Performance meets technology - an integrated evaluation of OBS nodes with FDL buffers

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ABSTRACT

In this paper, we show the benefit of an integrated analysis of performance and technology, as both signal degradation and burst losses limit the effective throughput of optical burst switching nodes. The investigation covers the Tune-and-Select (TAS) base architecture as well as extensions with dedicated and shared FDL buffers. First, we describe these node architectures and the OBS reservation scheme considered. Then, we analyze OBS nodes separately from a performance and from a technological/signal degradation point of view. Finally, we present results from the integrated scalability analysis. It is shown that reducing burst loss probability by applying more complex FDL buffers yields smaller maximum throughput due to smaller OBS nodes and in total even a reduced effective throughput under dynamic traffic.

Keywords: node architecture, FDL buffers, scalability, performance evaluation, semiconductor optical amplifier, wavelength converter

1. INTRODUCTION

Optical Burst Switching (OBS) has potential to become an efficient and flexible switching paradigm for a highly dynamic future optical data plane [1]. In recent years, a lot of work in the research community has been devoted to fully understand and explain specifics of OBS and to improve its performance and functionality. Burst reservation and scheduling, burst assembly, quality of service (QoS), contention resolution and survivability have attracted huge interest and resulted in several publications. Relatively few work has focused on realization issues or tried to integrate realization and performance topics. However, due to the analogue operation of photonic components technological and physical constraints have to be considered assessing new architectures and protocols. Thus, an integrated analysis can provide a better and more balanced view on the design and potentials of OBS. We support this claim by analyzing advanced architectures first separately from a performance and a technological/signal degradation point of view and then from an integrated point of view.

Optical bursts with variable length have a typical duration between a few µs and several 100 µs [2]. Therefore, switching times of burst switching nodes should be below 1 µs. Switches based on semiconductor optical amplifiers (SOA) with switching times in the ns range are well suited for this application. To reduce cost and signal degradation only one-stage node architectures for OBS are considered. A power budget analysis shows that compared to “Broadcast and Select” (BAS) switching node the so-called “Tune-and-Select” (TAS) switching node [2, 3] is the more promising architecture for OBS applying SOAs. TAS and two extensions with dedicated and shared FDL buffers are investigated in this paper.

In general, throughput of an OBS node can be increased by a greater number of input and output fibers as well as by more wavelength channels per fiber or by a higher line rate. As realistic backbone networks typically have node degrees of 4 or less [21] we restrict our analysis to nodes with 4 input/output fibers and concentrate on the impact of number of wavelengths and bit-rate. In contrast to digital electronic switches, photonic switches are analogue and signal regeneration is not implicitly performed. Several impairments like noise and crosstalk of WDM channels lead to signal degradation and an increased bit error rate (BER). These effects limit the maximum node size and the maximum throughput of the node [3].

In most OBS approaches, bursts are sent without an acknowledgement of successful path set-up (one-pass reservation) and burst loss can occur in case of contention. Burst loss probability can be reduced by contention resolution in the wavelength domain using wavelength conversion and/or in the time domain using FDL buffers [25]. For a given maximum burst loss probability, maximum throughput and utilization determine the effective throughput for dynamic traffic [4].

The remainder of the paper is structured as follows: After an introduction to OBS we describe the TAS architecture as well as two extensions with dedicated and shared FDL buffers. Then, the performance of several architectural options of OBS nodes with FDL buffers is evaluated. An evaluation of signal degradation effects yields maximum node size and maximum throughput. The effective throughput of such optical burst switching nodes is limited by both signal degradation and burst losses. Finally, results from the integrated performance evaluation by considering traffic consideration and physical constraints are discussed in detail.

2. OPTICAL BURST SWITCHING (OBS)

2.1 Principle of Optical Burst Switching

In an OBS network as depicted in Figure 1, edge nodes assemble several IP-packets with the same egress node and QoS class electronically into bursts of variable length. Typical burst lengths considered here are in the order of several 100 kbit which corresponds to a burst duration between a few µs and several 100 µs. The key characteristic of OBS is the hybrid approach depicted in Figure 1: Header control information is sent out-of-band and processed electronically, while the data burst stays in the optical domain throughput the OBS network. In order to minimize pre-transmission delay in edge nodes, the so-called "one-pass reservation" scheme is used, i. e., network resources are reserved for each individual burst but are not acknowledged before sending the data [1].

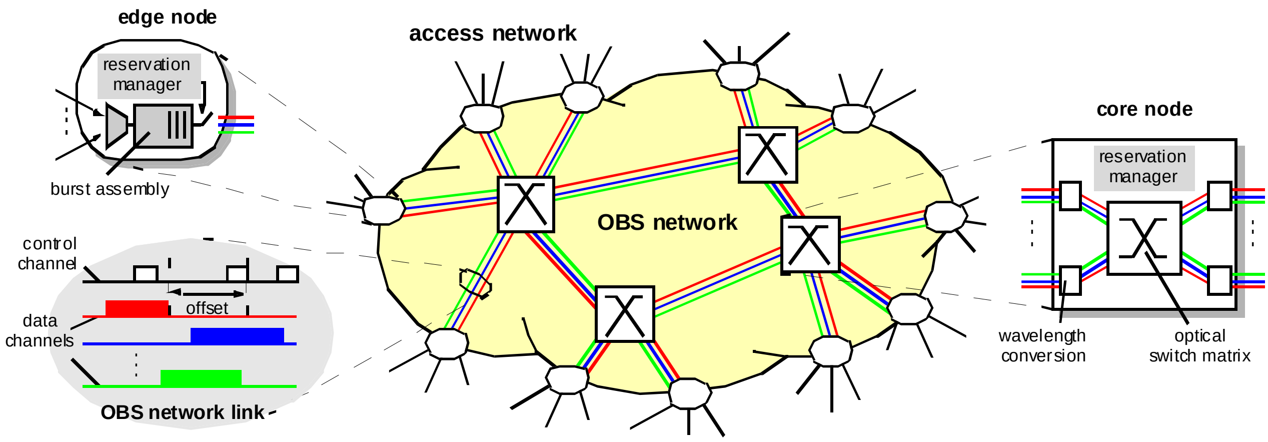

Figure 1. Principle of an optical burst switching network.

Upon arrival of the control packet, the burst node must have enough time for reservation and switching operations (reading the header, processing and reconfiguring the switching matrix) before the data burst arrives. In order to compensate for these switching operations header packets are either sent with a time offset prior to the transmission of the data burst or both are sent simultaneously and the data burst is delayed at the input of the OBS switch in an FDL (Figure 1) while the control packet is being processed. Whereas the offset-based approach assumes knowledge on the number of traversed hops along the path and has been shown to interact with QoS and FDL reservation [24, 9] the input FDL approach only employs an additional short fiber span. For a time offset of 10 µs, e.g., a 2 km optical fiber delay line (FDL) for data bursts is needed per input fiber.

Burst loss probability due to failed reservation can be kept low by applying many wavelengths per fiber in combination with wavelength conversion (burst 2 in Figure 2) [7, 8] and optionally by using optical delay lines (FDL) as buffers solely for contention resolution [9]. In case of successful burst reservation a new control packet is sent to the next node. When the data burst arrives at the switch matrix the reconfiguration is already performed and the burst is forwarded to the output like burst 1 and 2 in Figure 2. In case burst reservation fails the burst (e.g. burst 3 in Figure 2) is discarded.

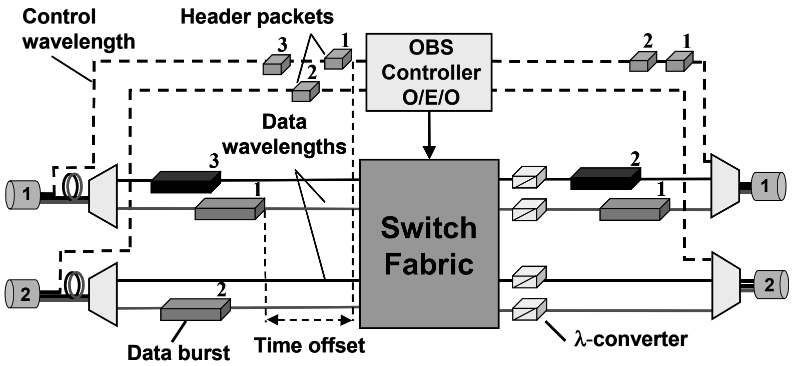

Figure 2. Schematic node architecture for optical burst switching.

2.2 Wavelength and FDL buffer reservation

Just-enough-time (JET) is a flexible reservation strategy for wavelength channels on the output fiber and in the FDL buffer [26, 27]. It considers the exact predetermined start and end times of each burst for reservation, which allows reserving bursts in gaps between other already reserved bursts and leads to most efficient utilization of resources. Applying a reservation scheme which can exploit gaps is a key difference to most work on FDL buffers in OPS [6, 28]. Resources for transmission on the output fiber and for potential buffering have to be reserved in a coordinated way. Here, all resources are reserved when the control packet arrives to the node which we refer to as pre-reservation (PreRes) in the context of FDL buffers [9]. Reserving the output channel for a buffered burst using PreRes results in an early reservation and a prioritization similar to offset-based QoS. Thus, if a burst finds a buffer space it can also reserve an output wavelength channel with high probability.

3. NODE ARCHITECTURES FOR OBS

3.1 Requirements for OBS nodes

OBS will only be a feasible switching solution for core networks if fast and large switching nodes can be built. Some requirements on such switching nodes can be deduced from characteristics of OBS [2]. First the required switching time depends on the switching granularity and signaling method (end-to-end vs. one-pass reservation). For bursts with a mean transmission time between a few µs and several 100 µs, switching times should be in the µs range or even shorter for efficiency reasons. Otherwise the capacity loss in transport network due to switching times grows. Due to the timing conditions for OBS a fast switch technology such as gates of semiconductor optical amplifiers (SOA) or integrated electro-optic switches ($LiNbO_3$ or InP based) [10, 11] are necessary. In comparison with other fast switches the semiconductor optical amplifier (SOA) gate is one of the most attractive candidates, since $LiNbO_3$ switch is driven by high voltage, has a large insertion loss and a large crosstalk. The advantages of SOA are the high on/off ratios (> 50 dB), the loss compensating capabilities (the gain), and the broad amplification bandwidth. So all node architectures considered in this paper use SOAs as basic switching elements. The SOA gating functions is based on the gain dependency on the injected bias current: At a high bias current the gain is high ('on' position), at low or zero current the light is absorbed in the amplifier and efficiently blocked ('off' position). The disadvantage of SOA gates is the power consumption and the noise. To keep the power consumption as low as possible, the node architecture for OBS must have as few switching elements as possible. Since optical space switches are in fact analogue devices, there are no digital regeneration functions as automatically accomplished by digital switching in electronics. To reduce cost and avoid accumulation of signal degradation the number of cascaded SOAs in the signal path must be as low as possible. So a one-stage switch architecture is preferable. Optical amplification is inevitably associated with spontaneous emission noise, so SOAs optimized for low noise figure should be used. Using wavelength conversion all wavelengths on a fiber can be considered a shared resource. This is highly effective for contention resolution [7, 8] as it greatly improves statistical multiplexing gain. Finally multicast function may be desirable.

3.2 Broadcast and select architectures

Based on the arguments provided above, we choose SOA as basic switching element because they provide fast enough switching times, gain, and excellent on/off ratios off above 50 dB. To reduce cost and signal degradation we consider architectures with only one SOA in the signal path. For strictly non-blocking switches, so-called "Broadcast and Select" architectures can be used. Those and similar one-stage architectures have been investigated for OPS [5, 12, 13, 14, 15]. For OBS this concept has been adapted as shown in Figure 3 for Broadcast-and-Select (BAS) node (a) and the Tune-and-Select (TAS) node (b). The node has *N* input/output fibers and *M* wavelengths per fiber. They are strictly non-blocking and have multicast capability. For both nodes N^2*M SOAs are necessary as on/off-switches.

In the previous work a simple power budget analysis [2, 3] has shown the limitation of BAS architecture. Compared to TAS only small nodes (e.g. a 16x16 node with 4 fibres and 4 wavelengths per fibre) can be built with BAS. Additionally, in the BAS architecture the SOA amplifies all *M* wavelengths instead of only one in TAS, resulting in large crosstalk. Fast tuneable filters with a tuning time less than 1 µs, which are essential for BAS are also not available today. So we focus the following analysis on TAS node architecture and consider two variations with a dedicated and with a shared FDL buffer, which fulfilled the requirements above.

In the TAS-node the basic switch modules are the tunable wavelength converters and the SOA gates. The tunable wavelength converters are used in front of the gates. The input signals are wavelength demultiplexed and the bursts are converted to the desired output wavelength using the tunable wavelength converters (tune). With the following broadcast and select structure, the signal is split up into *N* signals (splitting loss 1/*N*), sent towards all output fibers and then selected by switching the appropriate SOAs on or off. At the output of the node, all signals switched to this fiber are combined which also accounts for a power loss of a factor of $N*M$ (c.f. splitting factors in Figure 3). For a node with *N* fibers and *M* wavelengths per fiber N^2*M SOAs and $N*M$ tunable wavelength converters with switching times less than 1 µs are necessary in this node.

The TAS node relies on tunable wavelength converters. A combination of an optoelectronic receiver and a transmitter can be used as wavelength converter (o-e-o conversion). In such wavelength converters 3R regeneration of the signal can be performed. For realizing tunability of the output wavelength tunable lasers with tuning speeds under 1 µs are needed. Several tunable lasers with sufficiently fast tuning time have already been demonstrated [16, 17, 18, 19]. All optical wavelength converters could also be applied. These wavelength converters, e.g., based on cross phase modulation have been developed during the last years [20]. They usually provide some degree of signal regeneration (noise suppression) but no full 3R regeneration.

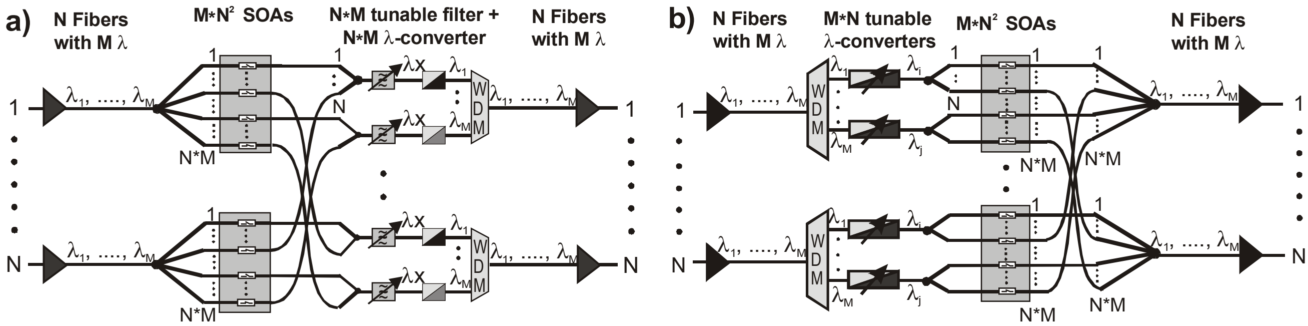

Figure 3. OBS switching nodes. (a) broadcast-and-select (BAS); (b) tune-and-select node (TAS).

a) TAS with dedicated FDL per output fiber (TAS-dFDL)

The first modification of the TAS node applies one dedicated WDM FDL per output fiber. It is called TAS with dedicated FDL (TAS-dFDL) and is depicted in Figure 4a. A TAS node with an FDL per input fiber is also feasible, but comparatively unfavorable due to higher losses in front of the SOA. The FDLs carry several wavelength channels and are used for contention resolution to reduce burst loss rate and to improve utilization [6, 9, 28]. Drawbacks of this node are higher splitting losses and larger switching arrays with $2*M*N^2$ SOA gates. The number of WDM FDLs per output fiber can be increased, but the size of the TAS-dFDL node will be reduced due to the increase of splitting losses. In this case additional erbium-doped fiber amplifiers (EDFA) could be required to compensate the splitting losses and fiber attenuation.

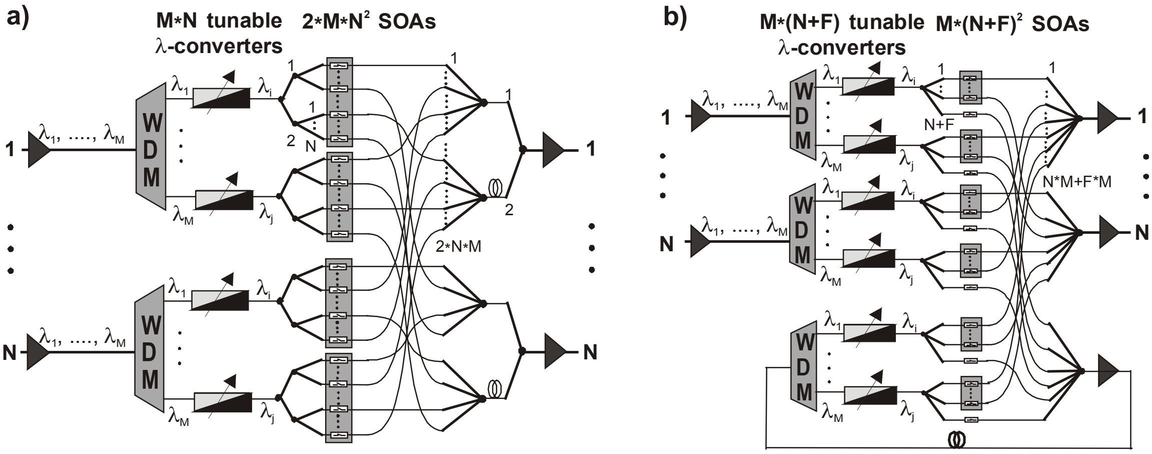

Figure 4. TAS node with (a) dedicated FDL and (b) shared FDL buffer (F = 1)

b) TAS with shared FDL buffer (TAS-shFDL)

Another modification of the basic TAS architecture uses an FDL buffer shared among all the output fibers of the node. It is called TAS with shared FDL buffer (TAS-shFDL) and is depicted in Figure 4b. The FDL buffer consists of one (F=1) or several (F>1) feedback FDLs of different lengths. The delay of the shortest FDL in the buffer is called basic delay b. In all our investigations, the delays of the longer FDLs are integer multiples of the basic delay b, i.e. FDL i has delay $i*b$, i=1, …,F.

Compared to the TAS architecture not only more SOA gates - $M*(N+F)^2$ instead of $M*N^2$ in TAS - but also more tunable wavelength converters ($M*(N+F)$) are needed. In this paper we consider TAS-shFDL nodes with up to F = 4 feedback FDLs. Comparing the number of SOAs of TAS-dFDL and TAS-shFDL for N=4 and a given number of wavelengths M, it can be seen that the complexity of a TAS-shFDL node with F=2 FDLs ($M*(4+2)^2$ SOAs) is in the same range as a TAS-dFDL node ($M*2*4^2$ SOAs).

Both node architectures with FDLs (TAS-dFDL and TAS-shFDL) apply the same number of wavelengths in the FDL and on the output fiber. This is not necessary but a reasonable assumption. In contrast to the TAS-dFDL architecture, the TAS-shFDL architecture requires an additional EDFA in each feedback loop to compensate splitting loss and fiber attenuation. Depending on the kind of wavelength converter, the TAS-shFDL architecture allows for multiple reloops. This is not considered in the following.

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 length of the FDLs. Here we assume that the FDLs are dispersion compensated, if necessary. The maximum length of the FDL is then limited by the requirement, that only one EDFA should be needed for the FDL.

Assuming that only one 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 about 260 µs. As will be shown in the next section, FDL delays should be in the order of a few mean burst durations. 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 260 µs it can be derived that the mean burst length has to be shorter than 10 kbyte, 40 kbyte and 160 kbyte for 2.5, 10 and 40 Gbps line-rate respectively. Thus, mean burst lengths in the order of Mbytes cannot be realistically stored in FDL buffers with only one EDFA.

4. PERFORMANCE EVALUATION OF OBS NODES WITH FDL BUFFERS

In this section, we present the principal behavior of OBS nodes with FDL buffers. For shared FDL buffers we discuss the impact of FDL delay and load on burst loss probability. Also, we analyze the impact of the number of FDLs in the buffer on burst loss probability. Here, in contrast to the integrated analysis presented below, we compare nodes with the same number of wavelengths per fiber and FDL.

Performance is evaluated by discrete event simulation. Control packets of bursts arrive in a stream according to a Poisson process. Only one service class is considered and the offset between control packet and burst is assumed to be the same for all bursts. Burst length is negative-exponentially distributed with mean 12.5 kbyte, i.e. a mean transmission time *h* of 40µs, 10µs and 2.5µs for 2.5Gbps, 10Gbps and 40 Gbps line-rate respectively. The term load refers to offered load per wavelength and is given with respect to the capacity of a wavelength channel. Destination of bursts is uniformly distributed over all *N*=4 output fibers. Also, selection of the wavelength on which a burst arrives to the node follows a uniform distribution. The same number of wavelength channels per output fiber and per FDL is used. All graphs include 95 %-confidence intervals based on the batch simulation method.

For load 0.8 and 16 and 32 wavelength channels, Figure 5 (left) depicts the impact of the basic FDL delay on burst loss probability. As the delays are normalized to the mean burst transmission time, the results apply for all bit-rates. All scenarios show that increasing the FDL delay reduces burst loss probability until a lower bound is reached for a basic delay in the range of 2 to 3 mean burst transmission times. For lower loads, this lower bound is only reached for larger delays which is not shown here. Similar results were published for TAS-dFDL in [9]. As increasing the basic FDL delay beyond 2 mean burst transmission times yields diminishing improvements in loss probability and considering the physical constraints on FDL length discussed above, we use this value as FDL delay for TAS-dFDL and basic delay for TAS-shFDL.

For TAS-shFDL nodes, Figure 5 (right) shows the impact of the number of FDLs *F* in the buffer for different basic FDL delays *b*. An increased number of FDLs in the buffer leads to a significantly reduced burst loss probability which could be motivation to employ FDL buffers with several FDLs. Again, it can be seen that increasing the basic delay beyond 2 mean burst transmission times has no significant impact.

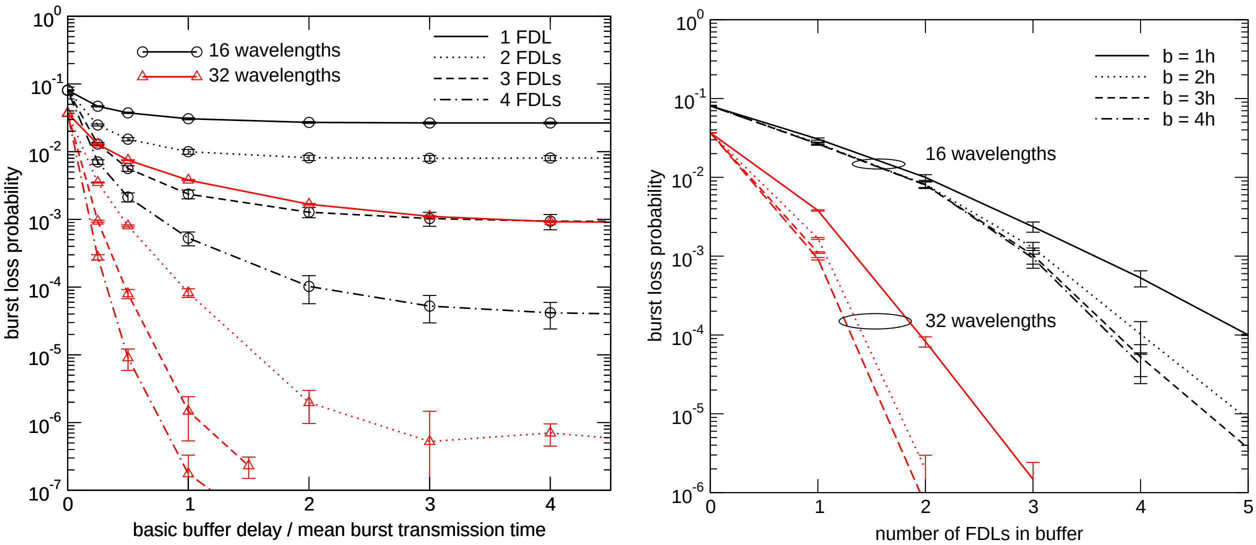

Figure 5. Left: Impact of basic FDL delay on burst loss probability, right: Impact of number of FDLs in the buffer on burst loss probability (*M*=16 and *M*=32, offered load 0.8)

For the integrated analysis, the utilization of an output fiber for a burst loss probability $B=10^{-6}$ has to be determined. For the TAS architecture this is calculated analytically [7] and is insensitive to burst length distribution. For the TAS architectures with FDL buffers this value is taken from simulations.

Figure 6 depicts the burst loss probability versus the offered load per wavelength for 16 wavelength channels and different node configurations. Due to the improved contention resolution capability, multi-FDL buffers have a lower loss probability for a given. The utilization for $B=10^{-6}$ used in the integrated analysis is extracted as indicated by the arrows. For a burst loss probability of $B=10^{-6}$, the utilization $\rho(1-B)$ approximately equals the offered load per wavelength channel ρ.

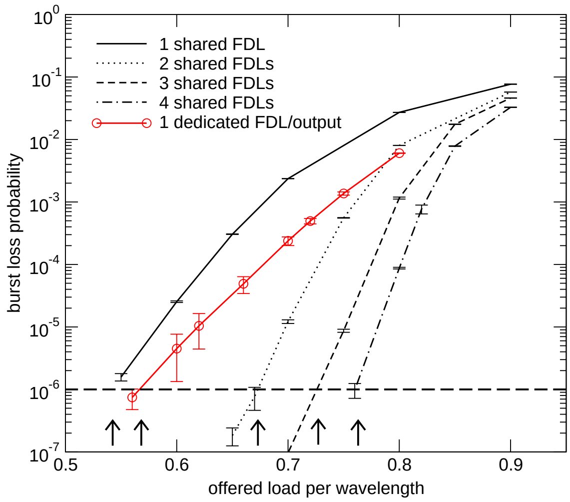

Figure 6. Burst loss probability vs. load for TAS-dFDL and TAS-shFDL with 1…4 FDLs (M=16)

5. EVALUATION OF SIGNAL DEGRADATION AND MAXIMUM THROUGHPUT

5.1 Signal degradation mechanisms in the nodes

The quality of a signal at the end of a path through the burst switched domain between two edge nodes is affected by several impairments: noise, crosstalk, amplifier saturation, fiber dispersion etc. While the fiber dispersion is an imperfection in the transmission line, which can be compensated to a high degree, the non-ideal optical switching node with SOAs as on/off gates introduces noise, crosstalk as dominant factors.

a) Noise

In our calculations only the noise generated by the optical amplifiers (EDFA and SOA) is considered. Generally, the design criterion for low noise is to keep the signal power as uniform as possible and not let it decrease too much. The most critical point is at the output of the large combiners behind the SOAs as the combiner is the component with highest splitting loss (TAS: $1/(N*M)$, TAS-dFDL: $1/(2*N*M)$, TAS-shFDL: $1/((F+N)*M)$). Due to the power levels in the critical area between output of wavelength converter and output of the node the SOA gain must be as high as possible, even though the noise powers from several SOAs will be merged behind the combiner (M for all architectures considered here). Furthermore, the SOA is the first amplifier in an amplifier cascade. The total noise caused by all amplifiers in the cascade will be mainly determined by SOA noise. So low-noise SOAs are very important for the switching node.

b) Crosstalk

We take two major crosstalk sources into account and perform a worst case calculation. The first source is the WDM demultiplexer with $M-1$ interfering signals. Power-addition crosstalk arises due to the difference in centre frequency between the interfering signals. The second is the non ideal extinction ratio of the SOA gates. For TAS $N-1$ switched-off amplifiers have the same input wavelength (TAS-dFDL: $2*N-1$; TAS-shFDL: $2*(N+F)-1$) as the considered channel with the consequence of coherent crosstalk.

5.2 Calculation of maximum node size

To determine the maximum size of the TAS-nodes the component parameters in Table 1 are used, which, to our best knowledge, represent the present state-of-the-art for a dynamic application case. In the analysis a signal path between two edge routers with a few burst switching nodes in between is considered, as shown in Figure 7. The links between the nodes are assumed to be 240 km long and have two inline EDFAs. As we assume regenerative (3R) wavelength converters the accumulation of signal degradation is terminated at each wavelength converter and only has to be considered between two neighboring nodes, i.e. consecutive wavelength converters.

The delay lines in the TAS-dFDL node have a delay of two mean burst transmission times which corresponds to 16/4/1 km of fiber for 2.5/10/40 Gbps. As introduced above, the ith FDL in a TAS-shFDL node with F FDLs has a delay of $2*i$ times the mean burst transmission times, i=1…F.

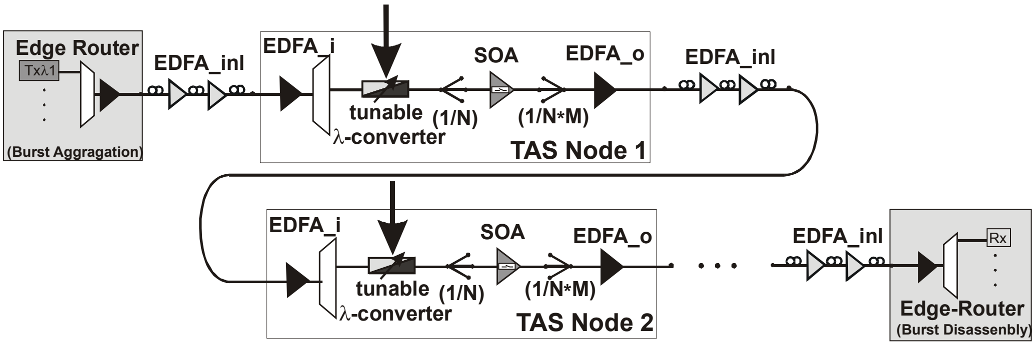

Figure 7. Signal path between two edge routers in an OBS network with many TAS-nodes.

In realistic backbone networks, the highest node degree (number of input/output fibers per node) is typically in the order of four [21], therefore we focus our analysis on nodes with four input/output fibers. The usable capacity in the fiber is directly dependent on the operating windows in the different bands and the spectral efficiency of the WDM systems, which can be defined as the ratio of the bit rate per channel to the channel spacing. The higher the spectral efficiency is, the higher the capacity that can be packed into a single fiber. The spectral efficiency of WDM system today is typically 0.4 [29]. This means new systems will have 10 Gbps channels spaced 25 GHz and 40 Gbps channels spaced 100 GHz. For 2.5 Gbps channels the channel spacing is 12.5 GHz due to available optical filters leading to a low spectral efficiency of 0.2. If only C-band is used the available number of wavelengths per fiber is 320 for 2.5 Gbps line-rate, 160 for 10 Gbps line-rate, and 40 for 40 Gbps line-rate. For 2.5/10/40 Gbps line-rates the maximum number of wavelengths *M* and hence the maximum throughput of the considered node architectures are determined within these constraints.

To determine the maximum number of wavelengths *M* for the considered node architectures at different bit-rates, the bit error rate respectively Q-factor is calculated. The Q-factor is a specially defined signal-to-noise ratio and is given in (1). S_1 and S_0 are the signal amplitudes for a mark and space, σ_1 and σ_0 are the respective variances. For Gaussian noise (2) describes the relation between bit error rate (BER) and Q-factor.

$$Q = \frac{S_1 - S_0}{\sigma_1 + \sigma_0} \qquad (1) \qquad\qquad BER = \frac{1}{\sqrt{2\pi}} \frac{\exp(-\frac{Q^2}{2})}{Q} \qquad (2)$$

The results presented here can be affected by several other impairments. To have enough margin for other impairments, *Q* equal 10 is taken as the limit of signal degradation. This means, the Q-factor of the investigated signal path must be greater than 10 which corresponds to a bit error rate less than $BER = 10^{-22}$. Based on this maximum number *M* of wavelengths, the maximum node throughput is calculated, i.e. the product of number of fibers $N = 4$, number of wavelengths *M* and bit-rate. Note that this maximum throughput does not consider dynamic burst traffic but assumes a constant bit stream.

5.3 Results

For the basic TAS architecture, the Q-factor versus the number of wavelengths *M* for *N* = 4 and different bit-rates are shown in Figure 8. The dashed line is for noise and the solid line for noise and crosstalk. The number of wavelengths is varied between 4 and 320 in steps of 4, powers of 2 are plotted in Figure 8 only. For a greater number of wavelengths, increasing noise and crosstalk leads to a smaller Q-factor. However, signal degradation is always dominated by noise.

From Figure 8, it can be derived that for a Q-factor greater than 10, a TAS node with four input/output fibers can be built with $M = 320$ (maximum C-band wavelengths with 12.5 GHz channel spacing) wavelengths for 2.5 Gbps line-rate, but only with $M = 148$ for 10 Gbps line-rate and with $M = 36$ for 40 Gbps line-rate. These values result in a maximum throughput of 3.2 Tbps for 2.5 Gbps, 5.92 Tbps for 10 Gbps and 5.76 Tbps for 40 Gbps.

Due to higher splitting losses and additional power loss in the delay line, Compared to TAS nodes TAS nodes with a dedicated FDL per output fiber (TAS-dFDL) can only be built smaller: $M = 212$ for 2.5 Gbps line-rate, $M = 76$ for

10 Gbps line-rate and $M = 16$ for 40 Gbps line-rate. These values result in a maximum throughput of 2.12 Tbps for 2.5 Gbps line-rate, 3.04 Tbps for 10 Gbps line-rate and 2.56 Tbps for 40 Gbps line-rate.

Node	input power	-16 dBm
	output power	0 dBm
EDFA	noise figure	6 dB
	max. gain	30 dB
	max. output power	19 dBm
SOA	noise figure	11 dB
	max. gain	17 dB
	max. output power	11 dBm
	extinction ratio	50 dB
Splitter/ Combiner	excess loss	0.3 – 3 dB
WDM MUX/DeMUX	excess loss	5 dB
	crosstalk	-30 dB
wavelength converter	input power	-16 dBm
	output power	5 dBm
Delay Line	loss	0,2 dB/km

Table 1: Technology parameters

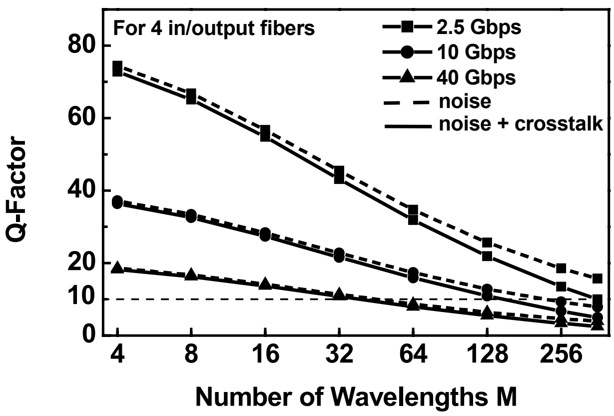

Figure 8. The Q-factor for TAS at different bit-rates versus number of wavelengths *M*. The number of the in-/output fibers is 4.

In TAS nodes with shared FDL buffer (TAS-shFDL) the signals going through the FDLs are fully regenerated after passing the feedback loop due to the regenerative (3R) wavelength converters assumed. To compensate the fiber attenuation and the splitting losses in the feedback loop additional EDFAs must be used. For FDL lengths considered here only one EDFA is needed per loop and no fiber dispersion compensation is required. To calculate the maximum size of a TAS-shFDL node two signal paths have to be considered separately: First, the signal path between the wavelength converter at the input of the node and the wavelength converter in the feedback loop; Second, the signal path between the wavelength converter in the feedback loop and the input wavelength converter in the downstream node. Primarily, the second path limits the size of TAS-shFDL nodes. The resulting maximum number of wavelengths and the maximum throughput of TAS-shFDL nodes are shown in Table 2 for different bit-rates and number of FDLs *F* varied from 1 to 4. Due to the lower losses in the second signal path (no FDL power loss; a smaller splitting loss for $F < 4$) larger nodes can be built with this architecture compared to the TAS-dFDL architecture.

Number of FDLs in TAS-shFDL (length of FDL)	**2.5 Gbps**	**10 Gbps**	**40 Gbps**
***F* = 1** (16/4/1 km for 2.5/10/40 Gbps)	$M = 312$ 3.12 Tbps	$M = 120$ 4.80 Tbps	$M = 28$ 4.48 Tbps
***F* = 2** (32/8/2 km for 2.5/10/40 Gbps)	$M = 280$ 2.80 Tbps	$M = 104$ 4.16 Tbps	$M = 24$ 3.84 Tbps
***F* = 3** (48/12/3 km for 2.5/10/40 Gbps)	$M = 252$ 2.52 Tbps	$M = 88$ 3.52 Tbps	$M = 20$ 3.20 Tbps
***F* = 4** (64/16/4 km for 2.5/10/40 Gbps)	$M = 228$ 2.28 Tbps	$M = 80$ 3.20 Tbps	$M = 16$ 2.56 Tbps

Table 2: Maximum number of wavelengths and maximum throughput of TAS-shFDL for different number of FDLs *F* and different line bit-rates with $Q>10$.

From Table 2 it can be seen that the number of FDLs in a TAS-shFDL node results in a smaller number of wavelengths and consequently in a smaller maximum throughput.

The maximum throughput of a specific architecture is almost identical for a line bit-rate of 10 and 40 Gbps, not for a line bit-rate of 2.5 Gbps at which the maximum throughputs is smaller due to crosstalk of large number of WDM channels.

6. INTEGRATED EVALUATION OF DIFFERENT ARCHITECTURES

Previous two sections have presented results of a performance evaluation comparing nodes with the same number of wavelengths but different FDL buffer configurations and of a scalability analysis regarding signal degradation. The maximum throughput calculated in the previous section did not account for dynamic traffic, i. e., the stochastic nature of burst arrivals and burst lengths. Now, this section integrates the latter evaluations by looking at the effective throughput that can be achieved under dynamic traffic in the presence of a burst loss probability of $B=10^{-6}$.

While application of FDLs in an OBS node (TAS-dFDL and TAS-shFDL) in general and increasing the number of FDLs in a TAS-shFDL node specifically are shown to effectively reduce burst loss probability and improve utilization in the performance evaluation, the scalability analysis indicates that both options reduce the node size and the maximum throughput. Also, the impact of the bit-rate which had no influence on the performance analysis above is essential when looking at maximum throughput. Thus, the question arises whether the effective throughput, i.e. the product of utilization and maximum throughput, increases or decreases when using more complex FDL buffers.

Figure 9 shows the number of wavelengths as well as the maximum and effective throughput for a node with 4 input/output fibers combining results of the scalability and the performance evaluation for 10Gbps and 40 Gbps line bit-rates.

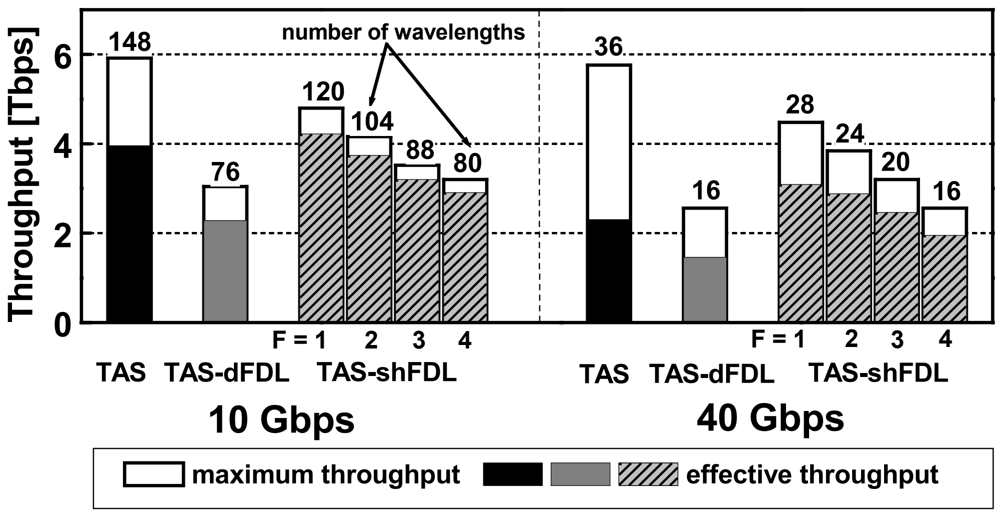

Figure 9. Maximum and effective throughput of TAS, TAS-dFDL and TAS-shFDL

The maximum throughput of all architectures is in the range from 3 to 6 Tbps. The highest maximum throughput (about 6 Tbps for 10 and 40 Gbps line-rates) can be achieved with TAS . With TAS-dFDL and TAS-shFDL, only rather small nodes can be built due to higher splitting losses and losses of the delay line. Comparing respective architectures, it can be seen that increasing the line bit-rate from 10 to 40 Gbps yields nearly the same maximum throughput, but smaller achievable number of wavelengths. The utilization of WDM channels decreases which results in lower effective throughput at 40 Gbps line-rate. Hence, due to cost, migration to 40 Gbps is only advantageous if the number of wavelength channels on the fiber has to be strictly minimized, i.e. cost for lighting and operating them is high compared to the node cost. For both line bit-rates, maximum throughput is highest for TAS and lowest for TAS-dFDL while the TAS-shFDL architectures lie in between.

Regarding the effective throughput, both utilization and achievable node size have to be considered. For the TAS-shFDL architectures, increasing the number of FDLs reduces burst loss probability but also limits node size. Both effects are balanced such that increasing the number of FDLs hardly changes the utilization and the effective throughput actually decreases. In comparison with TAS, only TAS-shFDL with a single FDL can achieve higher effective throughput for 10 Gbps line-rate. For 40 Gbps line-rate, the utilization of TAS is only 40% and therefore TAS-shFDL architectures with up to 3 FDLs achieve a higher effective throughput. The TAS-dFDL architecture always has the lowest effective throughput.

As has been mentioned above when introducing the TAS node architectures, a TAS-dFDL node and a TAS-shFDL node with 2 FDLs have approximately the same number of SOAs. However, when looking at maximum and effective throughput, the TAS node with shared FDL buffer performs significantly better.

7. CONCLUSION

In this paper we present an integrated analysis of optical burst switching (OBS) nodes accounting for technology and performance. We show the impact of physical and technological constraints of the Tune-and-Select (TAS) architecture for OBS.

We study the TAS architecture and two extensions with dedicated and shared fiber delay line (FDL) buffer with up to four FDL feedback loops and bit-rates of 2.5, 10 and 40 Gbps. Noise and crosstalk are considered as dominant factors for signal degradation limiting the number of possible wavelengths for a given node architecture. The maximum size and throughput of these nodes are calculated for a Q-factor of 10. The effective throughput is defined as the throughput at burst loss probability $B \leq 10^{-6}$ for dynamic traffic. Just-enough-time (JET) reservation strategy is used for wavelength channels on the output fiber and in the FDL buffer. For a buffered burst the output wavelength channel is reserved by using pre-reservation (PreRes) method.

Architectures with FDL buffers have an improved utilization and better efficiency but can only be built smaller by considering technological constraints. Regarding maximum and effective throughput they do not scale significantly better than the TAS architecture without FDLs—the node with dedicated buffer even has a lower throughput. Remarkably, increasing the number of FDLs in the shared buffer hardly changes the utilization due to the reduced node size, thus leading to decreased maximum and effective throughput. It can be concluded that studying architectural options only from the technological or only from the performance point of view does not provide balanced results. Consequently, there is a need for integrated analysis.

Future work should extend the integrated analysis to OBS node architectures applying other technologies, e.g. arrayed waveguide gratings (AWG). Also, in order to get a broader view on performance, traffic models considering the burst assembly process could be included.

REFERENCES

1. C. Qiao: Labeled Optical Burst Switching for IP-over-WDM Intergration, *IEEE Communications Magazine*, *Vol. 9,* September 2000, pp. 104 - 114.
2. H. Buchta, E. Patzak, J. Saniter, C. M. Gauger: Maximal and Effective Throughput of Optical Switching Nodes for Optical Burst Switching, *Proc. 4. ITG-Workshop on Photonic Networks*, April 2003, Leipzig, Germany.
3. H. Feng, E. Patzak, J. Saniter: Size and Cascadability Limits of SOA based Burst Switching Nodes, *Proc. ECOC 2002*, September 2002, Copenhagen, Denmark, 8.5.5
4. H. Buchta, E. Patzak, J. Saniter, C. M. Gauger: Limits of Effective Throughput of Optical Burst Switches Based on Semiconductor Optical Amplifiers, *Proc. OFC 2003*, March 2003, Atlanta, Georgia, USA, TuJ3
5. Guillemot, C. et al.: Transparent Optical Packet Switching: The European ACTS KEOPS Project Approach. *IEEE Journal of Lightwave Technology, Vol. 16, No. 12,* December 1998.
6. D.K. Hunter, M.C. Chia, I. Andonovic: Buffering in Optical Packet Switches, *IEEE Journal of Lightwave Technology, Vol. 16, No. 12,* December 1998, pp. 2081 - 2094
7. K. Dolzer, C. M. Gauger, J. Spaeth, S. Bodamer: Evaluation of Reservation Mechanisms for Optical Burst Switching. *AEÜ International Journal. of Electronics and Communications, Vol. 55, No. 1*, January 2001.
8. J.S. Turner: Terabit Burst Switching. *Journal of High Speed Networks, Vol. 8, No. 1*, January 1999.

9. C. M. Gauger: Dimensioning of FDL Buffers for Optical Burst Switching Nodes. *Proc. ONDM 2002*, Torino, Italy, February 2002.

10. M. Renaud, M. Bachmann, M. Erman: Semiconductor optical space switches. *IEEE Journal of Selected Topics in Quantum Electronics, Vol. 2, No. 2,* June 1996, pp. 277-288.

11. M.J.Potasek: All-Optical Switching for High Bandwidth Optical Network, *Optical Networks Magazine, Vol. 3, No. 6,* November/December 2002, pp. 30- 43.

12. P. Gambini et al.: Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project, *IEEE Journal on Selected Areas in Communications, Vol. 16, No. 7,* 1998.

13. D. Chiaroni et al.: Physical and Logical Validation of a Network Based on All-Optical Packet Switching Systems, *IEEE Journal of Lightwave Technology, Vol. 16, No. 12,* December 1998.

14. M.W. Chbat et al.: Toward Wide-Scale All-Optical Transparent Networking: The ACTS Optical Pan-European Network (OPEN) Project, *IEEE Journal of Selected Areas in Communications, Vol. 16, No. 7,* September 1998, pp. 1226-1244.

15. S.L. Danielsen, P.B. Hansen and K.E. Stubkjaer: Analysis of a WDM Packet Switch with Improved Performance Under Bursty Traffic Conditions Due to Tuneable Wavelength Converters. *IEEE Journal of Lightwave Technology, Vol. 16, No. 5,* May 1998, pp. 729-735.

16. K. Shrikhande et al. Performance Demonstration of a Fast-Tunable Transmitter and Burst-Mode Packet Receiver for *HORNET*. *Proc.* OFC 2001, Paper ThG2

17. M. Kauer et al.: 16-Channel Digitally Tunable Packet Switching Transmitter with Sub-Nanosecond Switching Time, *Proc. ECOC 2002*, September 2002, Copenhagen, Denmark, 3.3.3

18. J.E. Simsarian et al.: A Widely Tunable Laser Transmitter with Fast, Accurate Switching Between All Channel Combinations, *Proc. ECOC 2002*, September 2002, Copenhagen, Denmark, 3.3.6

19. J. Gripp et al.: 4x4 Demonstration of a 1.2 Tb/s (32 x 40 Gb/s) Optical Switch Fabric for Multi-Tb/s Packet Routers, *Proc. ECOC 2002*, September 2002, Copenhagen, Denmark, PD2.4

20. T. Durhuus et al.: All-Optical Wavelength Conversion by Semiconductor Optical Amplifiers, *IEEE Journal of Lightwave Technology, Vol. 14, No. 6,* June 1996, pp. 942-954.

21. S. Meyer: Quantification of wavelength contention in photonic networks with reach variation, *Proc. OFC 2002*, TuG3, pp. 36–37

22. J.M. Simmons: Analysis of wavelength conversion in all-optical eypress backbone networks, *Proc. OFC 2002*, TuG2, pp. 34–36

23. O. Gerstel, R. Ramaswami and.S. Foster: Merits of hybrid networking, *Proc. OFC 2002*, TuG1.

24. K. Dolzer and Ch. Gauger: On burst assembly in optical burst switching networks - a performance evaluation of Just-Enough-Time, Proc. 17th International Teletraffic Congress (ITC 17), Salvador da Bahia, Brazil, 2001, pp. 149-160.

25. C. M. Gauger, Performance of Converter Pools for Contention Resolution in Optical Burst Switching, Proceedings of OptiComm 2002, Boston, August 2002

26. M. Yoo, M. Jeong, and C. Qiao, A high speed protocol for bursty traffic in optical networks," in 3rd SPIE Conference on All-Optical Communication Systems, pp.79--90, (Dallas), November 1997.

27. Y. Xiong, M. Vanderhoute, and C. Cankaya, "Control architecture in optical burst-switched WDM networks," IEEE} Journal of Selected Areas in Communications, 18, pp. 1838--1851, Oct. 2000.

28. F. Callegati, W. Cerroni, and G. Corazza, "Optimization of wavelength allocation in WDM optical buffers", Optical Networks Magazin, 2, pp. 66--72, November 2001.

29. O. Gerstel, R. Ramaswami and.S. Foster: Merits of hybrid networking, *Proc. OFC 2002*, TuG1, pp. 33-34