Clos lives on in Optical Packet Switching

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Abstract

While the technological evolution since Clos's seminal paper on multistage switch architectures has been huge, his work and ideas still live on. In this paper we discuss node architectures for Optical Packet Switching (OPS) and show how the multi-stage approach proposed by Clos can be adopted to solve scalability issues and construct switches with large port counts. As in the old days, the driving factors behind the introduction of the multi-stage concepts also include economical issues: compared to a single-stage architecture, the number of components to realize the switching fabric will be reduced.

Introduction

In the era where Clos produced his seminal paper [1], the dominant telecommunication technology was that of analogous telephony using copper wire as transport medium. Clos's work helped in developing large switches: the multi-stage architectures proved to need far less crosspoints. This reduction of number of cross-points was a very important issue, since it greatly determined the cost. Indeed, since Shockley, Bardeen and Brattain had only developed the transistor a few years earlier, large scale integration as we know it today was still a quite ambitious research topic. The main achievement of Clos was to circumvent technological boundaries, while also reducing the cost.

Communication technology has seen many advances since the days of Clos. Telephony is still there (albeit now mostly digital), but it is apparent that with the advent of the Internet, a large portion of traffic now consists of data rather than voice. Still, the concepts of the "old" telephony world are still in use. In essence, classical telephony is a circuit-switched concept: communication between two parties is realized by establishing a connection, which is reserved for their use only, for the entire duration of their conversation. Prior to their communication, signaling takes place through the exchange of messages to set-up the connection through the various switches on the path between the two parties. This same idea of connection-oriented communication prevails today, and a circuit-switched approach is also taken in so-called backbone networks to provide high-bandwidth interconnections between e.g. telephone PBXs. However, in the Internet world, a packet-switched concept dominates. Instead of reserving a certain amount of bandwidth (a circuit) for a certain period of time, data is sent in packets. These packets have a header containing the necessary information for the switching nodes to be able to route them correctly, quite similar to the postal services.

To provide the bandwidth necessary to fulfill the ever-increasing demand (cf. Internet growth), the copper networks have been upgraded and nowadays to a great extent replaced with optical fiber networks. Since the advent of optical amplifiers (e.g. Erbium Doped Fiber Amplifiers, EDFA) allowed the deployment of Dense Wavelength Division Multiplexing (DWDM), the bandwidth available on a single fiber has grown significantly. Whereas at first these high capacity links were mainly deployed as point-to-point interconnections, real optical networking using optical switches is possible today. The resulting optical communication network still is exploited in a circuit-switched manner: so-called lightpaths (comprising an entire wavelength) are provisioned [2]. Optical Cross Connects (OXCs) switch wavelengths from their input to output ports. To the client layer of the optical network, the connections realized by the network of OXCs are seen as a virtual topology, possibly different from the physical topology (containing WDM links), as indicated in Figure 1. These links in the logical plane thus have wavelength capacity. To set-up the connections, as in the old telephony world, a so-called control plane is necessary to allow for signaling. Enabling automatic set-up of connections through such a control plane is the focus of the work in the ASON-framework: Automatically Switched Optical Networks. Since the lightpaths that have to be set-up in such an ASON will have a relatively long lifetime (typically in the range of hours to days), the switching time requirements on the OXCs are not very demanding.

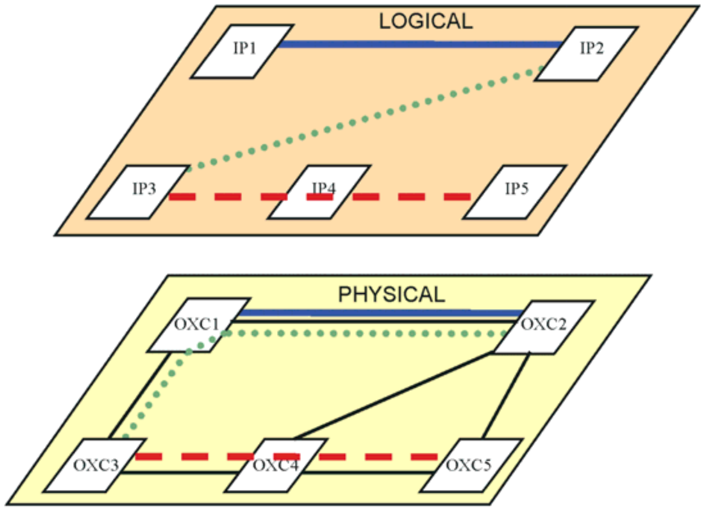


Figure 1. Circuit switching with OXCs. Physical links (black lines) carry multiple wavelengths in (D)WDM, logical links consist of wavelength(s) on these fibers, interconnected via OXCs, e.g. logical link IP2-IP3 using OXC1 (dotted).

It is clear that the main disadvantage of such circuit-switched networks is that they are not able to adequately cope with highly variable traffic. Since the capacity offered by a single wavelength ranges up to a few ten Gbit/s, poor utilization of the available bandwidth is likely. A packet-switched concept, where bandwidth only is effectively consumed when data is being sent, clearly allows more efficient handling of traffic that greatly varies in both volume and communication endpoints —such as in nowadays' dominant Internet traffic.

During the last decade, various research groups therefore have focused on Optical Packet Switching (OPS), aiming at more efficiently using the huge bandwidths offered by WDM networks. The idea is to use optical fiber to transport optical packets rather than continuous streams of light, as sketched in Figure 2. Optical packets consist of a header and a payload. In an OPS node, the transported data (payload) is kept in the optical domain, but the header information is extracted and processed using mature control electronics, as optical processing is still in its infancy. To limit the amount of header processing, client layer traffic (e.g. Internet's IP traffic) will be aggregated into fairly large packets. To unlock the possibilities of OPS, several issues arise and are being solved today. A major issue is the lack of optical Random Access Memory (RAM), which would be very welcome to assist in contention resolution, which arises when two or more packets simultaneously want to use the same outgoing switch port. Still, workarounds for the contention resolution problems have been found in optics [3]. Since the time scales at which a switch fabric needs to be (re)configured in OPS are much smaller than in e.g. the ASON case, other switching technologies have been devised to unlock the possibilities of OPS.

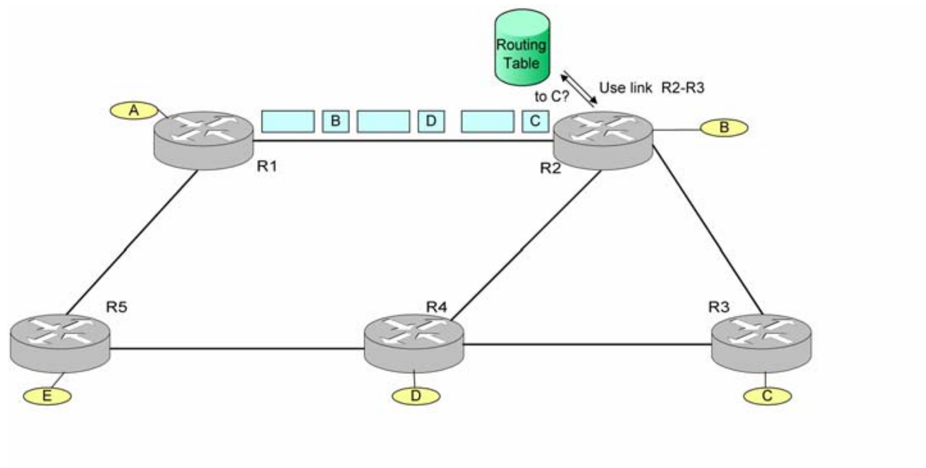


Figure 2 Optical packet switching: network with packets as opposed to circuits in Figure 1.

These packet switched networks can be operated in two different modes: 1) synchronous: packets can only start at certain discrete moments in time, each timeslot packets on different channels are aligned; 2) asynchronous: packets can arrive at any moment in time, without any alignment.

In subsequent sections we will discuss the major architectures for OPS switches. To be competitive with other solutions (electronic, or ASON-like), the OPS node cost needs to be limited, and the architectures should be future proof, i.e. scalable. In this context, the work of Clos has been inspiring: again, the driving factors that lead to multi-stage architectures were reducing switch complexity (thus cost) and circumventing technological constraints. We will discuss these issues from an architectural design point, rather than elaborating on e.g. packet scheduling and routing problems in multi-stage switches. Recent progress in solving those difficulties can be found e.g. in [4] and references therein.

Clos design for optical networks

Obviously, similar challenges as encountered in OPS were faced for optical circuit-switched approaches. Here, we briefly outline recent work in the world of optical switching where Clos's ideas proved to be quite influential.

A thorough analysis of photonic multi-stage switches, performing switching in space, time and wavelength dimensions was given by Thompson and Hunter in [5]. Various combinations of these dimensions are studied, culminating in a full-blown OPS switch based on Clos networks of elementary switching blocks switching in one domain. Special attention is given to limitations in case of wavelength and time switching.

Other extensions of Clos' work have focused on expandability. Indeed, in Clos' multi-stage switches, there is a tight coupling between the size of the central submatrices and the number of peripheral submatrices. In [6] MacDonald proposes to "distribute" the functionality of the central matrices into the peripheral matrices. In this way all building blocks of a node are equal (*SKOL* node) and adding one of these standard matrices can expand nodes. It alleviates the modularity problem of Clos architectures: the size of the building blocks depends on the final (maximal) size of the switch to be implemented and thus encompasses initial overbuilding. By distributing the central stages of a classical Clos architecture over SKOL in- and output modules, even though overbuilding is still required, the cost of an initial (partial) matrix configuration is significantly reduced.

For circuit-switched approaches, various authors start from Clos's ideas to exploit particular traffic characteristics to reduce the switch matrix sizes. The authors of [7] continue earlier work by others to reduce switch size in case of bidirectional traffic, i.e. a connection between A and B always implies a connection from B to A. Exploiting this bidirectionality allows making significant cost cuts compared to traditional Clos networks. Similar approaches have been proposed for designs of multicast switches.

From a technological point of view, the multistage approach has been demonstrated in various domains. Micro-Electro Mechanical Systems (MEMS), using tiny mirrors (range of some tens of microns) to switch light from input to output ports, have also exploited Clos's basic ideas [8]. Such Clos-based MEMS solutions to date show rather poor reliability, esp. compared to electronic switches [9], but this is likely to improve as technology matures (meanwhile, it can be alleviated by adding some redundancy). Still, Clos design can be an important factor in lowering optical losses in MEMS optical switches [10].

To switch in the wavelength domain, Fiber Bragg Gratings (FBGs) are quite suitable because of their wavelength selective reflective properties [11]: wavelength switches can be realized by putting FBGs in series or parallel, and tunable approaches are also possible. Using them as building blocks in a Clos network, a large OXC can be built. Size limiting factors are physical impairments including insertion loss and crosstalk.

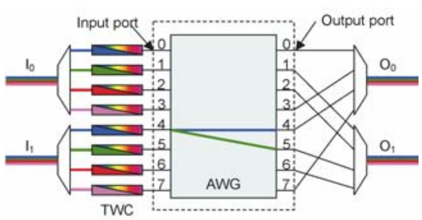
Also Lithiumniobate based switches have been proposed in a multistage architecture [12]. Since these switches are able to switch fast, they may be suitable for Optical Packet Switching. These switches showed good behavior, particularly regarding number of crosspoints and insertion loss.

Despite a reasonably wide-spread use of the Clos-approach for optical circuit switched approaches, we found few traces in research literature for OPS architectures. In the following section, we highlight the major OPS architectures, and subsequently illustrate how Clos's seminal work also proved useful in this OPS context.

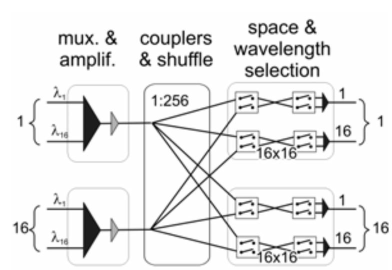
Multi-stage approaches for OPS

Node architectures for OPS

One of the most well-known, or at least quite impressive, optical switching technologies is that of Micro-Electro-Mechanic Systems (MEMS) using tiny mirrors to deflect light from a particular input to a particular output port. Both 2-D variants (where mirrors are either tilted up or lie down and let light pass) and 3-D variants (with mirrors tilting along two axes) have been demonstrated. While the characteristics in terms of optical signal quality distortion are quite good, this approach is not feasible in an OPS concept where very fast switching times (range of ns) are mandatory. Two approaches that are quite wide-spread are (i) one based on an Arrayed Waveguide Grating (AWG) with Tunable Wavelength Converters (TWCs), and a second based on a broadcast-and-select (B&S) concept using e.g. SOA technology.



Input ports	Output ports			
	0	3	4	7
0	λ_0	λ_3		
1		λ_2	λ_3	
2		λ_1	λ_2	
3		λ_0	λ_1	
4			λ_0	λ_3
5	λ_3			λ_2
6	λ_2			λ_1
7	λ_1			λ_0



(a) (b)

Figure 3. Two well-known OPS architectures: (a) an AWG-based switch used in STOLAS, (b) the broadcast-and-select switch proposed in DAVID.

The AWG approach is a. o. studied in the European research project STOLAS [13]. An AWG component has the interesting feature that when light is inserted via one of its input ports, the output port it will come out depends on the wavelength used. In Figure 3a, a signal entering on input port 4 will end up at either output port 4 or port 5, when it is on the blue respectively the green wavelength. Thus, by providing wavelength converters at the AWG's inputs, we can exploit the structure as a space switch. What wavelength to use to reach a particular output from a given input can be found by a table look-up operation: a sample table and switch is illustrated in Figure 3a.

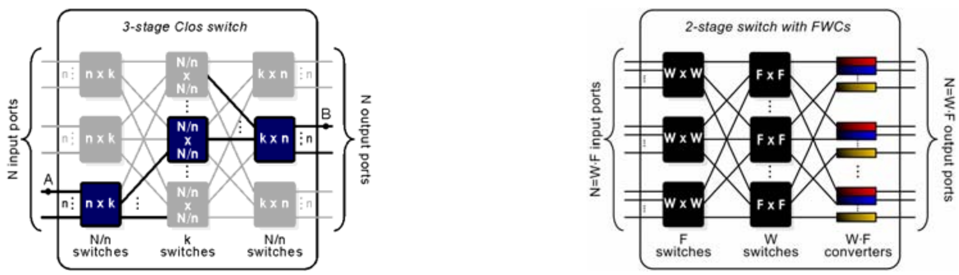
The broadcast-and-select approach is deployed in the recent research project DAVID [14]. The switch fabric's architecture is sketched in Figure 3b. It comprises several sub-blocks. In the first block a couple of input ports, which use different wavelengths is multiplexed into a single optical fiber. Each of these fiber signals is broadcast through a splitting stage to each of the output ports. Using two successive SOA stages, a single wavelength signal is kept per output port. The first SOA array is used to select only one of the input fiber signals for each output port. The second selection stage uses a SOA array and a wavelength selective component to keep only a single wavelength per output port.

The main advantage of the B&S architecture clearly is its inherent multicast capability, which the AWG approach lacks. However, the asset of the AWG-based architecture is that it relies on a passive component and does not suffer from splitting losses as the B&S does.

Clos applied to OPS

In both the B&S and AWG approaches, scalability issues will arise, as will be discussed further in this paper. A solution is to employ multi-stage architectures similar to the ones proposed by Clos. Let us first define the terminology on blocking we will adopt in the remainder of the paper. We call a switching architecture *strictly non-blocking* when it is always possible to connect any idle input port to any idle output port irrespective of other connections that already present. A switch is *rearrangable non-blocking* if it is possible to connect any idle input port to any idle output port, but some of the existing connections have to be reconfigured in order to do so. After the reconfiguration all connections are functional again. When a switch cannot guarantee to be able to always connect an idle input to an idle output port, it is said to be *internally blocking*.

The scheme of a 3-stage Clos switch is outlined in Figure 4a for an NxN switch. The N input ports are grouped per n, and both the first and third stage have a switching fabric for each such group of n ports. The second stage contains k switches, which each in turn are connected to each of the N/n first and third stage switches. Thus, the first stage comprises nxk switches, the second N/nxN/n, and the last one kxn. Now, a crucial question is how many second stage switches have to be foreseen. The answer to this question depends on the degree of blocking we want to realize.



(a) (b)

Figure 4. Multi-stage switches: (a) a three-stage Clos switch, (b) a switch with two switching stages and fixed output wavelength converters.

In case of circuit-switching, it is clear that the lifetimes of the circuits may overlap, but the start and end times will most likely not coincide: thus, once we have chosen to route a connection from input A to output B along a certain second stage switch, we have to stick to this choice for the entire duration of the connection. Thus, the switch needs to be strictly non-blocking. However, with synchronous OPS, we have a packet switching concept where the switch adopts a slotted mode of operation, i.e. each timeslot the packets at the inputs are inspected and switched jointly to the appropriate output. The next timeslot, all these packets are finished, and the switch may be completely reconfigured. It is clear that in this case of synchronous OPS, it is sufficient to have a rearrangeable non-blocking switch: each slot in turn, we can choose the second stage switch.

As Clos showed in his seminal paper, to achieve strictly non-blocking, the number of second stage switches needs to be $k \geq 2n-1$. However, for a rearrangeable non-blocking switch, $k \geq n$ suffices. (For a theoretical proof of these conditions, we refer to [15].) Thus, we need only about half as much second stage switches for synchronous OPS, than in asynchronous OPS.

Now, in OPS, part of the solution to contention resolution (see above) is to employ wavelength conversion: when two or more packets need to be switched to the same outgoing fiber, one or more of them may be converted to another wavelength to allow their simultaneous transmission on the output fiber. So in packet switching we are not interested on which exact wavelength channel the packet is put, we only want it on the correct output fiber. This allows a simplification of the design: if we choose to have all outputs of a third stage switch going to the same output fiber (thus e.g. $n=W$, with W the number of wavelengths per fiber), we can replace the third stage switch by Fixed output Wavelength Converters (FWCs). An FWC converts any incoming wavelength into a predefined (thus fixed) wavelength. Thus, we obtain a three-stage switch architecture with only two stages comprising smaller (full) switch fabrics, and one with only FWCs, as in Figure 4b.

Reducing the number of SOAs for a B&S switch

The major impairment of the B&S switch architecture outlined in Fig3b is the splitting stage, which degrades the optical signal. It is clear that this will limit scaling this architecture to very large port counts. By combining smaller sized switches in the Clos-like multistage approaches of Figure 4 —obviously with some regeneration stages in between— we can overcome this problem. From a cost perspective, we may assume that the number of SOA gates used gives a good indication. Thus, in the following, we will compare three different architectures in terms of number of SOA gates used: (i) single stage, (ii) three-stage Clos, (iii) two-stage with wavelength converters.

The architecture of the DAVID switching fabric was discussed earlier and sketched in Figure 3b. The number of SOA gates needed to construct a single-stage N×N switch is given in eq. (1): for each of the N output ports, N/w_i gates are needed for space selection, while w_i gates are needed for wavelength selection. Since the switching matrix will be surrounded with wavelength converters (actually 3R regenerators) the number of wavelengths w_i can be optimized (and chosen different from W, the number of wavelengths on the input/output fibers) to minimize the number of SOA gates. The optimal choice is $w=N^{1/2}$, which leads to the minimal number of SOA gates for a single-stage switch.

$$s(N,w) = N\cdot(N/w+w) \quad (1)$$

For OPS switches, we have indicated that the number of second stage switches needed to provide a non-blocking fabric to operate in slotted mode is k=n. The optimization of n to reduce the number of SOA gates in the overall multistage architecture leads to the choice $n=0.5\cdot N^{1/2}$. In case of the proposed two-stage architecture, the number of SOA gates can also easily be calculated.

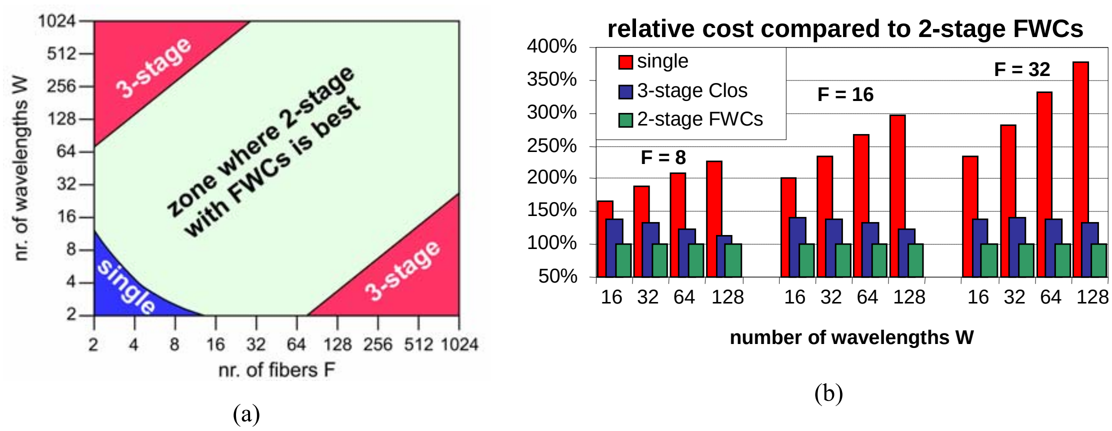


Figure 5. The advantages of a Clos-like approach for B&S switches in OPS: (a) dimensions for which a multistage architecture requires less SOAs, (b) comparison of the required number of SOAs per architecture.

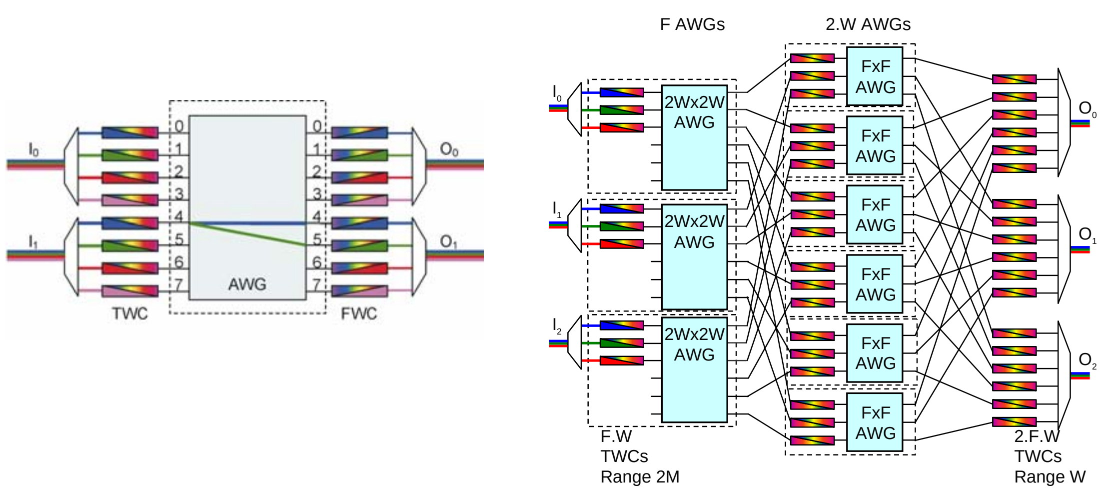
Inspection of the number of SOA gates needed leads to the choices as illustrated in Figure 5a. On the horizontal axis, the number of I/O fibers F is indicated, whereas the vertical axis denotes the number of wavelengths W per fiber of our OPS switch. For a particular combination of F and W, the color of the zone where the point with coordinates (F,W) belongs to shows the cheapest choice in terms of number of SOAs (eg. a switch with 8 fibers and 16 wavelengths per fiber requires the fewest amount of SOAs in a 2-stage architecture with FWCs). From this graph, we see that the single stage architecture is only advantageous for small port counts ($N=W \cdot F<12$). The two-stage architecture with FWCs is generally the cheapest choice: the three-stage Clos architecture only can be advantageous when either the number of wavelengths per fiber or the number of input/output fibers is very large. The amount of cost reduction for a selected range of switches is shown in Figure 5b. This illustrates that for 8–32 fibers with 16–128 wavelengths each, a three-stage Clos architecture needs 15–40% more SOA gates, while a single stage architecture would need 65–275% more SOAs than the two-stage architecture (or even be unfeasible because of the high splitting factor in the broadcast block).

From this case study, it is apparent that not only to solve scalability issues, but also for cost reduction purposes Clos-like approaches can be very helpful for broadcast-and-select based OPS switches.

A strictly non-blocking AWG-based switch for asynchronous operation

The STOLAS project uses the AWG-based approach outlined before, in Figure 3a. The multiple (W) wavelength channels carried in (D)WDM on incoming fibers are demultiplexed, and each of them is led through a Tunable Wavelength Converter to control the output port of the AWG it needs to be switched to. The outputs of the AWG are then coupled into output fibers. Since the set of wavelengths used on in- and output fibers should be the same, the range of the TWCs should not exceed those W wavelengths. However the design as in Figure 3a leads to an internally blocking switch. Still, when the switch is used for slotted OPS, we have shown that the internal blocking can be overcome and the performance is very close to that of a rearrangeable non-blocking switch [16]. However, for asynchronous switching, the blocking problem cannot easily be alleviated [17].

To construct a strictly non-blocking switch with an AWG for asynchronous operation, we need to increase the range of the input TWCs to F·W, i.e. as many wavelengths need to be used as there are switch ports. To limit the wavelength range on the output fibers to W, we then need to provide output wavelength converters. Those output converters can be Fixed output Wavelength Converters. The resulting configuration is shown in Figure 6a.



(a) (b)

Figure 6. A strictly non-blocking switch architecture with AWGs and wavelength converters: (a) single stage, (b) multistage

The non-blocking switch's requirement of TWCs with range F·W raises a scalability issue. It is quite intuitive that the technological evolution of the range of wavelengths for tunable transmitters (the core part of a TWC) will closely follow the increase in number of wavelengths used on the fibers. Thus, for the blocking node where only a range of W is required for the TWCs, we foresee no serious scalability problem. However, when the range needs to be extended to F·W, this may be an issue, certainly when a large number of fibers F is involved.

To overcome this scalability limit, a Clos-like multistage design can help out. The eventual switch design is depicted in Figure 6b, which is similar to the generic structure of Figure 4b presented earlier: a first switching stage comprises Wx2·W switches, a second consists of FxF switches, and the last stage only contains TWCs. As we are designing a strictly non-blocking node the converters at the output can no longer be fixed output wavelength converters. The range of the TWCs for each of the three stages respectively is 2·W, F and W. When we assume that the range of the TWCs is limited to W wavelengths, we end up with the condition that $F \leq W/2$. This is a quite realistic assumption, given the fairly broad range of wavelengths available already today. The multi-stage design of Figure 6b also uses smaller sized AWGs than the single stage approach, which allows overcoming potential technological limitations.

To conclude the discussion on the multi-stage AWG architecture, note that the Clos-like approach did not lead to a reduction of the number of components or crosspoints, as in most other Clos-based approaches. Indeed, we now need 5·F·W converters, whereas the original design (recall Figure 6a) needed only 2·F·W of which F·W were fixed output (which are cheaper). However, the demands on those F·W converters were quite unrealistic in terms of tunability range. The Clos approach's merit in this case thus is that it enables circumventing technological limitations. Even though TWCs are, at this point in time, rather complex and thus expensive devices, we do expect that their cost will drop severely. Indeed, research on these devices continues and integration of the converters with tunable lasers has already been proposed in [19] [20], allowing production at a substantially lower price. Thus a TWC seems a viable candidate component for usage in OPS, being a technology for the mid- to long-term future. An additional quality of wavelength conversion particularly useful in the multi-stage solutions at hand is its side-effect of amplification.

Conclusion

Despite the fact that both the information characteristics and communication technology has greatly evolved since the time of Clos's seminal paper, his ideas on multi-stage switches still prove to be very useful. In this paper, we have focused on their application in optical networking. We outlined a range of examples in the field of circuit switching, and then focused on Clos-like design in Optical Packet Switching.

We presented the two most wide-spread architectures for OPS: broadcast-and-select switches using SOAs, and AWG-based switches. The former profits from a Clos-like multi-stage architecture to reduce the number of SOA gates needed, and to enlarge the switch size to high port counts. The AWG-based design was shown to be prone to internal blocking when the tunability range of wavelength converters is limited. To overcome this blocking problem, we showed that a multi-stage design inspired by Clos networks offers a viable solution.

As in the “old days”, multi-stage approaches thus are still very useful to either reduce costs (i.e. number of components used) or to circumvent technological limitations.

Acknowledgement

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