AWG-based architecture for optical interconnection in asynchronous systems

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Abstract—We present a novel architecture for strictly non-blocking multistage photonic switches implemented using tunable wavelength converters and arrayed waveguide gratings. Clos networks, studied mostly in electronic domain, are required when the physical switching needs exceed the capacity of the largest feasible single crossbar switch. Unfortunately, straightforward extensions of these networks to the photonic domain show that the switch size has to be severely limited by the coherent crosstalk in each of the AWGs. We describe how recursive Clos networks free of coherent crosstalk can be built taking into account the current physical limitations of arrayed waveguide gratings.

Index Terms—Photonic switching, optical interconnection, AWG, Clos network, crosstalk.

I. INTRODUCTION

With the deployment of Internet, largely relying on the Wavelength Division Multiplexing (WDM) techniques for the long-haul transport, many new bandwidth-intensive applications have emerged. For the efficient support of these bandwidth-intensive applications, switching systems (which serve as the switching core of network routers and crossconnects to implement the actual switching function) is expected to have the switching capability in the order of several Tbit/s or even Pbit/s.

Although the electronic switch/router technologies are mature and easy to implement, their capacity growth is historically slower than the growth of optical link capacity [1]. Also, the power consumption of network switch/router has exponentially increased beyond the standard acceptable level in past years [2]. This is why switches/routers have increasingly become a bottleneck for Internet communications. Furthermore, the upgrade of current electronic switch/router solutions is becoming extremely costly and difficult due to the strong dependence of switching hardware on data bit-rate and transmission protocols. Therefore, some future alternative solutions for switch/router design are mandatory.

The Arrayed Waveguide Grating (AWG) is a very attractive passive optical device for constructing high-speed large-capacity WDM optical switches, because it is scalable to large size, consumes little power, offers high wavelength selectivity, low insertion loss, small size, potentially low cost and fast switching time [3]. As a matter of fact its switching speed is determined only by the speed of wavelength conversion, which is in the order of nanoseconds [4] and sub-nanosecond [5] in the Tunable Wavelength Converters (TWCs) located at the ingress ports of the AWG. Moreover, AWGs and TWCs have the advantage to be commercially available components. These are key features that enable the design of an optical AWG-based switch that is cost-efficient [6].

AWGs are passive devices behaving as multiport interferometers. In the $1 \times N$ ($N \times 1$) configuration, AWGs act as wavelength multiplexers (demultiplexers). In the $N \times N$ configuration, AWGs behave as wavelength routers. The information at an input port is forwarded to an output port depending on the selected wavelength.

Commercial AWGs provide uniform transfer functions, and extinction ratios among adjacent channels in the order of 30-40 dB. These physical layer characteristics are largely sufficient for multiplexers and demultiplexers, which are indeed commonly used in commercial WDM systems. However, significant coherent crosstalk figures were reported in $N \times N$ AWGs with large port counts [7]. If the same wavelength is used at all AWG inputs, the maximum admissible value of $N$ is severely limited [8]. However, to be competitive with electronic solutions the optical architecture should be future proof, i.e., scalable. In this context multistage architectures, like Clos network, are able to circumventing technological constraints.

In this paper, we propose a method to design Zero-Coherent-Crosstalk (ZCC) and Strictly Non-Blocking (SNB) AWGs-based switches. An AWG-based switch is ZCC if each wavelength is not reused more than one time in any instant time. Moreover it is also SNB if the information can be transferred by an unused wavelength from any unused switch input to any unused switch output without changing the routing/wavelength of any previously established connection. The coherent crosstalk suppression allows us using these AWG-based switches in asynchronous networks. Otherwise, without the ZCC condition, given a subset of currently routed connections, a high number of future connections may be blocked if their provisioning leads to a high level of crosstalk which corrupts the signal of incoming or existing connections. Based on this contribution we propose a Clos network which guarantees connections between a large amount of inputs/outputs with negligible crosstalk, high throughput, low optical path loss, low power consumption and good reliability.

The work described in this paper was carried out with the support of the BONE-project (“Building the Future Optical Network in Europe”), a Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme.
The paper is organized as follows. Sec. II introduces basic concepts on the AWGs and their crosstalk constraint. Moreover, we overview the background work on the AWG-based architectures and on the available solutions to reduce the coherent crosstalk in AWGs. Sec. III formulates the problem of AWG coherent crosstalk constraint in asynchronous networks. In Sec. IV we propose the technological solution to suppress the coherent crosstalk in single-stage $N \times M$ AWG-based switch, for any values of $N$ and $M$. Based on ZCC/SNB AWG-based switches, in Sec. V we propose ZCC/SNB $k$-stage Clos networks to solve scalability issues and construct switches with large port counts. Finally, Sec. VI draws some conclusions.

II. BACKGROUND CONCEPTS

In this section we first summarize the basic properties of an AWG and then how the coherent crosstalk is generated. Then, we overview the optical AWG-based switches presented in literature and the techniques to alleviate the coherent crosstalk.

As shown in Figure 1, the AWG routes light based on its wavelength from any input port to any output port, similar to a diffraction grating. Data envelopes arriving from the ingress side of the line cards are sent via TWCs through the AWG into receivers and from there to the egress line cards. Therefore an AWG can be used as a strictly nonblocking full-convertible wavelength permutation router. As a wavelength router, an $N \times N$ AWG accepts $N$ wavelengths $\Lambda = \{\lambda_0, \lambda_1, ..., \lambda_{N-1}\}$, from each input port $s$ ($0 \leq s \leq N - 1$), in the set of the AWG input ports $S$, and routes each wavelength to a different output port $d$ ($0 \leq d \leq N - 1$), in the set of the AWG output ports $D$. Each optical frequency gives routing instructions that are independent of the input port. More precisely, $\lambda_n$’s routing information is to exit the output port that is $n$ ports below the corresponding input port $s$ (i.e., wavelength $\lambda_n$ entering at input port $s$ is routed to output port $d = (s + n) \mod N$). For instance, $\lambda_1$ goes from input port 1 to output port 2 and from input port 4 to output port 5. If $s + n \geq N$ the wavelengths are wrapped around, i.e., wavelength $\lambda_n$ entering at input port $s$ is routed to output port $d = s + n - N$. This cyclic behavior is typical of the interferometric nature of the AWG, whose routing behavior is replicated over the wavelength axis with a period called Free Spectral Range (FSR). Note that each output port receives $N$ different wavelengths, one from each input port.

As reported in Table I, the traffic that can be forwarded by a generic $4 \times 4$ AWG shown in Figure 1 can be described by a wavelength matrix $T = [T_{d,s}]$, where $T_{d,s}$ is the set of wavelengths that can be utilized to connect the input port $s$ with the output port $d$. Note that, with our wavelength assignment rule, the wavelength used to reach output $d$ from input $s$ is $\lambda_{(d-s) \mod N}$.

Other wavelength assignments are possible, depending on the design of the AWG device. These different wavelength behaviors can in some cases be modeled by relabeling wavelengths and ports in our formalization, so that the properties outlined in the sequel hold for several AWG wavelength assignments.

However, given that each input interface has the same set of wavelengths $\Lambda$, it is easy to predict that, without loss of generality, if $\lambda_2$ from input port 0 leaks to output port 3, it gives a detrimental effect on the performance of transmission between input port 1 and output port 3. This crosstalk problem, defined as coherent or in-band crosstalk, is severe because the leakage (crosstalk light) has the same wavelength as the signal and can not be removed at the destination node. The impact of coherent crosstalk is typically high given its in-band characteristics, and severely limits the maximum admissible value of $N$ [8].

A. Prior work

Different AWG-based optical switching architectures have been studied in the technical literature [9]–[12]. These proposals assume very large AWG port counts, even if this turns out to be unfeasible without counter-measuring the crosstalk impairments. These large crosstalk can only marginally be reduced by improving the physical layer behavior of the device [13]. One possibility to overcome this impairment is to exploit homologous wavelengths in several Free Spectral Ranges (FSRs) [14]. However, this increases the operational bandwidth of the system (possibly preventing the utilization of optical amplifiers); furthermore, the behavior of the device outside the principal FSR often degrades rapidly. The alternative approach pursued in [15], [16] is to prevent coherent crosstalk by controlling AWG-based slotted switches with scheduling decisions that avoid using simultaneously the same wavelengths at too many different inputs. However, this techniques limit the throughput of the system given that the switch scheduler is restricted to use only a subset of permutations of interconnections per time in a synchronous system.

III. PROBLEM STATEMENT

The considered $N \times N$ switch handles fixed-size packets that arrive at input ports and leave output ports in an asynchronous manner. When a fixed-size packet arrives to an empty input

![Basic architecture of the optical switch fabric.](image_url)

TABLE I

<table>
<thead>
<tr>
<th>Input Ports S</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Ports D</td>
<td>$\lambda_0$</td>
<td>$\lambda_1$</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
</tr>
<tr>
<td>0</td>
<td>$\lambda_0$</td>
<td>$\lambda_1$</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
</tr>
<tr>
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<td>$\lambda_3$</td>
<td>$\lambda_2$</td>
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<tr>
<td>2</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
<td>$\lambda_0$</td>
<td>$\lambda_1$</td>
</tr>
<tr>
<td>3</td>
<td>$\lambda_3$</td>
<td>$\lambda_2$</td>
<td>$\lambda_1$</td>
<td>$\lambda_0$</td>
</tr>
</tbody>
</table>

Fig. 1. Basic architecture of the optical switch fabric.
port for an empty output port the scheduler define a scheduling decision. At each scheduling decision, at most one packet can be sent from each input port and at most one packet can be sent to each output port. If the input port or the output port are busy the packets are temporarily buffered at input ports according to an Input Queueing (IQ) architecture, waiting for the availability of the output line. To balance electronic and optical complexity, each input port is equipped with a single TWC. Since, at each output port, packets are received at a wavelength depending on the transmitting input port and at most a single packet is received at each output per time, there is no need for tunable receivers at the outputs, and a single wideband receiver suffices. Thus, each scheduling decision is a single interconnection between an input port and an output port. Each interconnection has a holding time in the switch which is the time needed to transport a packet from the input to the output port. Until the holding-time is not expired, the relative pair of input/output ports and the internal optical components in the switching fabric are considered busy. The holding time is constant and equal for each packet given that all the interconnection paths have the same length, traverse the same optical components (without internal buffering) and the packets have the same fixed-size.

Given that in an asynchronous system the interconnections that are currently established are known but information on future interconnection demands are not be known in advance, the coherent crosstalk can not be suppressed simply restricting the scheduler to use only a certain type of permutations (this further possibility would lead to a synchronous network where the connections are simultaneously established). Without any technological solution, this could easily lead to high level of crosstalk to avoid blocking state.

IV. ZERO-COHERENT-CROSSTALK AWG-BASED SWITCH

We propose an optical switch fabric using combinations of an AWG and WDM couplers in order to eliminate the problem of the coherent crosstalk.

A. \( N \times N \) ZCC/SNB AWG-based switch

Let us formalize the properties of a generic \( N \times N \) ZCC/SNB AWG-based switch. In our analysis we exploit the wavelengths in AWG inside only one single FSR.

Definition 1: the coherent conflict set is the set of the outputs of the switch \( J \) that can be reached from the inputs \( I \) by at least one common wavelength.

Lemma 1: the implementation of an \( N \times N \) ZCC/SNB AWG-based switch requires an AWG with \( \frac{N^2}{2} \times \frac{N^2}{2} \) ports if \( N \) is even, and \( (\frac{N+1}{2})^2 \times (\frac{N+1}{2})^2 \) ports if \( N \) is odd.

Proof: To relax the coherent crosstalk constraint in the switching fabric we split the set of wavelengths \( \Lambda \) into the set of even \( \Lambda_{\text{even}} \) wavelengths and the set of odd wavelengths \( \Lambda_{\text{odd}} \); then, we construct the switch so that each input \( i \) can reach the even outputs \( J_e = [j]|j|0,2,4,... \) by the wavelengths in the set \( \Lambda_{\text{even}} \) and the odd outputs \( J_o = [j]|j|1,3,5,... \) by the wavelengths in the set \( \Lambda_{\text{odd}} \). In this way the coherent crosstalk conflict set is split into two groups of outputs, even outputs \( J_e \) and odd outputs \( J_o \). Therefore if \( N \) is even, the two coherent conflict sets have the same cardinality \( C = N/2 \); if \( N \) is odd, one conflict set (relative to \( J_e \) set) has a cardinality \( C_e = \lfloor N/2 \rfloor \) and the other (relative to \( J_o \) set) has a cardinality \( C_o = \lceil N/2 \rceil \).

To be ZCC and solve the conflicts, each output \( j \) needs to be reached by at least a number of wavelengths equals to the cardinality of the conflict set which \( j \) belongs to. To match this condition, output \( j \) is connected with at least \( C \) (or \( C_e \) or \( C_o \)) AWG output ports by a WDM coupler with a coupler degree equal to \( C \) (or \( C_e \) or \( C_o \)).

To guarantee the splitting of the conflict sets, the cyclic behavior of the AWG needs to be considered. For simplicity, suppose to connect the input ports of the switch \( I \) with the first even input ports of the AWG \( S_e = \{s|s = 0,2,4,...,2(N-1)\} \). In order that each input port \( i \) reaches with the set of wavelengths \( \Lambda_{\text{even}} \) each output port \( j \in J_e \) and with the set of wavelengths \( \Lambda_{\text{odd}} \) each output port \( j \in J_o \), the amount of input \( |S| \) and output \( |D| \) ports of the AWG needs to be an even number. Moreover, to guarantee the splitting of the coherent conflict sets, each switch output port \( j \) needs to be connected with consecutive AWG output ports distant an even number of ports, i.e., \( N \) if \( N \) is even and \( N+1 \) if \( N \) is odd. Therefore, if \( N \) is even, each output port \( j \) needs to be connected with the ports \( d = j + x N \), where \( 0 \leq x < C \); if \( N \) is odd, each output port \( j \in J_o \) needs to be connected with the ports \( d = j + x(N+1) \), where \( 0 \leq x < C_o \).

Hence, to implement an \( N \times N \) ZCC/SNB AWG-based switch, if \( N \) is even, each output port \( j \) needs to be connected with \( N/2 \) output ports of the AWG. Therefore the AWG requires \( N^2/2 \) input/output ports. Each input \( i \) has \( N/2 \) possibilities to reach the output \( j \) by the wavelengths \( \lambda_{2i+j+xN \mod (N/2)} \), where \( 0 \leq x < N/2 \). Analogously, when \( N \) is odd, depending on the cardinality of the conflict set, the output \( j \) needs to be connected with \( [N/2] \) or \( [N/2] \) AWG output ports. Given that each output port \( j \) needs to be connected with consecutive AWG output ports which, in case of odd \( N \), are distant \( N+1 \) ports, the AWG requires \( [N/2](N+1) = (N+1)^2/2 \) input/output ports. Each input \( i \) has \( [N/2] \) possibilities to reach each output \( j \in J_e \) by the wavelengths \( \lambda_{2i+j+x(N+1) \mod ((N+1)^2/2)} \), where \( 0 \leq x < (N+1)/2 \), and \( [N/2] \) possibilities to reach each output \( j \in J_o \) by the wavelengths \( \lambda_{2i+j+x(N+1) \mod ((N+1)^2/2)} \), where \( 0 \leq x < (N+1)/2 \).

By way of illustration, Figures 2a and 2b show the \( 5 \times 5 \) and \( 6 \times 6 \) optical switches. The wavelength interconnections that can be established into the respective optical switch are reported in Tables II and III. For sake of terseness, switch implementations with higher port counts are not reported.

As shown in Tables II and III, the coherent crosstalk constraint is suppressed thanks to the multiple choice of wavelength to reach the output ports \( J \) from the input ports \( I \). From Table I we know that with a traditional AWG-based switch, due to the crosstalk impairments, the most difficult traffic to
and 6. ZCZN SNB AWG-based switches realized via
table 3. Wavelength interconnections patterns for the 6x6 switch

<table>
<thead>
<tr>
<th>Input Ports</th>
<th>Output Ports</th>
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<tbody>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
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<td>3</td>
<td>6</td>
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<tr>
<td>4</td>
<td>7</td>
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<tr>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

**Lemma 3:** The implementation of an N x M ZCZN SNB AWG-based switch has the same basic construction of an M x M switch, with N > M, requires an AWG with \((M^2 + M)/2\) ports if M is odd. The implementation of an M x M switch, with N > M, requires an AWG with \((M^2 + M)/2\) ports if M is even and \((N - M - 1)/2\) AWG ports are needed to connect the AWG inputs as in the basic construction of an M x M switch. However, also the other M - M switch inputs need to be connected to an equal number of AWG even input ports of \((N - M - 1)/2\) AWG ports if M is odd.

**Proof:** N x M ZCZN SNB AWG-based switch, with N > M, has the same basic construction of an M x M switch. Therefore, the new optical switch is split into two cases: the coherent conflict set needs to be split into two groups of outputs. As a matter of fact, the implementation of an AWG with \((M^2 + M)/2\) ports if M is odd, or plus \((N - M - 1)/2\) AWG ports if M is even, requires an AWG with \((M^2 + M)/2\) ports if M is odd, or plus \((N - M - 1)/2\) AWG ports if M is even.

**AWG ports required to realize an N x M ZCZN SNB AWG-based switch:**

<table>
<thead>
<tr>
<th>AWG ports</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>698</td>
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<td>696</td>
<td>506</td>
<td>44</td>
<td>343</td>
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<tr>
<td>698</td>
<td>767</td>
<td>696</td>
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<td>698</td>
<td>767</td>
<td>696</td>
<td>506</td>
<td>44</td>
<td>343</td>
</tr>
</tbody>
</table>

**Fig. 3:** Number of AWG ports required to realize an N x M ZCZN SNB AWG-based switch.
based switch, with $M/2 \leq N < M$, requires an AWG with $\frac{M^2}{2} \times \frac{M^2}{2}$ ports if $M$ is even, and $(\frac{M+1}{2})^2 \times (\frac{M+1}{2})^2$ ports if $M$ is odd. However, if $N < M/2$, ZCC/SNB AWG-based switch can be build by an AWG with $NM \times NM$ ports.

Proof: An $N \times M$ ZCC/SNB AWG-based switch, with $N < M$, has to support at most $N$ connections per time. Consider the worst case, i.e., that a subset of these inputs $I$ requires to be interconnected with outputs $J$ belonging to the same coherent conflict set. If $N$ is greater than or equal to $M/2$, the cardinality of the conflict set is $M/2$ if $M$ is even, or $\lceil M/2 \rceil$ and $\lfloor M/2 \rfloor$ if $M$ is odd. Then it is required an AWG equal to the one utilized in an $N \times M$ switch with $N = M$. Consequently, the output ports $J$ be connected at the same manner as in the $N \times M$ switch with $N = M$ simply leaving some AWG inputs unconnected. However, if $N$ is smaller than $M/2$, the cardinality of the conflict set is equal to $N$, because no more than $N$ wavelengths can be in conflict at the same time. In this case, the coherent crosstalk is avoided connecting each output $j$ with at least $N$ AWG outputs. Therefore, it is required an AWG with $NM \times NM$ ports, either if $M$ is even or odd. Figure 5 shows a $3 \times 5$ switch implementation. The wavelength configuration that can be forwarded by the switch is reported in Table V.

In this section the multi-stage approach proposed by Clos [21] can be adopted to solve scalability issues and construct switches with a larger port counts. As discussed in Sec. IV, commercially available $40 \times 40$ AWGs limit the scalability of the ZCC/SNB AWG-based switches. Therefore, from Figure 3 we infer that our ZCC/SNB AWG-based switches are limited to a number of ports equal to $8 \times 8$, constructed via a $32 \times 32$ AWG.

Lemma 4: If the AWG maximum dimension is constrained to a $32 \times 32$ port count, then a $32 \times 32$ ZCC/SNB 3-stage Clos switch can be built.

Proof: Each ZCC/SNB AWG-based switch in the first stage can be connected with at most 8 ZCC/SNB AWG-based switches in the second stage, because through a $32 \times 32$ AWG, a $8 \times 8$ ZCC/SNB AWG-switch can be created. However, to achieve strictly non-blocking conditions, the number of ZCC/SNB AWG-based switches in the second stage needs to be $m = 2n - 1$, where $n$ is the number of input ports of each ZCC/SNB AWG-based switch in the first stage. Under these constraints, the maximum value of $n$ is equal to 4, which requires 7 ZCC/SNB AWG-based switches in the second stage to respect the strictly non-blocking condition. Therefore, the second stage is characterized by 7 ZCC/SNB $8 \times 8$ AWG-based switches, while the first stage is composed by 8 ZCC/SNB $4 \times 7$ AWG-based switches (built by $32 \times 32$ AWGs). Finally, in the third stage $8 \times 4$ ZCC/SNB AWG-based switches are adopted (built by $14 \times 14$ AWG). With this approach, a $32 \times 32$ ZCC/SNB three-stage Clos switch is built and it is outlined in Figure 6.

Theorem: If the AWG maximum dimension is constrained to a $32 \times 32$ port count, then a $2^{(k+2)} \times 2^{(k+2)}$ ZCC/SNB $k$-stage
Clos switch can be built, where $k$ is an odd number.

Proof: Networks with more than three stages can be built by iterating the basic three-stage construction. Clos showed [21] that a five-stage strict-sense non-blocking network can be recursively built starting from the basic three-stage non-blocking network by designing each matrix of the second-stage as a non-blocking three-stage network. In our case also the condition of zero-coherent crosstalk is maintained. The recursion can be repeated an arbitrary number of times to generate networks with an odd number of stages. Given that in our network design the AWGs are constrained to a maximum of $32 \times 32$ port count, independently from the number of stages, the first stage and the last stage are always characterized by $4 \times 7$ ZCC/SNB AWG-based switches and $7 \times 4$ ZCC/SNB AWG-based switches, respectively. The number of the AWG-based switches in the first stage and in the last stage in a ZCC/SNB $k$-stage Clos architecture is always equal to the amount of inputs/outputs in each matrix of the middle stage, which is built on the $(k-2)$-stage Clos architecture. Therefore, the port count of a ZCC/SNB $k$-stage Clos switch is exactly 4 times greater than the port count of a ZCC/SNB $(k-2)$-stage Clos switch. As reported in Figure 7, a ZCC/SNB five-stage network has $32 \times 32 \times 7 \times 4$ AWG-based switches in the first stage, $7 \times 32 \times 32 \times 32$ three-stage Clos network in the second stage, and $32 \times 7 \times 4$ AWG-based switches in the last stage. With this recursive approach the ZCC/SNB five-stage network supports a $128 \times 128$ port count.

VI. CONCLUSIONS

We have presented in this paper a novel technique suitable to suppress the coherent crosstalk in AWG-based switches which limits the maximum admissible amount of wavelength channel number. To eliminate the coherent crosstalk constraint, we have proposed an optical switching fabric, the Zero-Coherent Crosstalk (ZCC) AWG-based switch, which uses a combination of an AWG and WDM couplers. Differently from the previous approaches presented in the literature, the ZCC/SNB AWG-based switches are suitable to be utilized in asynchronous systems, where interconnections are established between idle inputs and idle outputs at random times. Based on this contribution, we have defined an optical ZCC/SNB Clos network which solves scalability issues and enable construction of switches with large port counts.

REFERENCES