Adaptive Hybrid Optical Switching: Performance and Energy Efficiency

Authors: Slavisa Aleksic, Matteo Fiorani and Maurizio Casoni

Adaptive Hybrid Optical Switching: Performance and Energy Efficiency

Invited Paper

Slavisa ALEKSIC [a,1], Matteo FIORANI [b] and Maurizio CASONI [b]

[a] *Institute of Telecommunications, Vienna University of Technology, Favoritenstrasse 9/388, A-1040 Vienna, Austria, E-mail:slavisa.aleksic@tuwien.ac.at.*

[b] *Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Vignolese 905, Modena, Italy*

E-mail: {matteo.fiorani, maurizio.casoni}@unimore.it

Abstract.

Hybrid optical switching (HOS) has the potential to provide highly efficient operation through combining various switching paradigms and different implementation options within the same network. The flexibility of choosing between circuit, packet or burst switching and electronic or optical implementation results in an improvement of both energy and data transport efficiency because the most appropriate method and less power consuming elements can be selected and used for transmission of data through the network while temporarily inactive elements are switched off or put in a low-power mode. In this paper, we introduce a novel network concept that we refer to as adaptive hybrid optical switching (AHOS) and present and investigate several architectures and realization options for AHOS nodes. The corresponding control plane comprises two layers, of which one implements routing, signalling and link management functions as defined in the GMPLS standard while the other is responsible for managing already established circuits and scheduling the transmission of packets and bursts. We present results on both performance and energy consumption for different AHOS node realizations, network configurations and traffic patterns, which prove the potential for a high improvement in energy efficiency with respect to conventional electronic packet-switched networks.

Keywords. Energy efficiency, hybrid optical switching, performance evaluation

Introduction

When observing the current Internet traffic one can conclude that many applications require establishing a connection. Thus, despite the connectionless nature of the Internet protocol (IP), the use of the core network is very connection oriented. It has been proven by measurements that above 90% of traffic within backbone networks is using the trans-

[1]Corresponding Author: Institute of Telecommunications, Vienna University of Technology, Favoritenstrasse 9/388, A-1040 Vienna, Austria, E-mail:slavisa.aleksic@tuwien.ac.at.

mission control protocol (TCP) [1,2]. Especially new bandwidth-intensive applications such as IP television (IPTV), voice over IP (VoIP), video conferencing, and interactive gaming set very high requirements on the quality of service that cannot be easily met with pure packet switching. Driven by the need for more dynamics and a better manageability of metropolitan and wide are networks, different signaling mechanisms for circuit provisioning have been specified including the multiprotocol label switching (MPLS) [3], the generalized multiprotocol label switching (GMPLS) [4], the automatic switched transport network (ASTN) [5], the optical channel (OCh) and optical data unit (ODU) switching [6,7] as well as TCP switching [8]. Furthermore, recent efforts in developing bandwidth variable transceivers promise more flexibility in creating and managing optical paths. When using such transceivers and introducing flexible spectrum allocation the available bandwidth can be dynamically allocated, and thus it can be more efficiently utilized because optical paths with variable data rates are realizable. This is the main idea behind the concept of flexible or elastic optical networks (EONs) [9].

In a nutshell, there is a need for a more dynamic bandwidth provisioning in the optical domain, which could be satisfied by developing a novel network concept that: i) makes use of high-speed and adaptive optical systems and ii) allows integration of circuit switching in the core of the packet-switched Internet in a dynamic and efficient way [10]. Such an approach could be a kind of dynamic circuit switching, optical flow switching [11] or an integrated approach combining within a single network circuit, burst, and packet switching in both optical and electronic domains, which is referred to as hybrid optical switching [12,13,14,15].

Hybrid optical switching (HOS) has gained particular attention in recent years because it has the potential to optimize the overall network performance and to allow considerable cost savings and improved node scalability [12,15,16]. This network concept could efficiently accommodate heterogeneous traffic with diverse quality of service requirements in order to optimally support advanced applications and services. The term hybrid has been used to describe both a combined optical and electronic implementation and a coexistence of different switching paradigms such as packet, burst and circuit switching. The most research efforts on hybrid switching focus on network performance evaluation and estimation of potential improvements through using hybrid switching instead of a single-technology approach, but only a few of them address architecture of hybrid optical switches [15,16] and report on experimental demonstrations of such a system [17,18]. Several recent studies address integration of the GMPLS control plane [4] with the OBS control plane [19,20]. However, to the best of our knowledge, definition of an efficient and interoperable control plane for HOS networks is still missing.

In our previous work [10,21,22,23], we developed a combined analytical and simulation approach, i.e. a hybrid model for evaluation of both performance and power consumption of HOS core nodes. In the study presented in this paper, we extended the model by including additional to the core nodes also edge nodes in order to evaluate the performance and energy consumption of a complete end-to-end path through *adaptive hybrid optical switching* (AHOS) networks. In AHOS networks, the most appropriate forwarding mechanism is used to transport data originating from different applications through the core network in order to meet high requirements set by the applications and to improve network energy efficiency through utilizing low power-consuming switching technologies.

The paper is organized as follows. In the next section, we present a novel integrated and interoperable control plane and corresponding node architectures for adaptive hybrid optical switching (AHOS) networks. Section 2 is devoted to performance evaluation of AHOS network. In Sections 2.1 and 2.2, we present results on performance and energy efficiency respectively. Furthermore, we estimate the potentials for improving the energy efficiency of core networks when using the AHOS concept instead of a conventional electronic packet switching network. Finally, conclusions are drawn in Section 3.

1. Adaptive Hybrid Optical Switching

This section describes the concept of adaptive hybrid optical switching (AHOS) and presents structures of AHOS core and edge nodes.

1.1. The Concept of Adaptive Hybrid Optical Switching (AHOS)

The idea behind the concept of adaptive hybrid optical switching (AHOS) is to utilize electronic and optical switching technologies in an efficient way and to optimally support various types of traffic by using the most appropriate way for transporting client data through the core network. It utilizes electronic and optical switching at different time scales (packet, burst and circuit switching) and selects the most appropriate switching or multiplexing method on flow-by-flow basis. The nodes in an AHOS network are able to dynamically adapt their power consumption according to actual traffic conditions by switching off or putting in a low-power mode the inactive switch ports and line cards.

The adaptive hybrid optical switching network can be graphically presented using an overlay model as shown in Figure 1. It comprises three layers: the AHOS data layer, the AHOS control layer and the GMPLS control layer.

The *AHOS data layer* is responsible for all data plane functions such as optical signal generation, transmission, multiplexing, switching, synchronization, and aggregation of data bursts. There are four possible methods for transmitting data through AHOS networks, namely using *optical packets*, *short and long optical bursts* and *time-division multiplexed (TDM) circuits*. In general, circuits, bursts and packets do not necessarily need to be transmitted at the same data rate and using the same modulation format. That is, in addition to combining different switching paradigms within the same network, AHOS networks could also be capable of providing data rate adaptive optical links given that AHOS nodes are equipped with bandwidth variable transceivers. Although a flexible optical layer that is able to provide dynamic optical paths with variable bandwidth would most probably enhance the resource utilization of AHOS networks, we assume in this paper fixed-data-rate optical channels and the DWDM ITU grid in order to evaluate the AHOS concept in a standard environment and to be able to easily compare it to the current conventional approaches.

The *AHOS control layer* takes care about scheduling and forwarding of these four transmission types. It also performs resource reservation using a unified control packet for all three switching paradigms. The AHOS control packets are transmitted out-of-band and carry additionally to the GMPLS label stack also information needed for reservation of resources such as the type and length of corresponding data units, the offset time for bursts and the structure and occupation of TDM frames. A more detailed structure of the control packets and a description of each particular field can be found in [23].

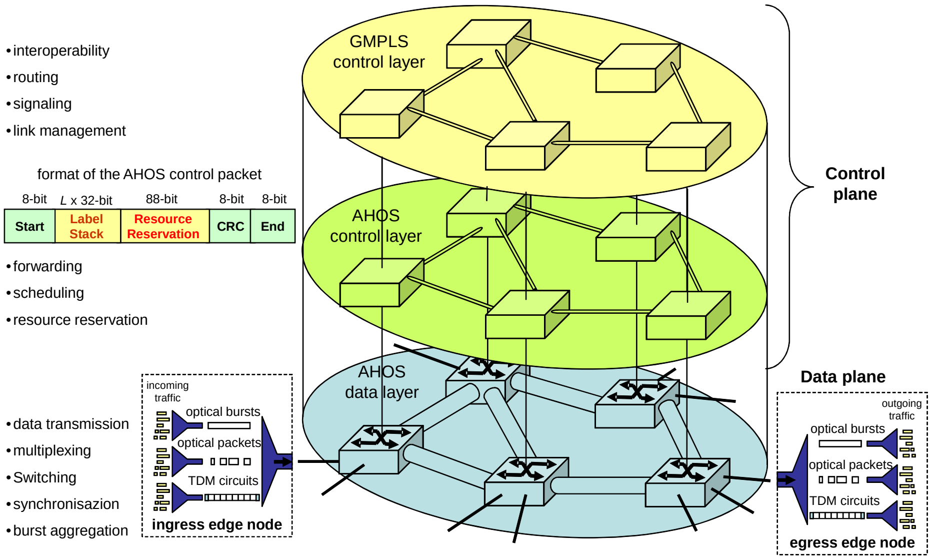

Figure 1. Schematic representation of the proposed network concept based on adaptive hybrid optical switching (AHOS). The AHOS core network is able to efficiently handle different types of traffic by dynamically adapting both switching resources and energy consumption of network nodes.

A unique feature of the AHOS control plane is its capability of scheduling packets in unused TDM slots (see Figure 2). Hence, if there is a free slot in a TDM frame at the time when collision occurs, and if the destination edge node is the same for both the colliding packet and the TDM frame, the packet can be transmitted in the free slot. The node that inserted the packet must inform all subsequent nodes along the path to the egress edge node that the occupation of slots in the affected TDM frame has changed. This is done by updating the slot occupation table in the resource reservation field of the corresponding AHOS control packet. The possibility of transmitting colliding packets in unused slots of TDM circuits increases utilization of TDM frames on the one hand and reduces packet blocking probability on the other.

The *GMPLS control layer* implements routing, signalling and link management functions. It ensures interoperability and communicates with the AHOS control layer through exchanging the information about resources utilization as well as label and link management.

1.2. AHOS Core Nodes

The architecture of AHOS core network nodes is presented in Figure 3a. The nodes comprise a fast and a slow switch. The slow switch is assumed to be based on an optical switching technology that provides switching times in the order of milliseconds or sub-milliseconds such as, for example, the optical micro-electro-mechanical systems (MEMS) switches. Because of their relatively long switching times, optical MEMS switches are best suited for switching circuits. Due to the fact that optical MEMS are transparent to wavelength, polarization, bit rate and modulation format, they have been already considered for implementing network nodes for elastic optical networks [24]. In AHOS networks, optical MEMS switches can be used for establishing adaptive optical

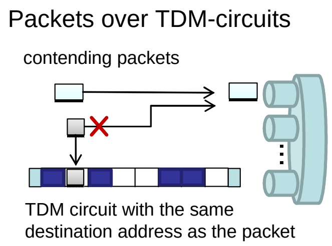

Figure 2. The principle of transmitting packets over unused slots of a previously established time-domain multiplexed (TDM) circuit. In case of contention, one of the contending packets is sent to the desired output port and the other is transmitted on a free slot within a TDM circuit with the same destination edge node as the contending packet.

paths. The fast switch can be either an electronic packet switch based on the conventional CMOS technology or an optical packet switch, e.g. a switch based on semiconductor optical amplifiers (SOAs). The optical channels at the input of the node are split in two ways by optical splitters. Thus, the optical signals from input ports are sent to both the slow and the fast switch. The decision about which switch is to be used is made by the control plane on the base of the received control information. Once the decision has been made, then one of the switches is selected to be active for a particular input port and wavelength channel, while the other is switched off or set in a low-power mode. Due to the fact that optical MEMS switches typically consume only a small fraction of the power usually needed for powering a high-performance electronic packet-switch, we assume here that the slow optical switch is always active and only the ports of the fast switch are switched off.

The control information is extracted at input ports using the control information extraction (CIE) units and sent to the control plane module for further processing. We assume here that the control signal is encoded together with the data signal on the same optical carrier using the subcarrier multiplexing (SCM) technique. At the output ports, the updated control packets are added to data signals using the control information reinsertion (CIR) units. Both the CIE and the CIR modules could be implemented using Fiber Bragg gratings (FBGs) as proposed and experimentally demonstrated in [25,26]. To estimate power consumption of CIE and CIR modules, all active components needed such as voltage-controlled oscillators (VCOs), radio frequency (RF) up- and down-converters, modulator drivers, RF amplifiers, and optical receivers have to be taken into account. Thus, the power consumption of such a module can be estimated to be approximately 17 W [21]. The main benefit of using SCM is that the need for a dedicated control channel is avoided because both control and data information are transmitted on the same optical carrier. Furthermore, the synchronization of data packets and TDM circuits with the corresponding AHOS control packets is simplified.

As already mentioned in the previous paragraph, the hybrid optical switching node can comprise either an electronic or an optical fast switch. We refer here the architecture with a fast electronic packet switch to as *optical/electronic hybrid architecture* and the architecture that uses optical technology for both slow and fast switches to as *all-optical hybrid node*.

The architecture of an *all-electronic packet-switched node* is presented in Figure 3b. It represents a generic architecture of a conventional IP router, in which the entire incoming traffic composed of individual packets is subject to optical/electrical (O/E) conver-

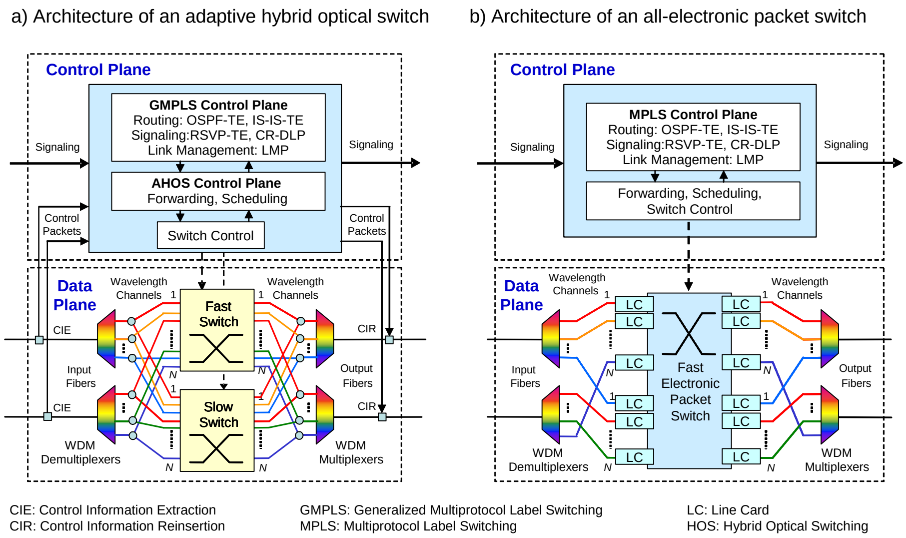

Figure 3. Architectures of a) an adaptive hybrid switching node and b) an all-electronic packet switching node.

sion. The incoming traffic is processed in the line cards (LCs) and forwarded to output ports by a fast electronic switch. The control information is transmitted in packet headers. A large buffering space is available for packet processing and collision resolution; thus the all-electronic node is capable of complex traffic processing and provides negligible packet losses. Additionally, the control and management plane of the all-electronic node implements MPLS functionality.

1.3. AHOS Edge Nodes

Connection of the AHOS core network to an access network or directly to high-end users is made through AHOS edge nodes. Interoperability is ensured by the use of the overlay model and the implementation of the GMPLS control plane. The AHOS edge nodes implement in addition to general edge node functionalities such as traffic classification, conditioning and grooming also some AHOS specific functions. The AHOS specific functions include mapping of ingress traffic into the four AHOS transmission types (optical packets, short optical bursts, long optical bursts and TDM circuits), burst assembly, resource allocation, extraction of packets from bursts and TDM circuits as well as generation and processing of AHOS control packets. The generic structure of an AHOS edge node is shown in Figure 4.

Mapping of different service classes into the four transmission types is performed by the classifier and traffic conditioner blocks according to the required service quality, e.g., with respect to the value of the differentiated services code point (DSCP) field. The aggregation of short and long bursts as well as TDM circuits is carried out in the traffic assembler. The resource allocator allocates output resources, i.e., the output wavelength channels, to the data waiting for transmission. The packets, bursts and TDM circuits received from the AHOS core network are first disassembled in the packet extraction module, and then the extracted packets are sent to destination output ports on the access network side. In real networks, edge nodes are often collocated with core nodes because

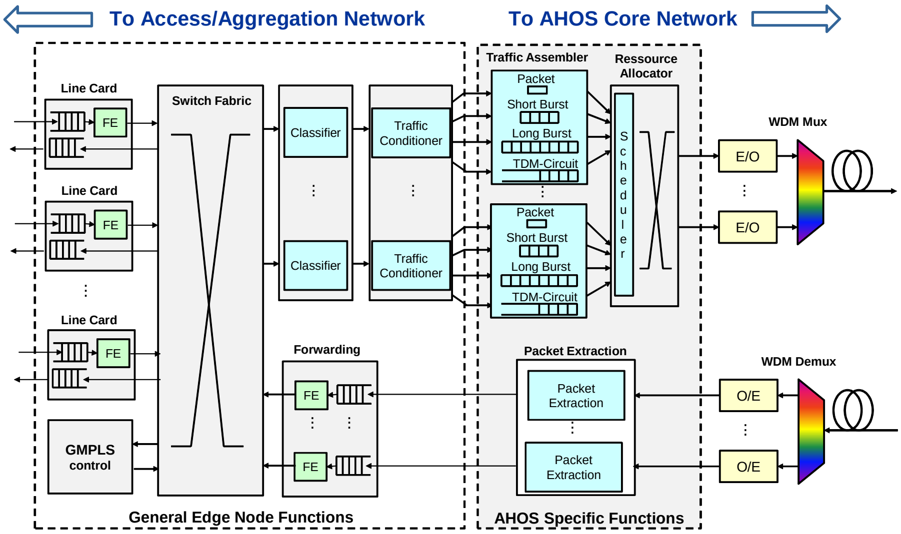

Figure 4. Generic architecture of an AHOS edge node (FE: Forwarding Engine, O/E: Optical/Electrical Conversion, GMPLS: Generalized Multiprotocol Label Switching, WDM; Wavelength-Division Multiplexing)

usually core nodes are located in the premises of network providers where also some local traffic is aggregated and added/droped to/from the core network. For this reason, we will consider additionally to a *core-only AHOS network* containing the core nodes as depicted in Figure 3a also an *end-to-end AHOS network*, in which edge nodes are collocated with core nodes and both edge and core functionalities are included. Such a structure of network nodes is shown in Figure 5, in which the edge node aggregates the local IP traffic, forms optical packets, bursts and circuits and sends them to the core node to which it is directly connected. Thus, the core node has a certain number of ports, of which a portion is connected to the edge node and used for handling the add/drop traffic, while the residual ports are connected to other core nodes and handle the incomming/outgoing AHOS core network traffic.

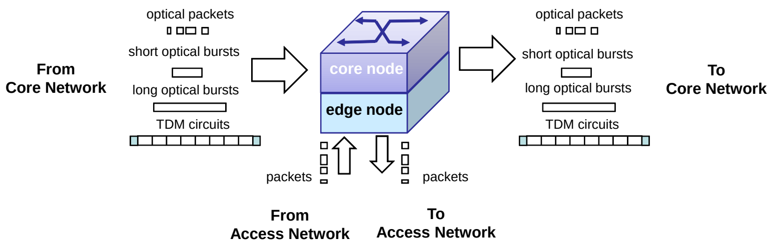

Figure 5. Combination of core and edge nodes for evaluation of energy efficiency of an end-to-end path through AHOS networks.

2. Performance and Energy Efficiency

We performed performance and energy consumption studies by means of event-driven simulations and analytical modeling. The model developed and applied within this study is described in [21,23]. In order to estimate potential improvements in energy efficiency of the adaptive hybrid optical switching concept, we compared the estimated energy efficiency of networks based on the two implementation options for AHOS nodes (optical/electronic hybrid and all-optical hybrid) with that of networks using conventional electronic packet routers. As a metric for the comparison we defined the *improvement in energy efficiency (IE)* as follows:

$$IE = \frac{\frac{Th}{P_{cons}}\big|_{hyb} - \frac{Th}{P_{cons}}\big|_{el}}{\frac{Th}{P_{cons}}\big|_{el}} \qquad (1)$$

where Th denotes the achievable throughput and P_{cons} is the node's power consumption. For a detailed description of both the AHOS control plane and the node architectures as well as for more information about the model developed and applied within this study, the reader is referred to [21,22,23]. The parameters used in the evaluation of both performance and energy efficiency are summarized in Tables 1, 2 and 3.

2.1. Performance Evaluation

To assess the performance of the considered network options, we developed and implemented an event-driven simulator [21,22,23] that we used in this study to obtain loss rates and required numbers of active components for various scenarios. The total network power consumption is then calculated using the power consumption model described in [10,21,28], which is applied to obtain the results presented in Section 2.2. The power consumption of AHOS nodes is calculated according to the number of active components and their utilization, which are in turn obtained from the performance evaluation model. The main simulation parameters used for the performance evaluation of AHOS networks are listed in Table 1.

2.1.1. AHOS Core Network

First, we evaluated performance of the two AHOS realization options when taking into account core nodes only, i.e., without considering the edge node functionality. We obtained packet and burst loss probabilities for various traffic patterns and different numbers of hops through the network. For this purpose, we implemented a model for a cascade of AHOS nodes shown in Figure 6a. In the simulations, a part of the input traffic is terminated at each node while the residual part traverses to the next hop. Additionally, there is a certain amount of local traffic added to the through traffic at each node in the cascade. The ratio of the through and the add/drop traffic was set to 0.25. For the all-electronic packet switching nodes we assume that the packet loss rate is zero.

The results on packet and burst loss rates for different traffic patterns and numbers of hops in an AHOS network are shown in Figures 6b - 6e. We observed loss rates at two values of offered load, namely at 60% and 80%. At 60% load, both packet and burst loss rates remain below 10^{-4} when 25% of traffic is carried by circuits (see Figure 6b). For more circuit-oriented traffic, the packet-loss rates increase to slightly above 10^{-4}, but

description of parameter	**value**
number of hops in the network (n)	2 - 8
percentage of traffic carried by TDM circuits	25% - 60%
percentage of traffic carried by packets	(1 - traffic carried by circuits)/3 $\times$ 100 %
percentage of traffic carried by short bursts	(1 - traffic carried by circuits)/3 $\times$ 100 %
percentage of traffic carried by long bursts	(1 - traffic carried by circuits)/3 $\times$ 100 %
node capacity (C_{node})	76.8 Tbit/s
length of TDM circuits	20 - 100 ms
slot length	1 - 4 kByte
number of slots in a TDM frame	10
traffic generation process	Poisson
packet length	1, 2, 3 or 4 kByte
length of short bursts	1 - 2500 kByte
length of long bursts	2500 - 5000 kByte
burst assembly algorithm	hybrid (both time and length based)

Table 1. Main parameters used in the performance evaluation of AHOS networks.

still remain at an acceptable low level (Figure 6d). Loss rates below 10^{-4} are achievable up to 70% of offered load [21], which is a good enough performance for many practical applications. For a high load of 80%, the packet and short burst loss rates increase to approximately 10^{-2} and 10^{-3}, respectively. However, the packets transmitted in TDM circuits experience no losses and the loss rate of packets transmitted in long bursts remains below 10^{-4} irregardless the number of cascaded nodes and the traffic pattern (see Figures 6c and 6e). Thus, at heavy loads, loss-sensitive traffic should be transmitted over TDM circuits and long optical bursts, while best-effort traffic can be transmitted over short optical bursts or optical packets.

2.1.2. End-to-end AHOS Network

Now we will consider an end-to-end path through the AHOS network by including also the edge node functionalities. The model used to obtain the results presented in Figure 6 has been extended to also include the edge nodes. Thus, in the model of an end-to-end AHOS network, the generated traffic is composed of packets only, which are then mapped and assembled into the four AHOS transmission types in the AHOS edge node and transmitted over the AHOS core network as an optical packet, in a short or long optical burst, or within a TDM circuit. While we assumed a uniform distribution of data unit lengths in the core-only network, in the end-to-end network the lengths of data units are not anymore uniformly distributed. This is because the traffic assembly algorithm implemented at the network edge strongly influences the characteristics of data units entering the core network. This has a negative impact on performance, especially at moderate loads (see Figures 7b and 7d in comparison to Figures 6b and 6d). In particular, optical bursts are most strongly affected by this effect because the burst aggregation time and

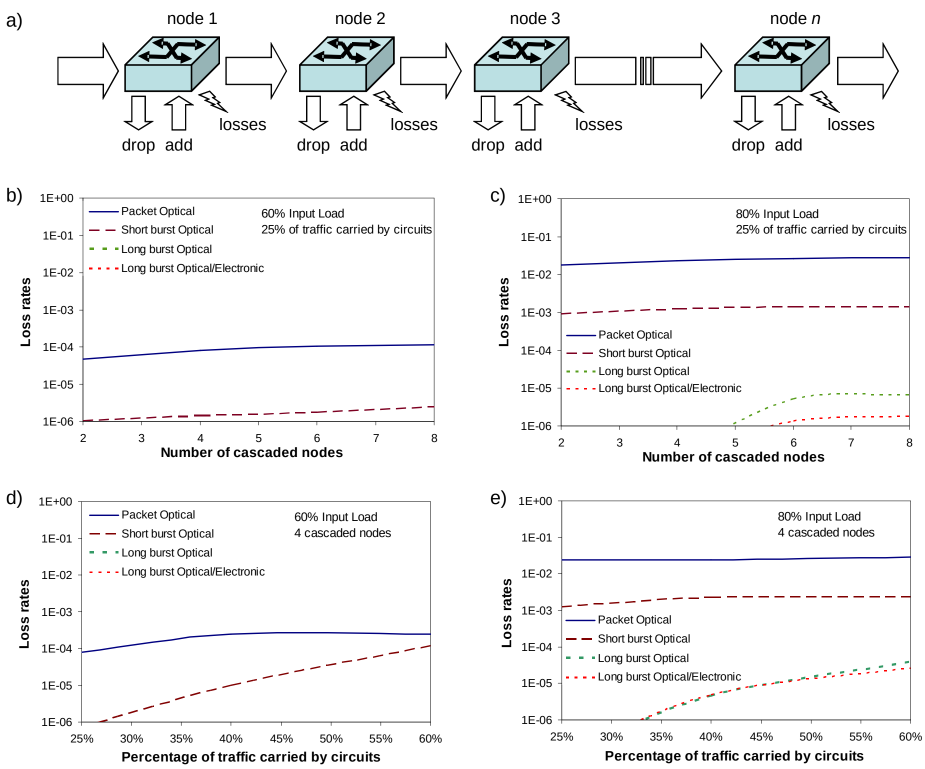

Figure 6. a) Data path model of *n* cascaded AHOS core nodes and results on packet and burst losses over 2 - 8 hops and various amounts of circuit oriented traffic for b) 60% of offered load and 25% of traffic carried by circuits, c) 80% of offered load and 25% of traffic carried by circuits, d) 60% of offered load and 4 hops and e) 80% of offered load and 4 hops. Note that nodes are capable of inserting packets in unused slots of already established TDM circuits.

the burst length depend strongly on both the algorithm used and the characteristics of the input traffic to edge nodes. At higher loads, the lengths of packets and short bursts become more uniform because the packet arrival rate is high. For this reason, the loss rates for packets and short bursts at 80% load (Figures 7c and 7e) are more similar to those in the core-only network, while the loss rate of long bursts increases.

Although the loss rates are significantly higher in the end-to-end network, similar conclusions to those drawn for the core-only network can also be drown for the end-to-end AHOS network regarding the transmission of data originating from different applications over the four AHOS transmission types. Yet the TDM circuits can be used for delay- and loss-sensitive applications because they guarantee both a lossless transport of data and a small deterministic end-to-end delay, while optical packets and short bursts are suitable for the best effort services. Long bursts also experience low losses (below 10^{-4}) at moderate loads, but for high loads and a high amount of circuit-oriented traffic, the long bursts losses increase to above 10^{-3}.

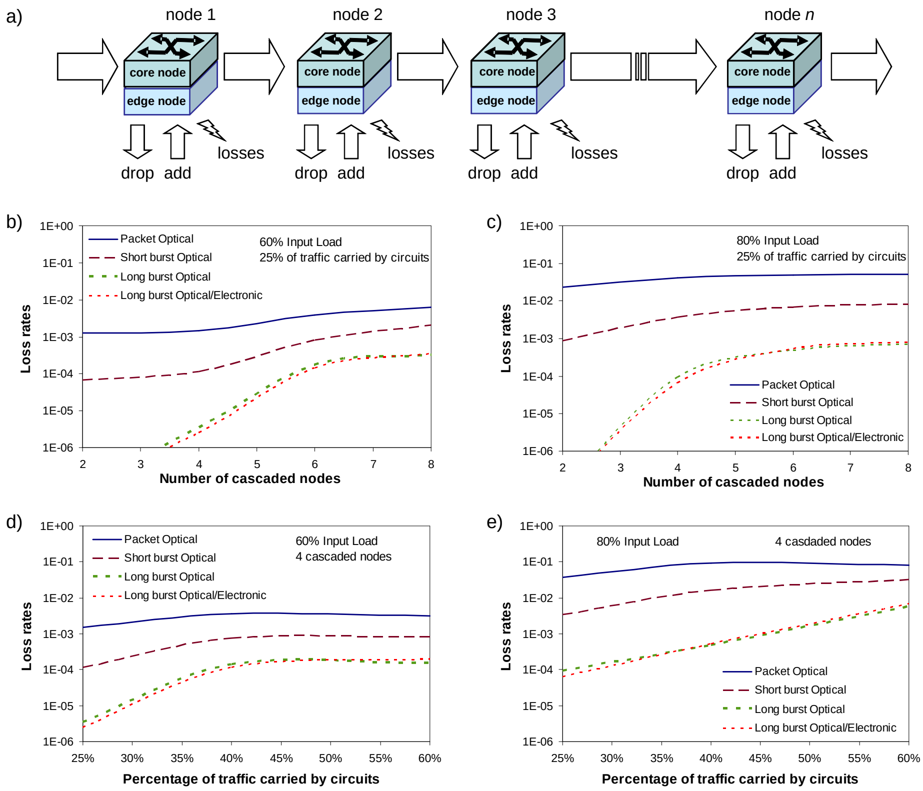

Figure 7. a) Data path model of n cascaded AHOS core and edge nodes and results on packet and burst losses over 2 - 8 hops and various amounts of circuit oriented traffic for b) 60% of offered load and 25% of traffic carried by circuits, c) 80% of offered load and 25% of traffic carried by circuits, d) 60% of offered load and 4 hops and e) 80% of offered load and 4 hops. Note that nodes are capable of inserting packets in unused slots of already established TDM circuits.

2.2. *Evaluation of Energy Efficiency*

As already mentioned at the beginning of the current Section, we defined a new metric for evaluating the energy efficiency of AHOS network options. The metric is referred to as improvement in energy efficiency (IE) and described by equation 1. This metric enables a fair comparison of different network concepts since it includes additionally to the power consumption of network nodes also the achievable node throughput, Th, which is calculated by taking into account both input load and data losses, i.e., $Th = (IL - L_{p,b}) \cdot C_{node}$, where IL is the total input load, $L_{p,b}$ are the total losses including both packet and burst losses and C_{node} is the capacity of the network node. The energy efficiency of the two AHOS network options is evaluated and compared with that of conventional electronic packet switching networks. Thus, we look at possible improvements of energy efficiency when using, instead of the all-electronic architecture depicted in Figure 3b, either the hybrid optical/electronic architecture, $IE_{OE/E}$, or the hybrid all-optical architecture, $IE_{O/E}$ (both shown in Figure 3a). The estimated values for power consumption that we used to evaluate the energy efficiency of AHOS networks are listed in Tables 2 and 3. Please note that we assume for AHOS network nodes that the ports of the fast switch which are temporarily not used because their input traffic is being handled by the slow switch - this is mostly the case for long bursts and TDM circuits - are switched off during their inactivity time. This feature of the AHOS network enables a traffic-dependant power consumption, which leads to high power savings at low loads and when a significant portion of the input traffic is carried by circuits.

all-electronic packet-switched core nodes	**power consumption**
line cards (40 Gbit/s)	300 W
switch fabric (per 40 Gbit/s)	8 W
optical booster amplifiers/preamplifiers (2 per fiber)	14 W
route processor (one per 16 line cards)	200 W
management card (1 per node)	300 W
hybrid all-optical core nodes	**power consumption**
fast optical SOA-based switch (per port)	20 W
slow MEMS-based switch (per port)	0.1 W
wavelength converters (per port)	1.69 W
optical booster amplifiers/preamplifiers (2 per fiber)	14 W
switch control unit (1 per node)	300 W
GMPLS control plane (1 per node)	150 W
AHOS control plane (1 per fiber)	560 W
Long reach WDM transceiver (1 per wavelength channel)	1.25 W
management card (1 per node)	300 W
hybrid optical/electronic core nodes	**power consumption**
line cards (40 Gbit/s)	300 W
switch fabrics (per 40 Gbit/s)	8 W
slow MEMS-based switch (per port)	0.1 W
wavelength converters (1 per wavelength channel)	1.69 W
optical booster amplifiers/preamplifiers (2 per fiber)	14 W
switch control unit (1 per node)	300 W
GMPLS control plane (1 per node)	150 W
AHOS control plane (1 per fiber)	560 W
Long reach WDM transceiver (1 per wavelength channel)	1.25 W
management card (1 per node)	300 W

Table 2. The values of energy consumption used for the evaluation of energy efficiency of the AHOS core nodes [21,23,28,29,30].

2.2.1. AHOS Core Network

Potential improvements in energy efficiency when using either the hybrid optical/electronic ($IE_{EO/E}$) or hybrid all-optical architecture ($IE_{O/E}$) are plotted in Figure 8. The hy-

General edge node functions	power consumption
line cards (40 Gbit/s)	300 W
switch fabric (per 40 Gbit/s)	8 W
route processor (one per 16 line cards)	200 W
traffic conditioner and shaper (one per line card)	62 W
management card (1 per node)	300 W
AHOS specific functions	**power consumption**
traffic assembler (one per line card)	62 W
resource allocator (one per fiber port)	340 W
packet extractor (one per line card)	25 W

Table 3. The values of energy consumption used for the evaluation of energy efficiency of the AHOS edge nodes [21,23,28,29,30].

brid all-optical nodes provide very high improvements between 800% and 1,000%, i.e., an improvement by approximately a factor of 10, while when using the hybrid optical/electronic architecture, improvements of 100% to 300% are achievable. It becomes evident from the figure that the change in traffic pattern has a stronger influence on the energy efficiency than the number of hops. The higher the portion of traffic carried by circuits the larger the difference in energy efficiency between moderate (60%) and high (80%) loads. Thus, although higher improvements in energy efficiency can be achieved for more circuit-oriented traffic, the decrease in energy efficiency due to increased losses at high loads becomes more evident (see Figure 8c). The same effect can be observed in Figure 8d, which presents the change of IE by varying the traffic pattern. IE increases with the increase of traffic carried by circuits at a load of 60%, but remains almost constat at a load of 80%.

2.2.2. End-to-end AHOS Network

Due to the fact that the inclusion of edge nodes results in an increase of both overall losses and energy consumption, the achievable improvement of energy efficiency for an end-to-end network is lower than that for the core-only network. However, improvements by a factor of 2 - 4 are still possible. The hybrid optical/electronic architecture provides an improvement of 2 to 3 times, while the all-optical architecture has the potential to achieve an improvement of 280% (by almost a factor of 4). While IE does not significantly change with the increase of the hop count in case of the all-optical network (see $IE_{O/E}$ in Figures 9a -9c), the optical/electronic network becomes more efficient for a higher number of cascaded nodes. This is because the fast ports of the hybrid optical/electronic nodes are equipped with electronic buffers for contention resolution, which leads to much lower packet and short burst losses than in the all-optical network. This difference becomes more evident for a larger hop count, which leads to a faster increase of $IE_{OE/E}$. Also here the traffic pattern has a more significant influence on IE than the number of cascaded nodes (see Figure 9d).

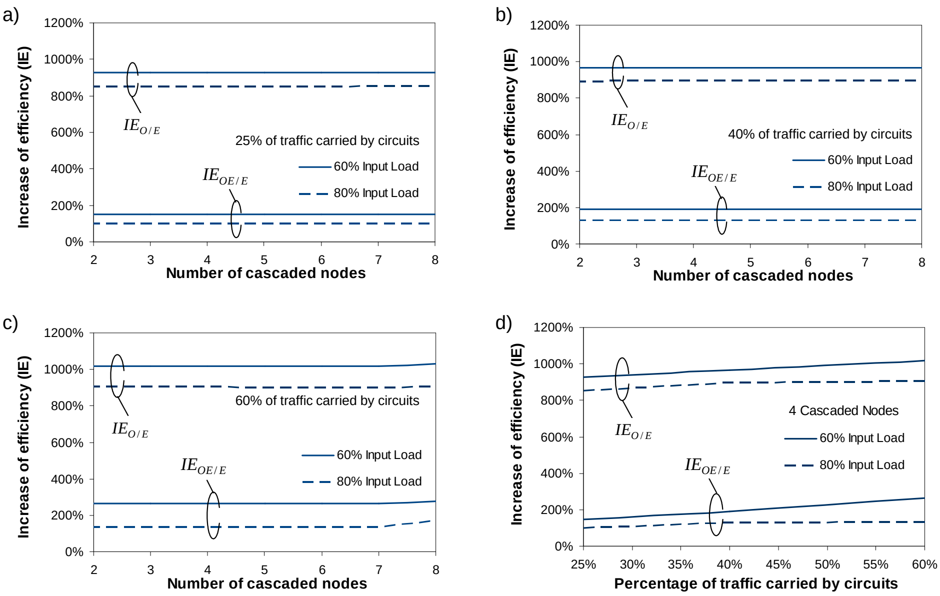

Figure 8. Estimated improvement of energy efficiency (IE) in all-optical ($IE_{O/E}$) and optical/electonic ($IE_{OE/E}$) AHOS core networks. The influence of the number of hops at a) 25% of circuit traffic, b) 40% of circuit traffic and c) 60% of circuit traffic. d) Improvement of energy efficiency with regard to traffic pattern.

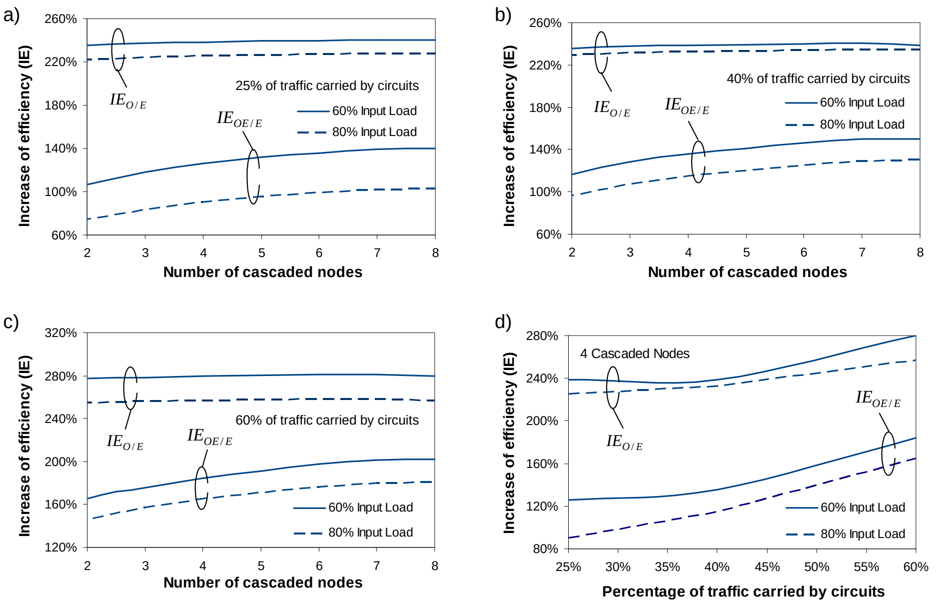

Figure 9. Estimated improvement of energy efficiency (IE) in all-optical ($IE_{O/E}$) and optical/electonic ($IE_{OE/E}$) end-to-end AHOS networks containing both core and edge nodes. The influence of the number of hops at a) 25% of circuit traffic, b) 40% of circuit traffic and c) 60% of circuit traffic. d) Improvement of energy efficiency with regard to traffic pattern.

3. Summary and Conclusions

In conclusion, hybrid optical switching has the potential to provide an efficient transport of different data types through core networks. We propose and describe a network concept that we refer to as adaptive hybrid optical switching (AHOS). Nodes of an AHOS network are capable of dynamically adapting the number of active slow and fast switch ports to the actual traffic situation. The control plane for AHOS networks is able to efficiently support packet, burst and circuit switching in the optical domain and to switch off or put in a low-power mode temporarily inactive switch ports and line cards. Unused slots in time-domain multiplexed (TDM) circuits can be utilized to transmit optical packets, which results in reduced packet loss rates. Interoperability is ensured through using GMPLS to configure and manage the virtual topology.

We developed and applied a simulation model to investigate both network performance and energy consumption of AHOS nodes. Two different realization options, of which one using optical technologies for implementing both fast and slow switches (hybrid all-optical) and another one comprising a slow optical and a fast electronic switch (hybrid optical/electronic), are proposed and investigated by means of their potential for an improvement in energy efficiency. The results show that the hybrid optical/electronic architecture has the potential to provide an efficiency gain of 90% - 200% in comparison to conventional electronic packet routers, while the all-optical architecture could improve the network energy efficiency by at least a factor of 3 for an end-to-end path through the AHOS network and even by a factor of 10 within the core network (without considering the AHOS edge nodes). The gain in efficiency does not change significantly with an increase in number of hops on a data path through the network. In contrast, an increase in circuit-oriented traffic generally leads to a higher energy efficiency of AHOS nodes.

References

[1] W. John and S. Tafvelin, ”Analysis of Internet Backbone Traffic and Header Anomalies observed”, 7th ACM SIGCOMM conference on Internet measurement (IMC 2007), San Diego, CA, USA, pp. 111-116, 2007.

[2] C. Fraleigh, S. Moon, B. Lyles, C. Cotton, M. Khan, D. Moll, R. Rockell, T. Seely, and C. Diot, ”Packet-level traffic measurements from the sprint IP backbone”, IEEE Netw. Mag., vol. 17, no. 6, pp. 6-16, Nov.-Dec 2002.

[3] IETF, ”Multiprotocol Label Switching Architecture”, RFC3031, January 2001.

[4] A. Banerjee, J. Drake, J. Lang, B. Turner,D.Awduche, L. Berger, K.Kompella, and Y. Rekhter, ”Generalized multiprotocol label switching: an overview of signaling enhancements and recovery techniques”, IEEE Commun. Mag., vol. 39, no. 7, pp. 144-151, Jul. 2001.

[5] ITU Telecommunication Standardization Sector, ”Architecture for the automatic switched transport network (ASTN)”, ITU-T Rec. G.807/Y.1302 ed, Nov. 2001.

[6] ITU Telecommunication Standardization Sector, ”Optical transport network (OTN)”, ITU-T Rec. G.709/Y1331 ed., Mar. 2003.

[7] ITU Telecommunication Standardization Sector, ”Optical transport hierarchy”, ITU-T Rec. G.871/Y.1301 ed., 2000.

[8] P. Molinero-Fernandez and N. McKeown, ”TCP switching: exposing circuits to IP”, IEEE MICRO, vol. 22, no. 1, pp. 8289, Jan./Feb. 2002.

[9] O. Gerstel, M. Jinno, A. Lord, and S. J. Ben Yoo, ”Elastic Optical Networking: A New Dawn for the Optical Layer?”, IEEE Communications Magazine, pp. 12 - 20, February 2012.

[10] S. Aleksic, , "Power Consumption of Hybrid Optical Switches", in Proceedings of OSA/IEEE Optical Fiber Communication Conference and Exposition (OFC 2010), San Diego, CA, USA, paper OThP6, March 2010.

[11] W.W.S. Chan, "Optical Flow Switching", in Proceedings of OSA/IEEE Optical Fiber Communication Conference and Exposition (OFC 2010), San Diego, CA, USA, paper OWI6, March 2010.

[12] H.L. Vu, A. Zalesky, E.W..M. Wong, Z. Rosberg, S.M.H. Bilgrami, M. Zukerman, and R.S. Tucker, "Scalable Performance Evaluation of a Hybrid Optical Switch", IEEE JLT, Vol. 23, pp. 2961- 2973, 2005.

[13] B. Chen and J. Wang, "Hybrid Switching and P-Routing for Optical Burst Switching Networks", IEEE JSAC, Vol. 21, No.7, pp.1071-1080, 2003.

[14] E. W. M. Wong and M. Zukerman, "Analysis of an optical hybrid switch", IEEE Commun. Lett., vol. 10, pp. 108-110, 2006.

[15] M. De Leenheer, C. Develder, J. Buysse, B. Dhoedt, and P. Demeester, "Dimensioning of Combined OBS/OCS Networks", WOBS 2008, 2008.

[16] D. Simeonidou, G. Zervas, and R. Nejabati, "Design considerations for photonic routers supporting application-driven bandwidth reservations at sub-wavelength granularity", BROADNETS 2006, San Hose, CA, USA, pp. 1-5, Oct. 2006.

[17] M. Takagi, H. Li, K. Watabe, H. Imaizumi, T. Tanemura, Y. Nakano, and H. Morikawa, "400Gb/s Hybrid Optical Switching Demonstration Combining Multi-Wavelength OPS and OCS with Dynamic Resource Allocation", OFC 2009, San Diego, CA paper OTuA6, March 2009.

[18] N. Takenouchi, R. Urata and T. Nakahara, "First Demonstration of a Prototype Hybrid Optoelectronic Router", ECOC 2009, Vienna, Austria, pp. 1 - 2, Sept. 2009.

[19] P. Pedroso, I. Sole-Pareta, R. Casellas, D. Careglio and M. Klinkowski, "An interoperable GMPLS/OBS Control Plane: RSVP and OSPF extensions proposal", CSNDSP 2008, Graz, Austria, pp. 418 - 422, July 2008.

[20] J. Triay, G. S. Zervas, C. Cervello-Pastor and D. Simeonidou, "GMPLS/PCE/OBST architectures for guaranteed sub-wavelength mesh metro network services", OFC2011, pp. 1-3, 6-10 March 2011.

[21] M. Fiorani, M. Casoni and S. Aleksic, "Performance and Power Consumption Analysis of a Hybrid Optical Core Node", OSA/IEEE Journal of Optical Communications and Networking, Vol.3, Issue 6, pp. 502 - 513, June 2011.

[22] S. Aleksic, M. Fiorani and M. Casoni, "Energy Efficiency of Hybrid Optical Switching" (invited), in Proceedings of the 14th International Conference on Transparent Optical Networks (ICTON 2012), Coventry, UK (eingeladen); 02.07.2012 - 05.07.2012; in: "Proceedings of the14th International Conference on Transparent Optical Networks (ICTON 2012)", IEEE, pp. 1 - 4, July 2012.

[23] M. Fiorani, M. Casoni, and S. Aleksic, "Analysis of a GMPLS Enabled Hybrid Optical Switching Network", in Proceedings of the 16th International Conference on Optical Networking Design and Modeling (ONDM 2012), Essex, Colchester, UK, IEEE, pp. 1 - 6, April 2012.

[24] B. Kozicki, H. Takara, Y. Tsukishima, T. Yoshimatsu, K. Yonenaga, and M. Jinno, "Experimental demonstration of spectrum-sliced elastic optical path network (SLICE)", Optics Express, Vol. 18, Issue 21, pp. 22105 - 22118, 2010.

[25] A. Martinez, D. Pastor, J. Company, D. Ortega, P. Fonjallaz, M. Popov, T. Berceli, T.Banky, "Experimental demonstration of sub-carrier multiplexed optical label swapping featuring 20 Gb/s payload and 622 Mb/s header conveyed at 18.3 GHz", 31st European Conference on Optical Communication (ECOC 2005), Glasgow, Scotland, pp. 959 - 96, Sept. 2005.

[26] N. Deng, Y. Yang, C. Chan, L. Chen, W. Hung, "All-optical OOK label swapping on OFSK payload in optical packet networks", Optical Fiber Communication Conference (OFC 2004), Los Angeles, CA; USA, February 2004, vol. 2, pp 3, 2004.

[27] RFC, "Generalized Multi-Protocol Label Switching (GMPLS) Architecture", IETF, October 2004.

[28] S. Aleksic, "Analysis of Power Consumption in Future High-Capacity Network Nodes", IEEE/OSA Journal of Optical Communications and Networking (JOCN), vol. 1, no. 3, pp. 245 - 258, 2009.

[29] S. Aleksic, N. Fehratovic, "Analysis of Scalability of Optical Intrasystem Interconnects", Journal of Networks (JNW), vol. 7, no. 5, pp. 791 - 799, 2012.

[30] M. Yano, F. Yamagishi, and T. Tsuda, "Optical MEMS for photonic switching-compact and stable optical crossconnect switches for simple, fast, and flexible wavelength applications in recent photonic networks", IEEE J. Sel. Topics Quantum Electron., vol. 11, pp. 383 - 394, 2005.