Maximal and Effective Throughput of Optical Switching Nodes for Optical Burst Switching

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Abstract

In this paper different variations of the so-called "Tune-and-Select" (TAS) switching node for Optical Burst Switching (OBS) are investigated. Both signal degradation and burst losses limit the effective throughput of such optical burst switching nodes. These limitations are analysed for different nodes with four input/output fibres at different bit rates. The impact of amplifier noise figure, amplifier gain, output power of wavelength converters and additional amplifiers are discussed.

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]. Optical bursts have a typical duration between a few µs and several 100 µs. Therefore switching time of the burst switching node should be below 1 µs. Semiconductor optical amplifier (SOA) based switches with switching times in the ns range are well suited for this application. As one promising node architecture for OBS the so-called "Tune-and-Select" (TAS) switching node [2, 3] and variations of its basic structure are investigated in this paper.

Several impairments like amplifier noise and crosstalk of WDM channels lead to signal degradations. The maximum size of such switching nodes is limited and therefore the maximum throughput of the nodes [3]. In OBS bursts are sent without an acknowledgement of successful path set up (one-pass reservation) and burst loss can occur in case of contention. The burst loss probability B can be reduced by using many wavelengths per fibre in combination with wavelength conversion and optionally by fibre delay lines (FDL) as buffers. Otherwise the burst loss rate (B) is the lower, the lower the utilization of the WDM channels. For a given maximum acceptable burst loss rate (B), node architecture and burst reservation scheme determine maximum utilization of WDM channels [4]. The product of maximum throughput and maximum utilization is the effective throughput of the node.

In this paper not only the maximum size of variations of TAS nodes is calculated, but also the effective throughput of such nodes with a theoretical traffic analysis.

First we extend our analysis of maximum size of OBS nodes [2, 3] by considering power loss, noise and crosstalk for different variations of TAS nodes, which aim at increasing of maximum throughput (TAS with wavelength converters of limited tuning range (TAS-LTR)) or improvement of effective throughput (TAS with one fibre delay line (FDL) per output (TAS-FDL)). As the number of fibres per node (node degree) is typically less than four in a realistic backbone network, we focus our analysis on nodes with 4 input/output fibres. For different line rates (2.5, 10, 40 Gbps) the maximum throughput is calculated for the different node architectures. Thereby, the number of possible wavelengths M is not only limited by noise and crosstalk, but also by reachable spectral efficiency and available optical bandwidth in the EDFA bands.

Next we determine the maximum utilization of WDM channels of the nodes for a burst loss rate of $B \leq 10^{-6}$ yielding in the effective throughput of the different nodes. The impact of several parameters like the amplifier noise figure, amplifier gain, output power of wavelength converters and additional amplifiers on maximum and effective throughputs is discussed.

A better understanding of the potential of future optical burst switching networks is achieved by considering both, physical constraints as well as results from performance evaluation of optical burst switches.

2 Optical Burst Switching (OBS)

2.1 Principle of Optical Burst Switching

In an OBS network edge nodes assemble several IP-packets with the same egress node and QoS class electronically into variable length bursts. The bursts stay in the optical domain until they reach the egress edge node. Typical burst lengths are in the order of several 100 kbits which corresponds to a duration between a few µs and several 100 µs. Variable length bursts are central to OBS.

The key characteristic of OBS is the hybrid approach. The header information is sent out of band and the header packets are processed electronically. The data stays in the optical domain while traversing the OBS network.

A special reservation scheme, the so-called "one pass reservation" is used. Network resources for each individual burst are reserved but not acknowledged before sending the data [1]. As depicted in Fig. 1 for each data burst a header packet is sent out of band on a separate wavelength channel and processed electronically by an OBS controller. The header channel can operate with a lower bit rate than the data channels. According to the information in the header packet the appropriate output of switching node is reserved for the burst and the switch is reconfigured accordingly. The burst node must have enough time for switching operations (reading the header, processing and reconfiguring the switching matrix) before the burst arrives. In the most common approach of OBS the header packets will be sent with a time offset prior to the transmission of the data bursts. This basic offset has to be large enough to process the header packets electronically and set up the switching matrix for the data bursts in all passed nodes. That means that the number of the traversed nodes must be known at the edge node and considered for determine the burst delay.

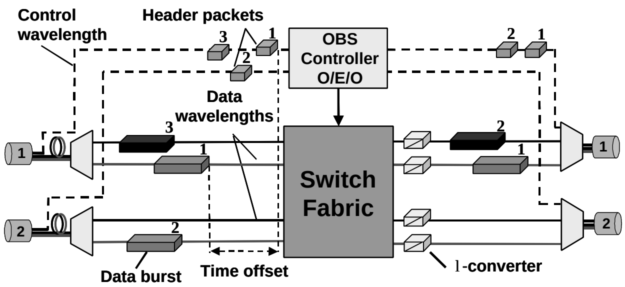

Fig. 1: *Principle of Optical Burst Switching (OBS).*

Another solution is to send the header packets and the data bursts simultaneously and to delay only the data bursts at each burst node before its entry in the switching matrix as shown in Fig. 1. Here only one FDL each node input fibre is need in opposition to complex fibre delay line (FDL) buffer architectures, proposed in the context of optical packet switching (OPS) in which each packet has to be stored during processing [5, 6],. For a time offset of 10 µs, a 2 km optical fibre delay line (FDL) for data bursts is needed in each OBS node.

In the case of successful reservation a new control packet is generated and sent to the output fibre. When the burst arrives at the switch the reconfiguration is already performed and the burst is forwarded to the output like burst 1 and 2 in Fig 1. If the desired output is still occupied by another burst (contention) the burst (3 in Fig 1) has to be discarded and reservation process is finished.

To keep the burst loss as low as possible, a strictly non-blocking switching matrix is required. Additionally the burst loss rate B can be reduced by using many wavelengths per fibre in combination with wavelength conversion (burst 2 in Fig. 1) [7, 8] and optionally by using optical delay lines (FDL) as buffers solely for contention resolution [9].

OBS allows fine granular switching and some gain due to statistical multiplexing like optical packet switching (OPS), but it has not the same problems, as it does neither rely on optical header processing nor on "store and forward" using optical buffering. It can be considered as a compromise between optical circuit and packet switching [1, 7].

2.2 Requirements on nodes for Optical Burst Switching

OBS will be only possible if fast and large switching nodes can be built. Some requirements on such switching nodes can be deduced from the characteristics of the OBS:

a) Fast optical switches

Optical space switches are the key element in OBS nodes. The most important performance parameters of the optical switches are switching speed, loss and crosstalk. While the switching time determines the application area of the systems, the last two put some constraints on the dimensions of the switching nodes (which will be considered separately in the next sections).

Some characteristic times which are important for the requirements on optical switches are shown in Fig. 2. The required switching time depends on the switching granularity and signalling method.

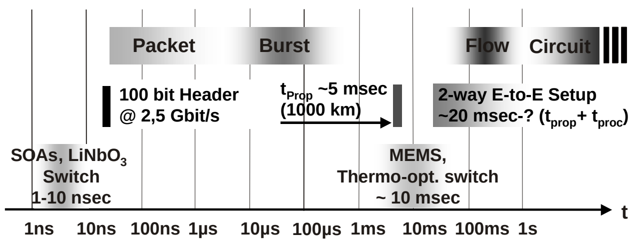

Fig. 2: *Characteristic times versus switching methods. First line: duration of the connection depending on switching granularity. Second line: transmission time of header or signalling information (only point-to-point propagation delay, no electrical processing time of the information). Third line: today available optical switches.*

If one assumes that the end-to-end signalling of a circuit needs some tens of a ms the mean duration of a circuit switched connection should be longer. In this case also the switching time does not need to be much shorter and Micro-electromechanical systems (MEMS) with switching times in the ms range would be a reasonable choice for building optical cross connect (OXC) [10].

For an OBS network the delay of IP-packets by assembling at the edge nodes has to be hold as small as possible. Thus the length of optical bursts must be limited. Bursts are generated according to a statistical process, depending on the arrival times of the packets. Therefore the burst length is distributed statistically with a mean burst length, which is usually in the order of several 100 kbits. This leads to a mean burst length between a few µs and several 100 µs, depending on bit-rates for data transmission. For example, a burst with mean 100 kbits leads to a mean length of 40/10/2.5 µs on a 2.5/10/40 Gbps line. For such bursts switching times should be in the µs or even ns range for efficiency reasons. Otherwise the capacity losses in transport networks due to switching grow (there is no transmission during switching). A mean burst length of 40 µs and a switching time of 1 µs lead to a 2.5 % capacity loss already. During this 1 µs a guard time must be included. Thus the real switching time of the optical switch should be well below 1 µs. These timing conditions also show, that on the other hand a full end to end signalling is inefficient for bursts switching. Consequently the previous mentioned one pass reservation scheme has to be used for OBS.

The switching granularity for OPS is finer than for OBS. For packets with length as assumed in Fig. 2, the switching times should be in the ns range.

Therefore a fast switch technology such as gates of semiconductor optical amplifiers (SOA) and integrated electro-optic switches ($LiNbO_3$ or InP based) [11, 12] are necessary for optical burst/packet switching. In comparison with other fast switches the semiconductor optical amplifier (SOA) gate is one of the most attractive candidates, since $LiNbO_3$ switches are driven by high voltage, have a large insertion loss and a large crosstalk. Additionally the advantages of SOAs are the high on/off ratios (> 50 dB), the loss compensating capabilities (the gain), and the broad amplification bandwidth. The SOA gating functions is based on the gain dependency on the injected bias current: At a high bias current the gain is higher ('on' position) compared to the case where the bias current is low ('off' position).

b) Low signal degradation

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 automatically accomplished by switching compared to electronic switching. To avoid accumulation of signal degradation the number of cascaded SOAs in the signal path must be as low as possible. Therefore an one-stage switch architecture is preferable.

c) Large switching matrices

Several cross connects or optical packet switches using SOAs have been implemented up to 16x16 [5, 13, 14] and 32x32 [15] in size. However the question is whether large switching nodes can be built for OBS.

Depending on the used node architecture, the dimensions of the OBS nodes are additionally determined by the performance of the deployed elements in the nodes. Signal degradation mechanisms like loss, noise, crosstalk and amplifier dynamics limit the maximum size of such nodes. We will discuss this in detail in the following sections.

d) Non-blocking architecture

A switch is non-blocking if each input port can be connected to any unused output port. In this case every input can be connected to every output. Blocking occurs when some connection patterns cannot be realized. For OBS non-blocking architectures are preferred, to avoide that additional burst losses are caused by the node architecture.

e) Essential role of wavelength switching – WDM and wavelength converters

Burst loss can be severe during contention situations due to the one-pass reservation scheme and the fact that an OBS node cannot employ large and flexible random access buffers. To reduce burst losses wavelength conversion can be used effectively [7, 8] allowing bursts to change their wavelength if needed. Thus all wavelengths transmitted on a fibre using WDM can be considered a shared resource which greatly improves the statistical multiplexing gain.

f) Multicast function may be desirable

In the future multicasting will be required for real-time multimedia applications like videoconferencing, shared collaborative workspaces and more. Therefore burst nodes with multicast function are desirable.

3 Node architectures for OBS, the investigated node architectures

3.1 Broadcast and Select Architectures

We choose SOAs as basic switching elements because they provide fast enough switching times and excellent on/off ratios off above 50 dB.

To reduce cost and signal degradation we consider architectures with one SOA only in the signal path. To build strictly non-blocking switches, the so-called "Broadcast and Select" architectures can be used. Such and similar one-stage architectures have been investigated for OPS [5, 13-16] and can be adapted for OBS as shown in Fig. 3: the broadcast-and-select (BAS) node in (a) and the one we called the tune-and-select (TAS) node in (b). The node has N input/output fibres and M wavelengths per fibre. They are strictly non-blocking and have multicast capability. For both nodes N^2*M SOAs are necessary as on/off-switches.

In the BAS-node the basic switch modules are the SOA gates used as on/off switches and the tunable filters for selecting one wavelength. For a node with N fibres and M wavelengths per fibre an fibre input signal is splitted into N*M (broadcast). The following SOA is switched on or off depending, if one of the wavelengths $\lambda_1, \ldots, \lambda_M$ has to be switched to the fibre connected to the output of the SOA or not. Afterwards a tunable filter selects this wavelength (select) and a λ converter with fixed output converts it into the desired output wavelength. Like the SOAs these M*N filters must be also tunable in less than 1 µs. Then the wavelength signals are multiplexed to their fibre. The akusto-optical filters with a tuning times in 10 µs range cannot be used as fast tuneable filters and the fast tuneable $LiNbO_3$ electro-optical filters are is still in development [17].

In the TAS-node the basic switch modules are the tunable wavelength converters and the SOA gates. The tunable λ 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 bursts are then switched to the desired output fiber, by switching the appropriate SOAs on or off (select). For a node with N fibres and M wavelengths per fibre N^2*M SOAs and N*M tunable wavelength converters with switching times less then 1 µs are required.

Both nodes need wavelength converters. A combination of an optoelectronic receiver and transmitter can be used as wavelength converter (o-e-o conversion). In such wavelength converter 3R regeneration of the signal can be performed. In the BAS node the transmitter output wavelength is fixed, but a tunable optical filter is needed, whereas in the TAS node the output wavelength has to be tunable. 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 [18-21]. 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 [22]. They usually provide some degree of signal regeneration (noise suppression) but no full 3R regeneration.

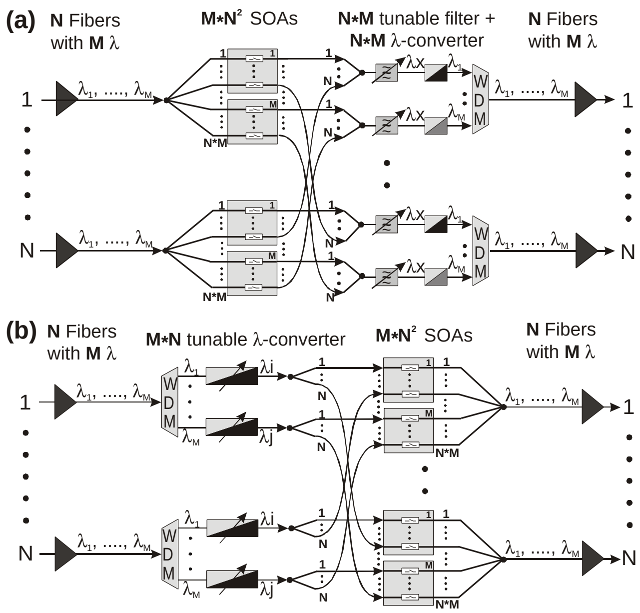

Fig. 3: *OBS switching nodes. (a) broadcast-and-select (BAS); (b) tune-and-select (TAS).*

Comparing both architectures, a simple power budget analysis [2, 3] has shown the limitation of BAS architecture. Only small nodes (e.g. a 16x16 node with 4 fibres and 4 wavelengths per fibre) can be built. Additionally, in the BAS architecture the SOA amplifies all M wavelengths instead of only one in TAS, resulting in large crosstalk [23]. So we focus the following analysis on TAS nodes and consider two variations of TAS architectures.

3.2 TAS with wavelength converters of limited tuning range (TAS-LTR)

A variant of the TAS node is a TAS architecture with wavelength converters of limited tuning range (TAS-LTR) (Fig. 4). The node architecture is very similar to Fig. 3b. Here, the wavelength converters have a limited tuning rang and each λ converter can only convert input signals to few output wavelengths (x = 8, 16, 32, 64 etc.) which leads to smaller output combiners and their partial replacement by WDM-MUX. Also, less noise contributions (from x SOAs instead from M SOAs for TAS) are disturbing the transmitted signals and a λ converter with a smaller tuning range may be easier to realize. Tunable lasers accessing 16 [20] and 32 [21] ITU channels with 100 GHz spacing in ns range have been already demonstrated. It is expected that simpler and larger sized nodes can be built with the TAS-LTR architecture, but the utilization of WDM channels will be small compared to the TAS node because of the limited tuning range of the wavelength converters.

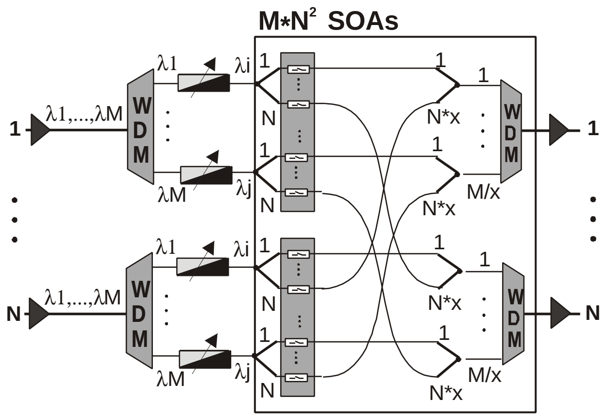

Fig. 4: *TAS-LTR node*.

3.3 TAS with one fibre delay line per output (TAS-FDL)

Another modification of the TAS node applies TAS with one WDM fibre delay line (FDL) per output fibre (TAS-FDL) (Fig. 5). A TAS node with one FDL per input fibre is also feasible, but in comparison unfavourable due to higher losses before the SOA. Such FDLs can resolve contention and reduce burst losses. Drawbacks of these nodes are higher splitting losses and larger switching arrays with 2*M*N^2 SOA gates. The number of WDM FDL per output fibre can be extended, but the size of the TAS-FDL node will be reduced due to the increase of splitting losses. But a lower burst loss rate can be expected and the efficiency of TAS-FDL nodes will be higher [6, 9].

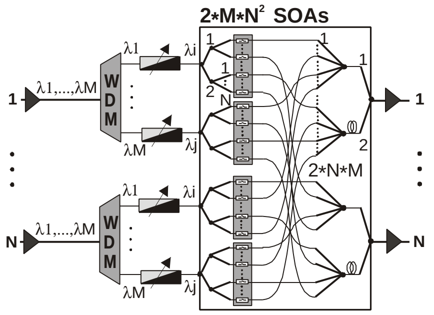

Fig. 5: *TAS-FDL node*

4 Component parameters and system environment

To determine the maximum size of the TAS-nodes the following component parameters (Tab. 1) are used, which, to our best knowledge, represent the present state-of-the-art:

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

Tab. 1: *Parameters for the calculations.*

In the analysis a signal path between two edge routers with burst switching nodes in between are considered, as shown in Fig. 6. The links between the nodes are assumed to be 240 km long and have two inline EDFAs. As regenerative (3R) wavelength converters are used, the accumulation of signal degradation is terminated at each wavelength converter and only has to be considered between two neighbouring nodes, i.e. consecutive λ converters.

In realistic backbone networks, the highest node degree (number of input/output fibres per node) is typically less than four [24, 25], therefore we focus our analysis on nodes with four input/output fibres. The usable capacity in the fibre 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 fibre. The spectral efficiency of WDM system today is typically 0.4 [26]. 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 fibre is 320 for 2.5 Gbps, 160 for 10 Gbps, and 40 for 40 Gbps. For C- and L-band the available number of wavelengths per fibre is doubled. For 2.5/10/40 Gbps the maximum number of wavelengths M and hence the maximum throughput of the considered node architectures are determined within these constraints.

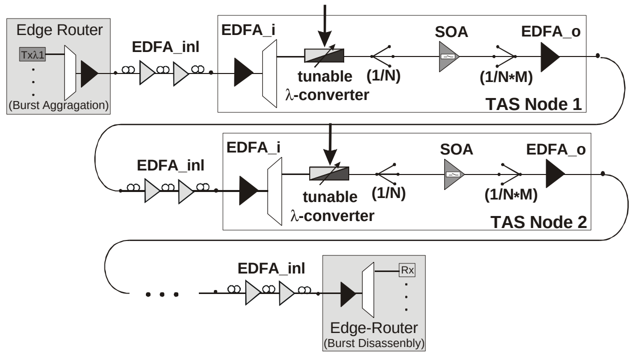

Fig. 6: *Signal path between two edge routers in a OBS network with many TAS-nodes.*

To estimate the effective throughput of the nodes the mean burst length is assumed to be 100 kbit which leads to a mean transmission time of 40/10/2.5 µs at 2.5/10/40 Gbps respectively. The delay lines in the TAS-FDL nodes have a delay of two mean burst transmission times which corresponds to 16/4/1 km of fibre for the different bit rates.

5. 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, fibre dispersion etc.. While the fibre 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 and signal distortion.

5.1 Noise

In our calculations only the noise generated by the optical amplifiers is considered. Due to the assumption of regenerative (3R) wavelength converters, we have to consider the signal path between two neighbouring nodes, i.e. consecutive wavelength converters as shown in Fig. 7 for the TAS nodes. The power levels in the signal path and particular at the input/output of the TAS node are also shown. In this case the noise sources are SOAs as on/off switches as well as amplifiers, input and output EDFAs in the switching nodes and the 3 inline EDFAs.

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 loss (TAS: 1/(N*M), TAS-LTR: 1/(N*x), TAS-FDL: 1/(2*N*M)). Due to the power levels in the critical area between the output of the wavelength converter and output of the node (marked area as shown in Fig. 7) the SOA gain must be as high as possible, even though the noise powers form several SOAs will be merged after the combiner (M for TAS and TAS-FDL, x for TAS-LTR). Furthermore because the SOA is the first amplifier in an amplifier cascade the total noise caused by amplifiers in the cascade will be mainly determined by the SOA noise. Thus low-noise SOAs are very important for the switching node.

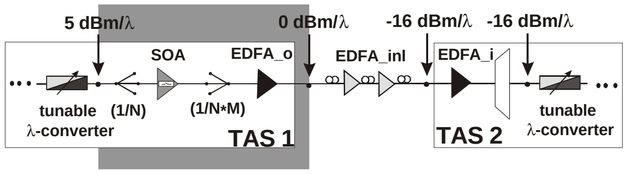

Fig. 7: *Power levels in the signal path between two neighbouring TAS-nodes.*

5.2 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. Due to the different wavelengths λ_1, …, λ_M, only the power addition of interfering signals caused by crosstalk has to be considered. The second is the non ideal extinction ratio of the SOA gates. N-1 switched-off amplifiers have the same input wavelength (TAS-FDL: 2*N-1) as the considered channel resulting in coherent crosstalk.

5.3 Amplifier dynamics (ISI)

The input-output characteristic of conventional SOA gates is non-linear. The gain decreases for high input signal power. For optical signals with data rates between 2.5 and 40 Gbps the gain saturation leads to signal distortion and inter-symbol interference (ISI). The extinction ratio for the output signal is decreased. Gain-clamped SOAs (GC-SOAs) can be used with laser oscillations inside the SOA gate to stabilise the gain of SOAs. The gain of GC-SOA is clamped to a fixed value by the power in the lasing mode, i.e. the laser oscillation creates what can be thought of as a carrier reservoir that shrinks when the input power is increasing and vice versa thus clamping the carrier density in the active region. By using GC-SOA instead of conventional SOA gates the signal distortion and inter-symbol interference can be reduced substantially. The exact analysis of the remaining signal distortion and the resultant impairment of signal quality at the output of the switching node is just in progress. This paper focuses on the analysis of noise and crosstalk to estimate the maximum size of the considered nodes.

6 Calculation of maximum node size and effective throughput

To determine the maximum number of wavelengths M of the considered node architectures at different bit rates, the bit error rate or the Q-factor is calculated. Accumulation of signal degradation is terminated at each wavelength converter due to the assumption of regenerative (3R) wavelength converters. Ithas to be considered only between two neighbouring nodes, i.e. consecutive wavelength converters. The results presented here can be affected by other impairments like amplifier saturation etc.. To have enough margin for other impairments, Q equal to 10 is taken as the limit of signal degradation. This means, the Q factor of the investigated signal path must be beyond 10 and this corresponds to a bit error rate less than BER = 10^{-22}.

The calculations result in the maximum throughput of the nodes, given as the product of the number of fibres N = 4, the number of wavelengths M and the bit rate.

Additionally the maximum utilization of an output fibre is calculated from the number of wavelengths per fibre M using models of burst loss probability which are based on a Poisson arrival process [1, 9, 27]. For TAS and TAS-LTR, results are analytically calculated and insensitive to burst length distribution. For TAS-FDL, exponential burst length distribution and a PreRes buffer reservation scheme are assumed and results are obtained from simulations [27].

To calculate the maximum and effective throughput of the nodes the standard parameters in Tab. 1 are used. Aditionally we looked at the impact of variations of parameters on the results. The variation of all parameters of all architectures would be beyond the scope of this paper. Therefore we only present some meaningful examples. We varied the SOA noise figure and gain for TAS nodes. Increasing the wavelength converter output power increases the throughput of all architectures. We exemplify this with the TAS-FDL node, where the effect is especially effective. For the TAS-LTR node we only vary the range of the wavelength converters.

6.1 Tune-and-select (TAS) nodes

To calculate the maximum number of wavelengths M of a TAS node with four input/output fibres we use the parameters in Tab.1. The input power of the SOA is in this case (5 dBm output power of wavelength converter) -4 dBm and the SOA provides a 15 dB gain not to exceed the 11 dBm maximum output power. As described above we only consider the transmission from one wavelength converter to the next wavelength converter of the neighbouring node. As shown in Fig. 8 the noise power in front of the second wavelength converter grows with the number of wavelengths per fibre. The bar diagram shows the relative contribution of every noise source. While the inline EDFAs generate the largest part of the noise for small M, the SOAs generate most of the noise for large M, since the total noise power of M SOAs increases with the increasing number of wavelengths. Keeping the power levels constant, the decrease of the SOA gain leads to a smaller noise contribution from the SOA, but the other noise contributions overcompensate this reduction and the total noise power in front of the second wavelength converter increases. Consequently we have to keep the gain of the SOA as high as possible.

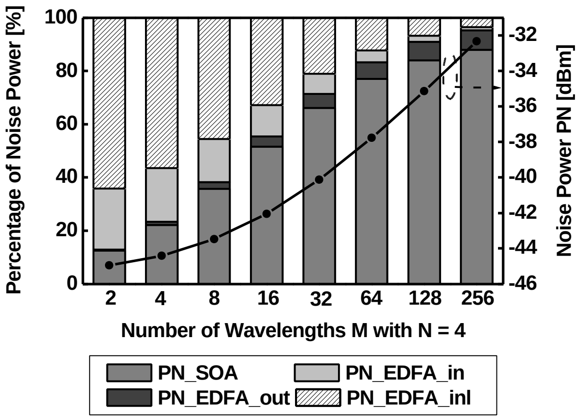

Fig. 8: *The total noise power and noise contribution of every noise source for a 10 Gbit/s line.*

In Fig. 9 the Q-factor versus the number of wavelengths M for different bit rates are shown. The dashed line is for noise and the solid line for noise and crosstalk. As shown in Fig. 8 the noise increases with the number of wavelengths, which determines the decreasing of the Q factor here. Together with crosstalk the Q-Factor becomes smaller especially for large numbers of wavelengths M, but the signal degradation is dominated by noise.

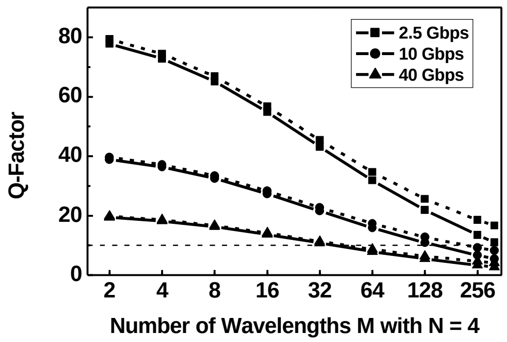

Fig. 9: *The Q-factor versus the number of wavelengths M for different bit rate. The number of the in-/output fibres is N = 4.*

With a Q-factor greater than 10, a TAS-node with four input/output fibres can be built with its maximum number of C-band wavelengths (M = 320) for 2.5 Gbps, but not for 10 Gbps and 40 Gbps. Only M = 128 (10 Gbps) and M = 32 (40 Gbps) can be reached, if we just consider the number of wavelengths as multiple of two. This results in a maximum throughput of 3.2 Tbps for 2.5 Gbps, and 5.12 Tbps for 10 Gbps and 40 Gbps.

The effective throughput depends on the maximum utilization of WDM channels. The WDM channels can only be utilized with 77 % of their max. capacity for 2.5 Gbps, 65 % for 10 Gbps and 38 % for 40 Gbps if the allowable burst loss rate is assumed to be B $\leq 10^{-6}$. As shown in Fig. 10 the effective throughputs are 2.46 Tbps for 2.5 Gbps, 3.32 Tbps for 10 Gbps and 1.94 Tbps for 40 Gbps.

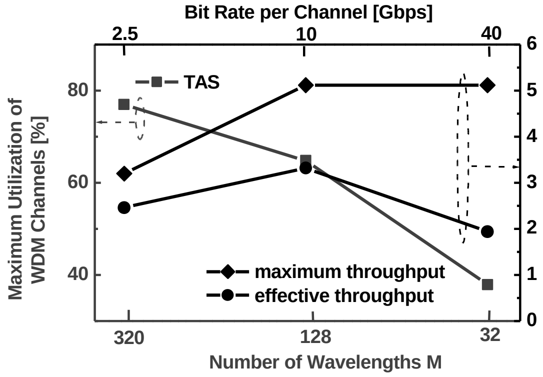

Fig. 10: *The maximum utilization of WDM channels and maximum/effective throughput for TAS with different bit rate.*

a) Variation of noise figure

As shown in Fig. 9, the maximum of wavelengths M of a TAS node is mainly determined by amplifier noise. The SOAs generate the largest part of the noise for large M (Fig. 8). Thus low-noise SOAs are required to build large TAS nodes for OBS. E.g. for 10 Gbps a TAS-node with four in-/output fibres can be built with its maximum number of C-band wavelengths (M = 160), if SOAs with noise figures equal to 10 dB are used. For 40 Gbps the maximum number of C-band wavelengths is M = 40 and SOAs with noise figures equal to 6 dB are necessary. With increasing bit rate per channel, components with a better performance are needed.

But there are still fundamental physical boundaries which limit the size of the TAS nodes: A noise figure better than 3 dB is not possible for SOAs and EDFAs. If all EDFAs and SOAs in our system had noise figures equal to 3 dB, a TAS-node with four in-/output fibres could be built with its maximum number of C- and L-band wavelengths for 10 Gbps (M = 320) and 40 Gbps (M = 80), but not for 2.5 Gbps (only M = 512 can be built instead of M = 640).

b) *Variation of SOA gain*

The demand for the SOA gain to be as high as possible is not sufficient to guarantee automatically large-sized switching nodes. The SOA gain in TAS nodes with a fixed number of input/output fibres (N = 4) depends on the input power of the SOAs (output power of wavelength converters) and the maximum output power of the SOAs. Using the parameters in Tab. 1 a TAS node with 4 input/output fibres can be built with 128 wavelengths per fibre for 10 Gbps. By holding the maximum SOA output power constant, the number of wavelengths decreases with the increasing SOA gain (decreasing output power of wavelength converter). Only 64 wavelengths can be reached by a 17 dB SOA gain. If the output power of the wavelength converters was raised from 5 dBm to 6 dBm (-3 dBm at input of SOA instead of -4 dBm), a SOA gain of 14 dB only is needed and the maximum number of C-band wavelengths for 10 Gbps (M = 160) can be reached. The gain of SOA can be varied between 14 dB and 11 dB without changing the maximum reachable number of wavelengths, only the Q-factor is reduced negligibly. However, the input power of SOAs cannot be raised arbitrarily due to the gain saturation of the SOAs as discussed in section 5.3.

6.2 TAS with wavelength converters of limited tuning range (TAS-LTR)

a) Variation of tuning range

The maximum size of a TAS-LTR node depends on the tuning range of the wavelength converter. Fig. 11 shows the maximum and effective throughput for different tuning ranges and bit rates. The number of wavelengths per converter x is varied from 8 to 128. Due to the lower number of SOAs contributing to the noise in front of the next wavelength converter of the neighbouring node (from x SOAs instead from M SOAs for TAS) larger nodes can be built with this architecture compared to the TAS architecture.

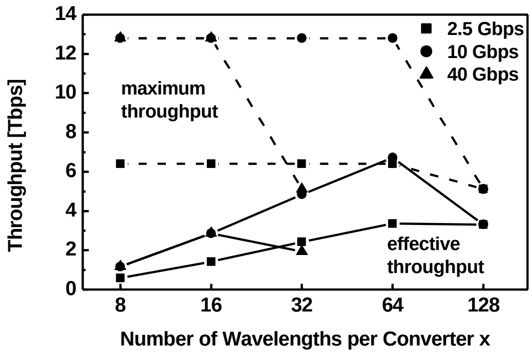

Fig. 11: *The maximum and effective throughput for TAS-LTR with different tuning range and bit rate.*

The maximum number of C- and L-band wavelengths and highest achievable maximum throughput can be reached for all bit rates, but the wavelength converters have different tuning ranges. For 2.5 Gbps (M = 640) and 10 Gbps (M = 320) the tuning range x must be between 8 and 64 and for 40 Gbps (M = 80) is the tuning range x = 16. On the other hand the limited number of the wavelengths per converter x leads to small utilization of an output fibre and hence small effective throughput as shown in Fig. 11. There is an optimal tuning range for the wavelength converters to achieve the highest effective throughput: x = 64 for 2.5 and 10 Gbps and x = 16 for 40 Gbps.

6.3 TAS with one fibre delay line per output (TAS-FDL)

One WDM FDL per output fibre is used to reduce burst losses during contention. Due to higher splitting losses and losses of the delay line only small nodes can be built, but the maximum utilization of WDM channels increases due to the fibre delay line for contention resolution. For a node with 4 input/output fibres and 128 wavelengths per fibre using the the TAS architecture the WDM channels can only be utilized with 65 % for a burst loss probability $B \leq 10^{-6}$. Using TAS-FDL architecture the WDM channels can be utilized with 92 %. More details are shown in Fig. 12. But overall the achievable maximum and effective throughput with TAS-FDL nodes are still small due to a lower achievable number of wavelengths.

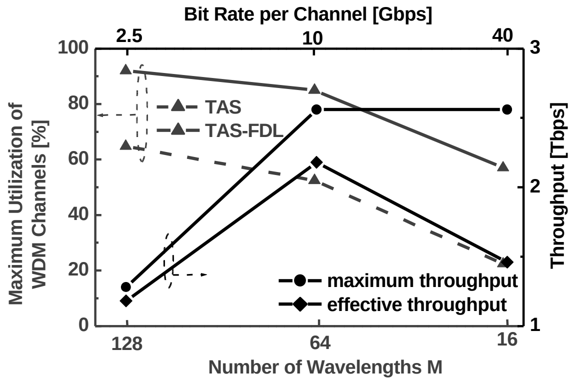

Fig. 12: *The maximum utilization of WDM channels for TAS-FDL (in comparison TAS with same wavelengths per fibre) and maximum/effective throughput for TAS-FDL with different bit rate.*

a) *Variation of output power of wavelength converters*

The output power of wavelength converters (input power of SOAs) can be changed to increase the achievable size of the TAS-FDL nodes. Using the parameters in Tab.1 the input of the SOAs is –7 dBm for 5 dBm output power of the wavelength converters. By holding the maximum SOA output power constant, the number of wavelengths increases with the increasing output power of the wavelength converters (increasing input SOA power and decreasing SOA gain). For 10 dBm wavelength converter output power the input power of the SOA is –2 dBm. A SOA gain of 13 dB only is needed and the maximum number of C-band wavelengths for all bit rates can be reached. However, the relative high input power of the SOAs can cause gain saturation of the SOAs and the signal distortions will lead to a decreasing Q-Factor, which we will analyse in the future. The achievable maximum and effective throughputs are shown in Fig. 13 for different output powers of the wavelength converters.

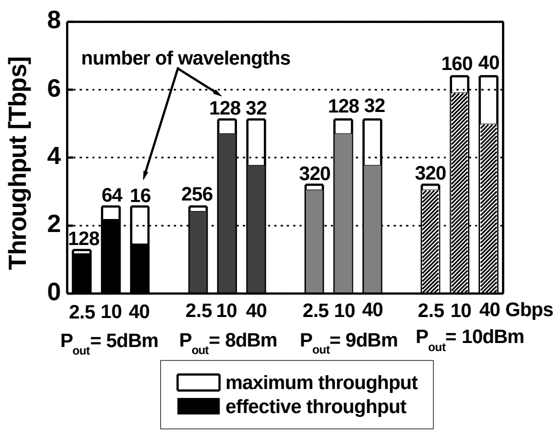

Fig. 13: *The maximum and effective throughputs for TAS-FDL for different output powers of the wavelength converters.*

6.4 Impact of additional amplifiers

The use of additional amplifiers to overcome the losses in the nodes seems to be an option to increase the maximum number of wavelengths per fibre. The cascading of many SOAs has to be avoided due to signal degradations caused by noise and gain saturation. Thus only EDFAs can be used as additional amplifiers. Due to the cost the number of additional EDFAs must be limited and their position in the node is very important. We placed EDFAs at different positions in the TAS nodes discussed in this paper. Our results can be summarized as follows: The additional EDFAs behind the SOA gates are not resulting in better noise performance. An improvement can only be achieved, if additional EDFAs are placed in front of the SOA gates. The drawback of this is the large number of additional EDFAs (N*M at least), which can be avoided by increasing the output power of the wavelength converters, as discussed in previous sections. However the output power of the wavelength converters is limited by gain saturation of the SOA gate caused by high input power and leads to signal distortions.

7 Comparison of different architectures

Fig. 14 shows the maximum and effective throughput for a node with 4 input/output fibres by using our standard parameters as shown in Tab. 1. For TAS-LTR the ranges of the wavelength converters have to be set. As shown in section 6.2 the highest maximum and effective throughput is achieved with a range of 64 wavelengths for 2.5 and 10 Gbps and 16 for 40 Gbps.

The highest maximum throughput (6.4 Tbps for 2.5 Gbps and 12,8 Tbps for 10 and 40 Gbps) can be achieved with TAS-LTR because only x SOAs instead of M SOAs contribute to the noise in one channel. With TAS-FDL, only rather small nodes (1.28 Tbps for 2.5 Gbps and 2.56 Tbps for 10 and 40 Gbps) can be built due to higher splitting losses and losses of the delay line. Maximum throughput of a specific architecture is identical for a bit rate of 10 and 40 Gbps, not for a bit rate of 2.5 Gbps at which the maximum throughput is smaller due to crosstalk.

As expected the TAS-LTR has the lowest efficiency in comparison with other architectures. But with this architecture the largest effective throughputs can always be achieved for all bit rates: about 3 Tbps for 2.5 and 10 Gbps and about 6 Tbps for 40 Gbps.

The best efficiency can be achieved by TAS-FDL architectures among the architectures studied. The highest utilization has the TAS-FDL at 2.5 Gbps with above 90 %. But only a small number of wavelengths , particularly for 40 Gbps (here only 16 wavelengths), is allowed due to the high splitting losses of the TAS-FDL. Consequently the maximum effective throughput is rather small: about 2 Tbps for 10 Gbps and about 1 Tbps for 10 and 40 Gbps. As shown in Fig. 13 the maximum and effective throughput can be increased by increasing the output power of the wavelength converters. In this case the utilization for the TAS-FDL at 2.5 and 10 Gbps is always above 90 % and at 40 Gbps an utilization above 70 % can be reached.

In comparison with lower line rates, 40 Gbps is less efficient due to a smaller achievable number of wavelengths. To increas the throughputs for nodes at 40 Gbps a high output power of the wavelength converters and a TAS-FDL node architecture are required.

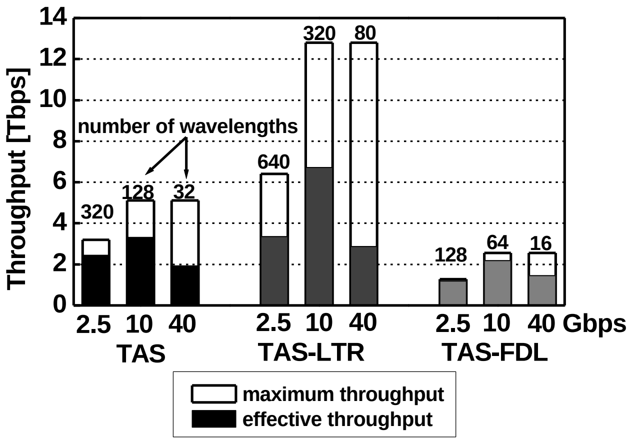

Fig. 14: *The maximum and effective throughputs for different node architectures with 4 input/output fibres.*

8 Conclusion

Three different architectures of optical burst switches with 4 input/output fibres and bit rates of 2.5, 10 and 40 Gbps have been analysed. Possible physical maximum throughputs as well as the effective throughputs are calculated based on a theoretical traffic analysis. Signal degradation caused by noise and crosstalk limits the number of possible wavelengths M for a given structure. The maximum size and throughput of these nodes is determined using a Q-factor of 10. The effective throughput is calculated for a burst loss probability of $B \leq 10^{-6}$.

Among the studied architectures, an OBS node based on wavelength converters with limited tuning range (TAS-LTR) at 10 Gbps has been shown to achieve the highest effective throughput of 6.7 Tbps. A node with one FDL per output (TAS-FDL) at 2.5 Gbps achieved a maximum utilization of over 90% ($B \leq 10^{-6}$). With the basic TAS architecture a effective throughput above 2 Tbps can be achieved.

The following general rules for design burst switching nodes can be established: The maximum size of the TAS nodes is mainly determined by noise. The noise figure of the amplifiers must be as low as possible. A high output power of the wavelength converters is needed. For SOAs as on/off switches high gain and high output power are required. For all here studied architectures using additional amplifiers are expensive to implement and provide little improvements. Finally the highest effective throughput can be achieved for a bit rate of 10 Gbps.

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