almost identical loss probabilities and minima as depicted in Figure 13 for $b=2h$. For two FDL's we conclude that assigning half of the available ports to both FDL's yields best results for a small port count while assigning more ports to the longer FDL is beneficial for a larger port count.

Based on the findings of the previous section, we introduce and evaluate four special strategies for assigning n_p ports to N_F FDL's. From the results of our evaluations for two FDL's, it can be deduced that depending on the total number of available ports, n_p, strategies that spread ports over FDL's uniformly or strategies that concentrate ports at either short or long FDL's lead to better loss performance. This categorization motivates the following four strategies:

- *spread head (tail) first*: The ports are assigned to FDL's one at a time based on a round robin scheme, starting with the shortest (longest) FDL until all ports are assigned.
- *concentrate head (tail)* with parameter $w_{max} \leq w_L$: w_{max} ports are assigned to the N_F-1 shortest (longest) FDL's each and all remaining ports are assigned to the longest (shortest) FDL.

Reasonable domains for the total number of ports, n_p, in the strategies *spread* and *concentrate* are $N_F \leq n_p \leq N_F \cdot w_L$ and $(NF\text{-}1)w_{max} < n_p \leq N_F \cdot w_{max}$, respectively. The lower limits account for the fact that there has to be at least one port per FDL and the upper limit accounts for the fact that assigning more than w_L ports to an FDL does not improve performance or that at most w_{max} are allowed.

Figure 14 compares the burst loss probability of the strategies *spread head first* and *spread tail first* for a given number of ports, n_p, and N_F=2,3,4. It can be seen that the curves of both strategies are very close together, with the *tail first* strategy always slightly better except for the points in which both strategies produce the same assignment already studied in Figure 11. However, for some medium values of n_p the improvement of *tail first* is about as big as the improvement achieved by adding an additional FDL but comes at much lower cost. As both

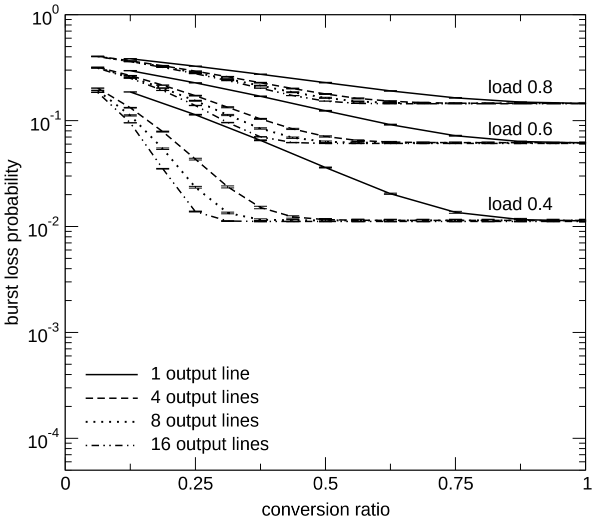

Figure 17: Burst loss probability vs. conv. ratio for Poisson traffic (M=8)

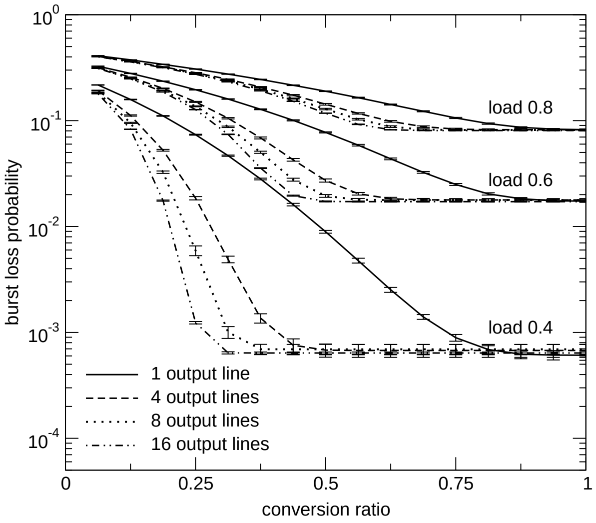

Figure 18: Burst loss probability vs. conv. ratio for Poisson traffic (M=16)

spread strategies have almost identical mean transfer times the *tail first* strategy is more suitable than *head first*.

The strategies *concentrate* depend on an additional parameter, w_{max}, and depending on that parameter are defined on a smaller domain than *spread*. Figure 15 depicts the burst loss probability for the strategies *concentrate* and two values of w_{max}. For w_{max}=8, the *concentrate tail* leads to significantly lower P_{loss} for all N_F except for the points in which both strategies produce the same assignment. While P_{loss} decreases rather uniformly in case of *concentrate head*, it drops more radically with *concentrate tail* for assignments in which there are only a few ports in the shortest FDL. For w_{max}=4, the difference is much smaller or even disappears. Thus, Figure 15 supports findings from Figure13: For a small n_p *concentrate head* and *tail* are almost identical while for a larger n_p *concentrate tail* definitely has a lower P_{loss}.

When *concentrate tail* is used and all N_F FDL's in a buffer are assigned w_{max} ports adding one more port means adding an additional longer FDL, shifting all ports assigned so far to the N_F-1 longest FDL's and assigning the *new* port to the shortest FDL. Thereby, the mean FDL delay is increased by approximately *b* which has some positive impact on losses (Figure 9). In order to quantify this impact, Figure 15 also contains values of P_{loss} (star symbols) for the case in which the shortest FDL is assigned no port but the N_F-1 longer FDL are assigned w_{max} ports each, e.g. for N_F=4 and n_p=24 ports. Comparing these values with P_{loss} obtained for the same n_p but N_F=3, it can be seen that the effect of adding one more port dominates the effect of the increased mean FDL delay.

In Figure 16, we finally compare *spread tail first* and *concentrate tail* which performed best so far. For N_F>2 *concentrate tail* and *spread tail first* perform almost equally for both values of w_{max}. However, for N_F=2 *concentrate tail* achieves lower losses for several values which has been discussed in Figure 13.

Concluding, we found that in case of N_F>2 the *spread tail first* strategy produced the lowest loss probability for by far most port counts, n_p, and should therefore be used to assign ports in the process of FDL buffer dimensioning. In the case of only two FDL's, *concentrate tail* is more advantageous.

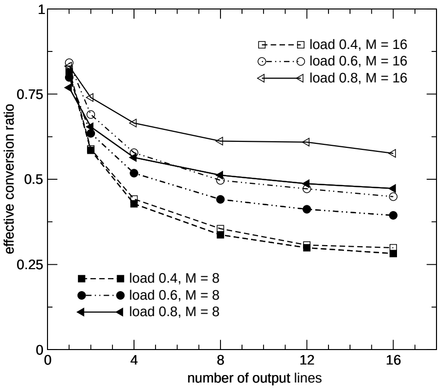

Figure 19: Effective conversion ratio vs. number of output lines

8.3.4 Wavelength Conversion

8.3.4.1 Impact of Conversion Ratio

In Figures 17 and 18, burst loss probability is shown versus the conversion ratio, $r_c = N_C/(N \cdot M)$ for different number of output lines and values of load for scenarios with 8 and 16 wavelength channels. In both scenarios, loss probability decreases steadily with increasing number of converters until it reaches a lower boundary. In case of 8 wavelengths and load 0.4, this boundary is reached at conversion ratios of approximately 0.25–0.5, i.e., between 50% and 75% of the maximum number of converters can be saved. For greater values of load the lower boundary is only reached for greater conversion ratios. When comparing respective curves for 8 and 16 wavelength channels it can be seen that the lower boundary is reached at approximately identical conversion ratios. However, loss probability decreases more significantly for 16 wavelength channels when increasing the number of converters. This can be explained by the multiplexing gain of the larger bundle of channels. From Figures 17 and 18 it can be seen that for a larger number of output lines the lower boundary is reached for a smaller conversion ratio. Again, this can be explained by the multiplexing gain which results from the larger number of converters in the pool. The curve for a single output line is included for reference and corresponds to a converter pool which is only shared for a single output.

In order to quantify the dependence on the number of output lines and to obtain values for the number of converters needed in order not to exceed a certain penalty in loss probability, the *effective conversion ratio* is introduced. It is defined as the conversion ratio which results in a 10% higher loss probability than the case of full conversion. Figure 19 depicts the effective conversion ratio versus the number of output lines for different values of load and 8 as well as 16 wavelengths. No confidence intervals are provided as data have been extracted from graphs. The effective conversion ratio decreases fast for a smaller number of output lines and much slower for a larger number of output lines. From approximately 8 ports on and a load of up to 0.6, the effective conversion ratio is less than 0.5 and can be as low as 0.25 which results in substantial savings of wavelength converters. Again, the curves for different numbers of wavelengths have similar shape but for more wavelengths the effective conversion ratio is greater which is due to the higher carried traffic, i.e.occupancy of the output lines.

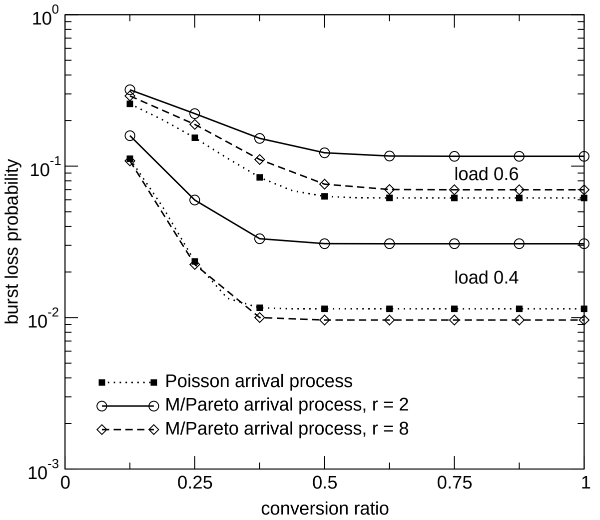

Figure 20: Burst loss probabilty vs. conv. ratio for self-similar traffic

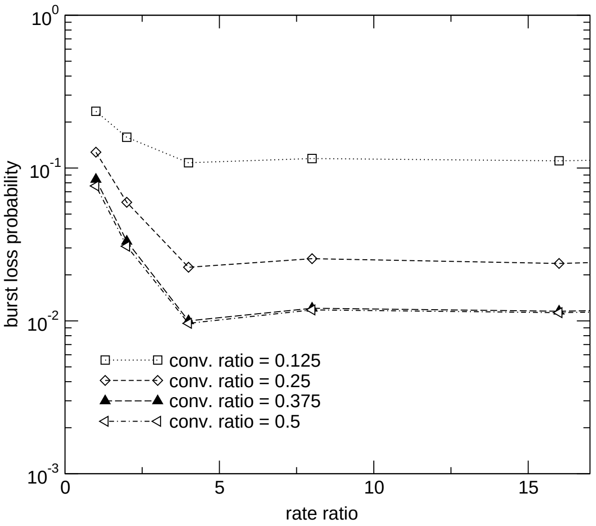

Figure 21: Impact of rate ratio on burst loss probability

8.3.4.2 Impact of Traffic Characteristics

Figure 20 compares the burst loss probability for the Poisson traffic model and for the self-similar traffic model for two values of the rate ratio, β. The number of output lines is 8 and in case of the self-similar traffic model there are in average $E\ [X_B]$ =8 bursts in a train of bursts and the Hurst parameter is 0.6. The M/Pareto arrival process with rate ratio β=8 results in an almost identical burst loss probability as the Poisson process. In case of rate ratio β=2, the lower boundary is reached for the same conversion ratio but the burst loss probability is significantly higher. As highly dynamic traffic is a key motivation for OBS, the impact of parameters of the self-similar traffic model on burst loss probability is studied. Results which are not included in figures show that varying the Hurst parameter between 0.6 and 0.7 and the mean number of bursts in a train of bursts have hardly any impact.

For an offered load of 0.4, Figure 21 depicts this dependence of the burst loss probability on the rate ratio for different values of the conversion ratio. Higher conversion ratios do not yield better performance and are therefore not included in the graph. It can be seen that for a small rate ratio loss probability is significantly higher than for a large rate ratio. Also, the improvement of loss probability due to wavelength conversion is smaller for a small rate ratio. It can be concluded that the higher the rate of individual streams compared to the aggregate rate the higher the loss probability and the less efficient the wavelength converter pool.

8.3.5 Combination of FDL Buffers and Wavelength Conversion

For a combination of a wavelength converter pool and an FDL buffer, Figure 22 compares the strategies *prefer conversion* and *prefer FDL* with respect to burst loss probability. Also, the case of no buffers is included for reference. A node with N=4 output lines, an FDL buffer with N_F=2 FDL's and N_C=8 wavelengths per fiber and FDL are assumed. Note that if an FDL buffer is applied the maximum number of converters in the converter pool is the sum of wavelength and FDL channels. However, in order to receive comparable results, the conversion, r_c, is still calculated with respect to $N \cdot M$ and could therefore exceed 1.

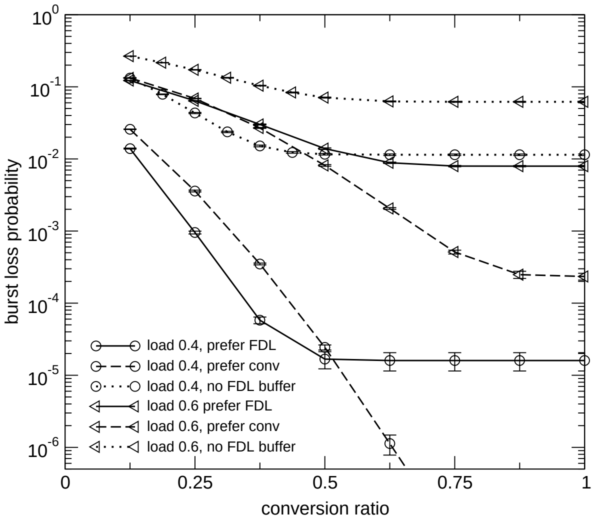

Figure 22: Impact of converter usage strategy on burst loss probability

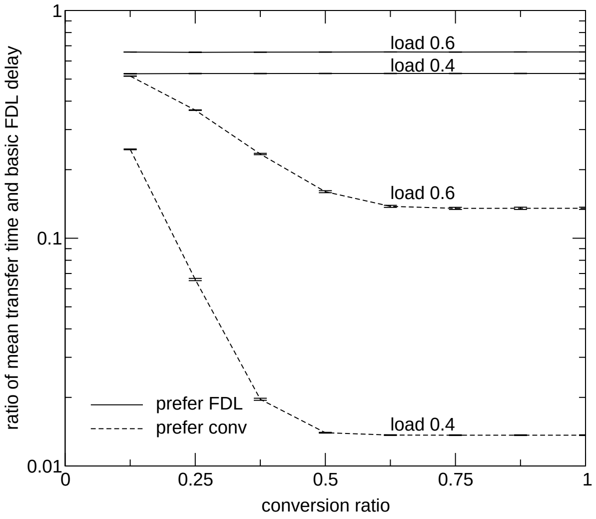

Figure 23: Impact of converter usage strategy on mean transfer time

First, it can be seen that the combination of a shared converter pool and an FDL buffer has a significantly reduced burst loss probability compared to the case without an FDL buffer. For a conversion ratio less than 0.5 and for load 0.4, the strategy *prefer FDL* leads to a lower loss probability than the *prefer conversion* strategy. For a large number of converters or higher values of load the *prefer conversion* strategy performs equally good or better. It can be seen that the strategy *prefer FDL* which tries to minimize converter usage can better utilize a reduced number of converters. *Prefer conversion* extensively uses converters which can be seen from the fact that the lower boundary is only reached for larger values of the conversion ratio.

The lower loss probability of the strategy *prefer FDL* comes at the cost of increased transfer delay. Figure 23 compares both strategies for the same set of parameters with respect to the transfer time normalized by the basic FDL delay which is chosen twice the mean burst transmission time. In case of the *prefer FDL* strategy, the transfer time stays constant while the transfer time in case of the *prefer conversion* strategy decreases when increasing the number of converters until a lower boundary is reached. This shows that for the *prefer conversion* strategy FDL usage decreases as the number of converters increases. In this scenario, the mean transfer delay is in the order of few tens of microseconds and can be neglected compared to propagation delay in long-haul networks or assembly delay in edge nodes. Increasing the FDL delay within the physical limits can further reduce the loss for low loads but also leads to increased transfer times.

8.4 Conclusion

In this report, key design parameters for application of converter pools and FDL buffers for contention resolution in optical burst switching nodes are discussed and studied. Investigations are performed for a Poisson and a self-similar traffic model including a study on the impact of traffic characteristics of the latter model. Dimensioning of feed-forward as well as feedback FDL buffer architectures for OBS networks has been investigated considering two reservation strategies for FDL buffers, PreRes and PostRes. The impact of key design parameters such as FDL delay, buffer architecture, total number of buffer ports as well as assignment of buffer ports to individual FDL’s on burst loss probability has been studied. For the assignment of buffer ports to FDL’s in multi-FDL feed-forward buffers four strategies have been introduced and compared. It is demonstrated that FDL delays in the range of a few mean burst transmission times yield close to optimal performance for all architectures and reservation strategies at high load. Increasing the number of FDL’s in feed-forward buffers or the number of recirculations in feedback buffers has significant impact for a large total number of buffer ports but leads to only minor improvements for a small number of ports. Assigning a given number of buffer ports to the FDL’s of a feed-forward buffer based on the introduced strategy *spread tail first*, which spreads ports over all FDL’s uniformly starting with the longest FDL, yielded lowest burst loss probability for more than two FDL’s.

The influence of number of converters in the converter pool, number of wavelengths per output line and number of output lines on burst loss probability is evaluated. Even for a rather small number of output lines a substantial reduction in the number of wavelength converters can be achieved. For the self-similar traffic model, a large ratio of mean burst arrival rate and burst arrival rate during a train of bursts is shown to yield a high burst loss probability. For the combination of a converter pool and an FDL buffer two usage strategies are introduced and investigated. A strategy that prefers FDL’s over converters for contention resolution is shown to achieve improved loss performance for converter pools with a small number of converters.

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