Optical Path Technologies: A Comparison Among Different Cross-Connect Architectures

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***Abstract*—The introduction of optical technology in the path layer of the transport network is expected to allow scalable and modular networks to be realized. In this paper, different optical cross-connect architectures, based either on space division or wavelength division switching, are analyzed. A comparative investigation is accomplished considering three issues of primary importance: cross-connect modularity, complexity, and transmission performance. In particular, the transmission performance of a generic path through the network is evaluated by upgrading a previously published analytical model, so to more accurately take into account the in-band crosstalk arising in the cross-connect.**

I. Introduction

THE TRANSPORT network has been analyzed to identify generic functionality which is independent of the implementation technology. This analysis leads to the individuation of a layered structure of the network composed by three layers, with a client-server association between adjacent layers. The layered structure, as defined by the ITU-T [1], is shown in Fig. 1 and described as follows:

- the *circuit layer* manages end-to-end connections (circuits) established dynamically or on the basis of short-term provisioning; each circuit is related to a particular service, as telephone, data transmission, and so on;
- the *transmission media layer* provides point-to-point interconnection between network nodes;
- the *path layer* bridges these two layers, mainly with Digital Cross Connect (DXC) systems. In particular, different circuits, related to different services, are united to form a path and routed through the network; network monitoring and restoration are also realized in this layer.

The layering concept allows us to simplify the design, development, and operation of the network and permits smooth network evolution in pace with user demand.

The increasing demand of traditional and new telecommunication services drives the trend toward higher and higher transport capacity. The requirement of a network node throughput of the order of 100 Gb/s is not far away. Moreover, the services demand evolves quickly so that operators need the possibility to respond with the same rapidity.

These requirements are hard to satisfy if the path layer is completely realized by DXC's. This would require a great increase in the dimension of the electronic switching fabric with a consequential increase in the DXC cost.

A transport network, robust to future evolution, would be achieved by introducing an optical path layer interfacing the transmission media layer with the electrical path layer [2], [3]. Very high capacity data streams are routed through the optical path layer by means of optical cross connects (OXC) that operate directly in the optical domain. To allow demultiplexing and routing at lower hierarchical levels, the OXC is interfaced with a DXC. However, if the high speed optical signal has to be directly delivered to the access network, it can be

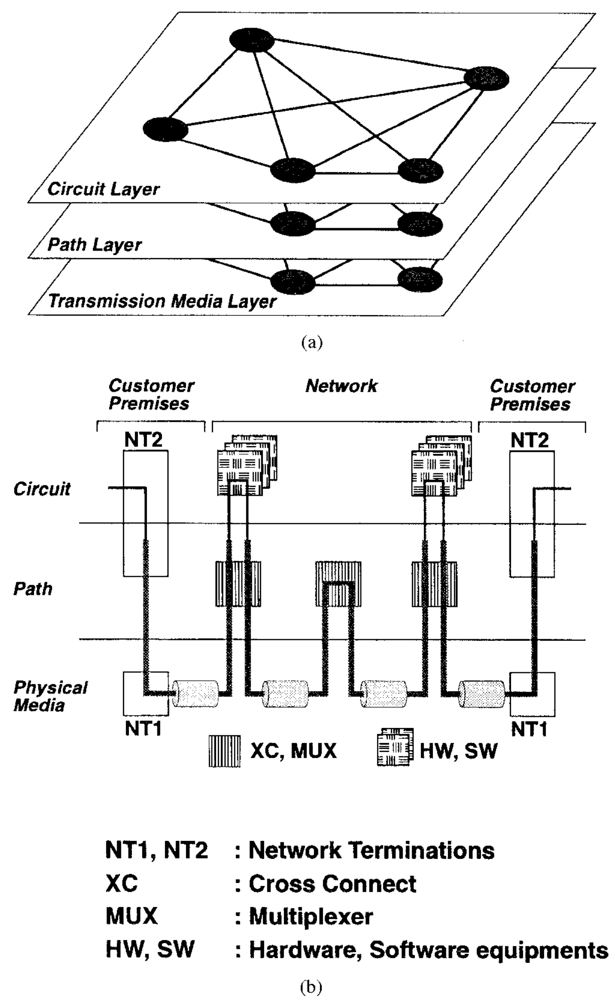

Fig. 1. Layered architecture of transport network. (a) Transport network layered architecture. (b) Functional configuration in each layer.

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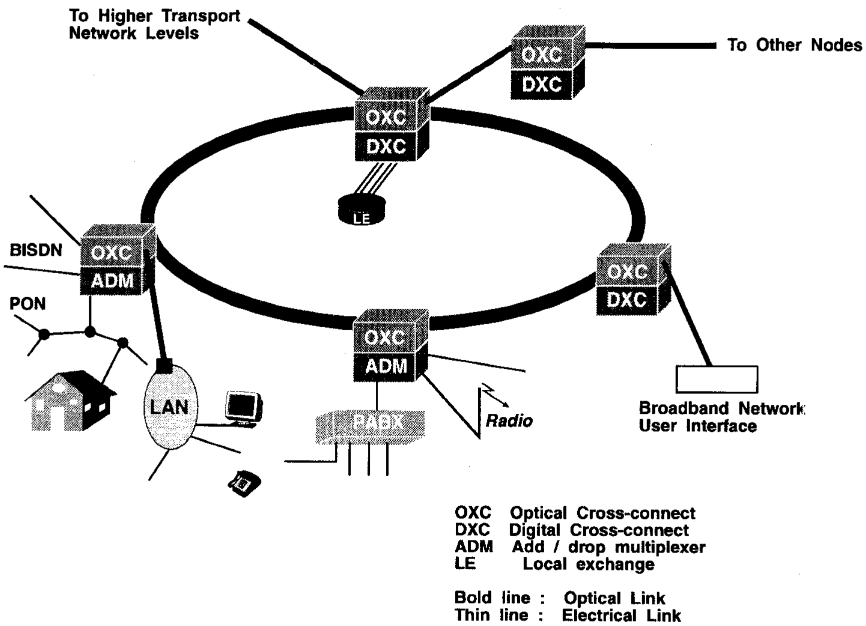

Fig. 2. Concept of an optical path layer in a transport network.

done, for example, by optical add-drop multiplexers. A picture of a transport network, including an optical path layer, is shown in Fig. 2. Functions such as optical path routing and network restoration can be directly realized in the optical path layer by optical technologies, allowing different electrical path technologies (as SDH and ATM) to be integrated over the same optical platform with a great advantage in network feasibility and flexibility [2], [3].

Among optical multiplexing technologies, needed to realize very high capacity data streams, wavelength division multiplexing (WDM) is a very promising approach. The fiber bandwidth is most easily accessed in the wavelength domain directly, rather than in the time domain; moreover, it is possible to take advantage of WDM by using wavelength to perform functions as routing and switching. WDM can employ mostly existing technologies associated with today's intensity-modulation, direct-detection systems. This evinces that WDM is expected to find broad applications for upgrading existing networks as well as in the future photonic networks. Thus, in this paper, an optical path layer based on WDM will be considered.

There are three issues of primary importance in the design of an optical transport network [3], [4]: the scalability, the modularity, and the transparency.

The scalability is the property of always being able to add more nodes to the network (network expandability).

The modularity is the feature of being able to add only a few nodes without altering the existing network structure but for the updating of the connectivity diagram.

Different definitions can be adopted for the transparency.

We say that a network is transparent to the transmission format if all network functions are independent of the signal modulation format and speed (if digital signals are involved, the bit-rate). In particular, this means that electronic signal regeneration is never performed along the signal route through the network. Transmission format transparency would be quite useful. For instance, it allows the management of high-speed channels obtained by subcarrier multiplexing (as is the case of CATV signals) besides standard digital channels. On the other hand, transmission format transparency set tough requirements to the optical technologies to be used in the network. For example, some kinds of wavelength converters that exhibit good performances can process only digital signals.

Another possible definition of the network transparency is the bit rate transparency. In this case, the network can process only intensity modulated signals, but the network functions are independent from the signal bit rate. Bit rate transparency is a weaker requirement with respect to transmission format transparency, but it is very useful to assure smooth network updating as the traffic demand increases.

The scalability implies that the number of wavelengths must be independent of the number of nodes in the network [4]. To build up a completely flexible network architecture that fulfills such a requirement, the concept of wavelength reuse has to be introduced.

The implementation of wavelength reuse can be done by partitioning the network into subnetworks to allow reuse of subset of wavelengths in each segment by, for instance, wavelength routing. However, the wavelength reuse increases the probability of contentions inside the OXC, occurring when two channels at the same wavelength, arriving from different inputs, are to be routed at the same output. A way to solve this problem is to adopt routing algorithms that intrinsically avoid such contentions, i.e., the wavelength path introduced in [5]. However, such algorithms limit the wavelength reuse level (number of different path using the same wavelength) inside the network. Another way to solve this contention is to change the wavelength of one of the colliding channels introducing wavelength translation inside the OXC. Moreover, the introduction of wavelength translation allows flexible routing and restoration techniques to be implemented [5], [6].

If a certain degree of transparency is to be preserved, wavelength translation has to be performed by opportune *transparent* devices.

In this paper, a transparent optical layer based on WDM technology is considered. A comparison is carried out among different OXC implementation architectures considering the OXC modularity, the complexity in terms of employed devices and, finally, the transmission performances of a network adopting such OXC's. Both architectures based on space division and wavelength division switching are considered.

In particular in Section II the OXC requirements are deduced on the ground of the desired network properties and the different OXC architectures are introduced. The modularity of the different OXC's is discussed and their complexity is estimated. In Section III the theoretical model for the evaluation of the network transmission performances is introduced, and in Section IV the transmission performances of different networks are compared. Finally, the obtained results are summarized in Section V.

II. Optical Cross-Connect Architectures

The OXC is the main network element of the optical path layer. Its function is the routing of high speed WDM data fluxes and the add/dropping of single channels from/to the DXC interface. If the optical path layer has to be modular, scalable, and transparent, the OXC has to fulfil some structural requirements.

If some sort of transparency is required, the devices adopted in the OXC must be suitably chosen.

The path layer modularity requires the possibility to add at the OXC input a new fiber to connect a new OXC without completely changing the OXC structure. This is possible if the OXC is *link modular*, that is, if new input/output fibers can be added without changing the OXC structure except for the addition of new components.

Moreover, during the scaling of the network, it can be needed to increase the capacity of a single WDM link. In this case, to preserve the path layer scalability, the OXC must be *wavelength modular.* This means that a new WDM channel can be added at each OXC input without changing the OXC structure except for the addition of new components.

Another useful OXC characteristic is the *add/drop flexibility.* An OXC is add/drop flexible if the number of added/dropped channels can be varied from zero to a certain number M_A depending on the traffic conditions. The higher M_A, the higher the degree of add/drop flexibility. The highest flexibility is obtained when M_A coincides with the number of OXC input channels.

Besides transparency, modularity, and add/drop flexibility, the OXC cost must be as low as possible. Thus, a significant parameter for the OXC is the number of the adopted optical components and the complexity.

Finally, optical paths, crossing several OXC's, must provide satisfactory transmission performances.

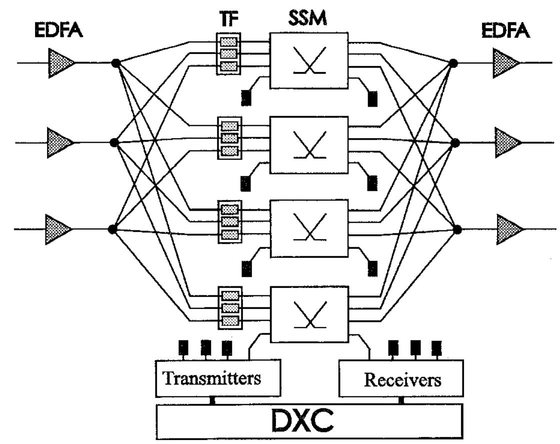

Fig. 3. Optical cross-connect architecture using space switches without wavelength converters. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; SSM: Space Switch Matrix; SC: Star Coupler; DXC: Digital Cross-Connect.

Two basic switching schemes can be adopted in an OXC: space switching and wavelength switching. In the following we will consider seven different OXC architectures: four based on space switching and three based on wavelength switching. Among the four architectures based on space switching two are based on the employment of optical space switching matrices, the others are based on deliver-and-coupling switches, introduced in [7].

A. OXC Architecture Based on Space Switching

1) OXC Architectures Based on Space Switching Matrices: The principle block diagram of a first kind of OXC of this type is shown in Fig. 3. Each of the N_f fibers at the OXC input carries a comb of M WDM channels, and M channels are add/drop to the electrical level through local transmitters and receivers. The incoming channels are discriminated through the optical splitters and the tunable optical filters. Then they are routed, by optical space switch matrices, either to the proper output or to the set of optical receivers if they have to be dropped to the digital level. On the other hand, locally generated channels directly enter the optical switch to be routed to the proper output. The combiners blend the wavelength channels into the output fibers. At the node input and output, erbium-doped fiber amplifiers (EDFA's) allow the losses to be compensated. It is to be remarked that up to M signals can be added/dropped at a node.

In discussing the characteristics of the OXC architecture shown in Fig. 3, it is worth noting that contentions could arise when channels entering the OXC at the same frequency from different fibers are sent to the same output. Contentions can be avoided by assigning a fixed wavelength to each optical path throughout the network (WP: Wavelength Path) [5]. In this case channels with the same wavelength are always routed to different outputs; however, the wavelength reuse and the network scalability are reduced.

Otherwise, contentions may be solved by detecting one of the channels by a local receiver and retransmitting it at a different wavelength. However, in this way, the OXC

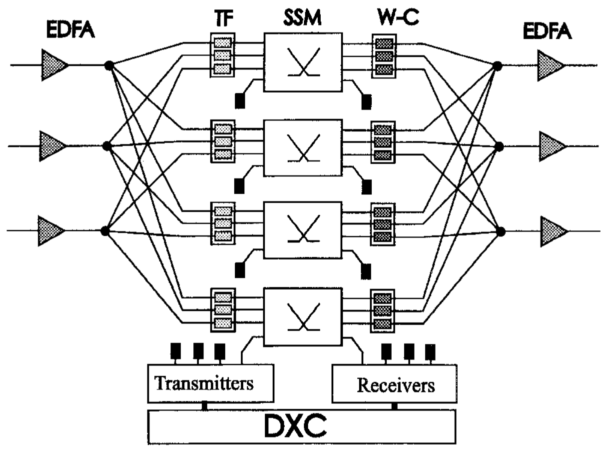

Fig. 4. Optical cross-connect architecture employing space switches and wavelength converters. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; SSM: Space Switch Matrix; W-C: Wavelength Converter; SC: Star Coupler; DXC: Digital Cross-Connect.

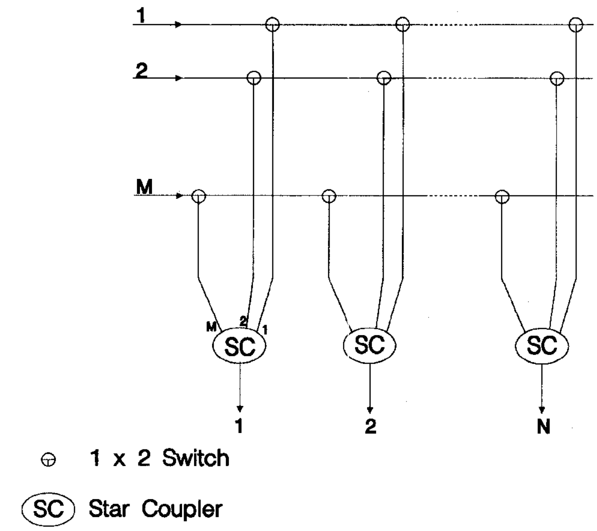

Fig. 5. Scheme of a $M \times N$ delivering and coupling switch (DCS).

transparency is lost and some node resources are turned away from the add/drop function.

As a result this architecture cannot be considered strictly nonblocking, but rearrangeably nonblocking.

The OXC needs M crossbar switching matrices, each with $N = (N_f + 1)$ inputs/outputs. Therefore, provided that the opportune redundancy is foreseen in the splitters, the OXC results to be wavelength modular. As a matter of fact, the addition of a channel per input fiber only needs the addition of N tunable filters and of a switch matrix. On the other hand, the OXC is not link modular since the addition of one input fiber requires the substitution of all the space switching matrices. The number of added/dropped channels can be changed from zero to M, providing an intermediate degree of add/drop flexibility.

To evaluate the complexity of the analyzed OXC scheme, two basic elements can be individuated: spatial cross-points and tunable filters. Since an $N \times N$ crossbar matrix need N^2 cross-points, each of which requiring a single gate, MN^2 cross-points are present inside the OXC, besides MN tunable filters.

The blocking characteristics of the previous architecture can be overcome by introducing wavelength conversion inside the OXC. The block diagram of this second architecture, in which one wavelength converter is placed after any output of the switch matrices, is shown in Fig. 4. In this case contentions are avoided by changing the wavelength of one of the channels and transparency can be preserved. This architecture is strictly nonblocking and allows the virtual wavelength path routing scheme (VWP) [5] to be employed. This scheme is based on the possibility to change the wavelength of the optical path inside the OXC and allows high wavelength reuse and network scalability to be achieved.

Three basic elements can be individuated to evaluate the complexity of the analyzed OXC scheme: spatial cross-points, tunable filters, and wavelength converters. Actually, MN^2 cross-points are present inside the OXC, besides MN tunable filters and NM wavelength converters. Moreover, using some kinds of wavelength converters, MN more tunable filters are needed after the wavelength conversion stage to suppress the optical pump needed in the wavelength conversion process. In this case the number of tunable filters is $2MN$.

2) Architectures Based on Delivering and Coupling Switches: Two architectures, which were reported in [7], are considered in this section. One is link modular, the other is wavelength modular. The switch used in these schemes is basically a space division switch; its structure is shown in Fig. 5 in the case of an $M \times N$ switch. The delivering and coupling switch (DCS) is based on star couplers and 1×2 optical switches (OS). Any OS has one input and two outputs and is characterized by four states:

1) the input signal is not transmitted;
2) the input signal is transmitted to the first output;
3) the input signal is transmitted to the second output;
4) the input signal is transmitted to both the outputs.

The DCS is a very flexible switch allowing, for example, the presence at its outputs of WDM signals obtained by multiplexing the input signals during the switch operation. Thus the DCS allows different OXC architectures to be designed. In this paper, we present only two schemes that seems to be promising for future application in the transport network.

The block diagram of the first OXC (the wavelength modular one) is shown in Fig. 6. The OXC behavior is somehow similar to that of Fig. 5, but with an important difference. Due to the combined effect of wavelength conversion and the adoption of DCS's, tunable filters at the OXC input are not needed and signal demultiplexing can be achieved by a static demultiplexer (for example, a grating), thus simplifying the input stage structure.

For the same reasons discussed in the previous section, the OXC is wavelength modular but not link modular. Moreover, it is strictly nonblocking and, due to the characteristics of the DCS, it has the maximum add/drop flexibility, provided that

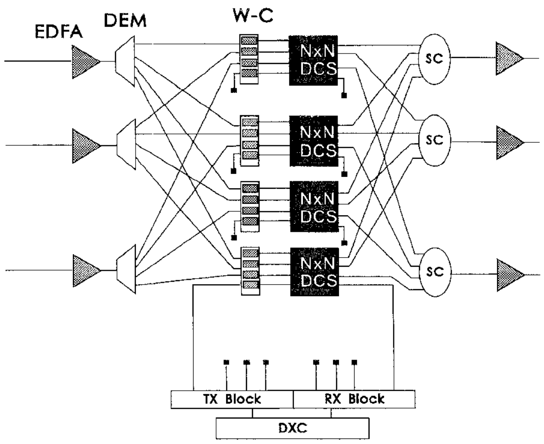

Fig. 6. Architecture of a wavelength modular optical cross-connect using delivery and coupling switches (DCS). EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; W-C: Wavelength Converter; SC: Star Coupler; DXC: Digital Cross-Connect.

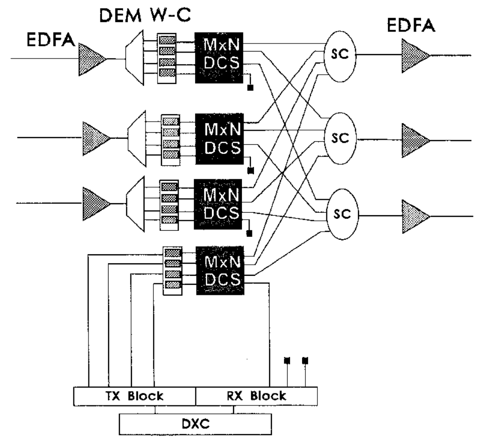

Fig. 7. Architecture of a link modular optical cross-connect using delivery and coupling switches (DCS). EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; W-C: Wavelength Converter; SC: Star Coupler; DXC: Digital Cross-Connect.

a sufficient number of transmitters and receivers are present in the TX and RX blocks.

Considering the OXC complexity, it is to taken into account that a single OS can be considered as a single crosspoint requiring two gates. Thus, MN^2 cross-points and $2MN^2$ gates are needed inside the OXC, besides MN wavelength converters. Depending on the wavelength converters type, NM tunable filters after the wavelength converters may be required.

The second OXC architecture, proposed in [7] to obtain link modularity, is shown in Fig. 7. It is based on a set of N DCS's with M inputs and N outputs. At the OXC input, after amplification by a set of EDFA's, the incoming channels are demultiplexed wavelength converted so to avoid contentions and feed the DCS's. It is to be noted that even in this case static demultiplexers are required, as for the scheme of Fig. 6. Each input fiber feeds a DCS and a DCS is reserved to the local channels. Each DCS output is connected to a different output fiber or to a local receiver so that, inside the DCS, all the channels directed toward the same fiber are delivered to the same DCS output. The channels from different DCS's are multiplexed onto the output fibers by a set of couplers and amplified by a set of EDFA's.

Link modularity is assured by the fact that each input fiber has its own DCS so that adding an input/output fiber requires adding two star couplers, M tunable filters and wavelength converters, a DCS, and two EDFA's. On the other hand, the OXC is not wavelength modular, since adding a new channel changes all the DCS's. Maximum add/drop flexibility is achieved.

Inside the OXC MN^2 cross-points are needed, besides MN wavelength converters. Thus the overall OXC complexity is the same of the wavelength modular OXC previously considered.

B. OXC Architectures Based on Wavelength Switching

Three OXC schemes are considered in this section: in all these schemes switching is performed directly in the frequency domain.

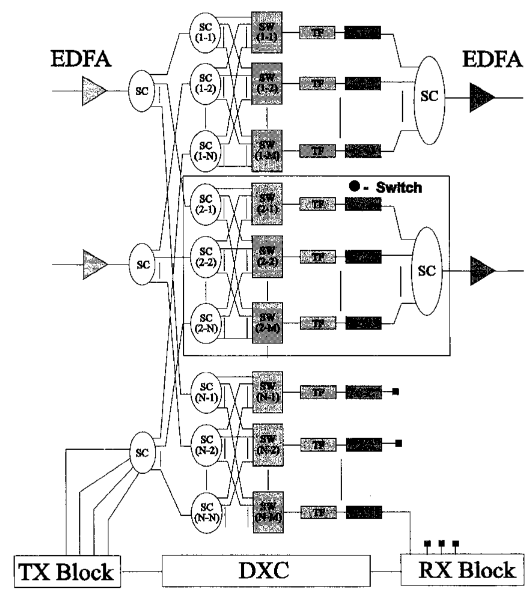

Fig. 8. Optical cross-connect architecture using parallel l-switches. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; W-C: Wavelength Converter; SC: Star Coupler; SW: (N:1) Switch; TX: Transmitters; RX: Receivers; DXC: Digital Cross-Connect.

The first one was reported in [7], and it is shown in Fig. 8. There are N switching units, called λ-switches, which are related to N-1 input/output fiber links and to one link for local traffic (one input port from the local transmitters and one output port for the local receivers). Each λ-switch contains the following elements:

- N star coupler of $(1 \times M)$ dimension;
- M switch of dimension $(N \times 1)$;
- M pairs of tunable filters and wavelength converters;
- one optical combiner, i.e., an $(M \times 1)$ star coupler.

The WDM comb from any of the N links are delivered to all the λ-switches. Each λ-switch receives all the incoming WDM combs, one per each input star coupler. The switch

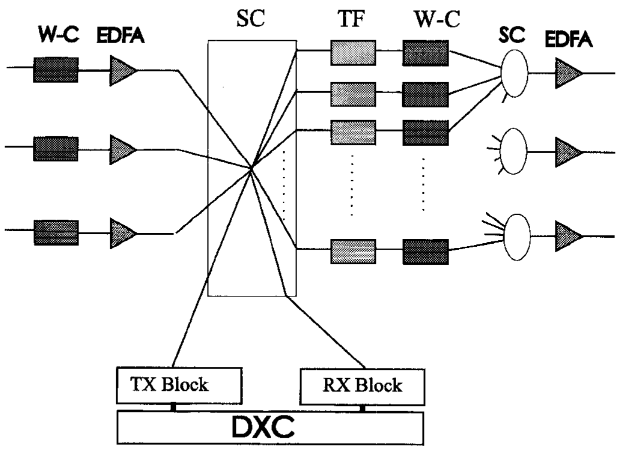

Fig. 9. Scheme of an optical cross-connect based on wavelength converters as switching elements. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; DXC: Digital Cross-Connect; W-C: Wavelength Converter; SC: Star Coupler.

$(N \times 1)$ inhibits all the input combs but one; any tunable filter/wavelength converter pair selects the respective channel from the comb and shifts it on the proper optical wavelength. Then the M channels are combined before reaching the output link.

This architecture results to be strictly nonblocking. Furthermore, it is link modular. In fact, the addition of one link requires the addition of one λ-switch and one star coupler connected to the incoming link. The number of additional components matches the number of additional links. On the other hand, it is not wavelength modular, because an increase of WDM channels changes all the λ-switches. Complete add/drop flexibility can be achieved if enough transmitters and receivers are available.

This scheme requires NM tunable filters, NM spatial cross-points, and NM wavelength converters. Depending on the wavelength converters type, NM tunable filters after the wavelength converters may be required.

The second architecture was reported in [8], and its block diagram is shown in Fig. 9. In some sense, this architecture is the equivalent of a T switching stage for a WDM network. As a matter of fact, all the incoming channels are multiplexed together inside the switch fabric.

At the OXC input, the WDM combs carried by the input fibers are wavelength-translated so as to occupy contiguous parts of the optical spectrum. This operation can be carried out by $(N-1)$ wavelength converters since there exist optical wavelength converters that are able to translate an entire WDM comb [9]. After translation, the signals are amplified by a set of EDFA's and feed the inputs of an $N \times NM$ star coupler. At the coupler center all the incoming optical channels are wavelength- multiplexed onto a single comb. At the coupler output, any tunable filter select one channel and the succeeding wavelength converter set its wavelength to a suitable value to allow multiplexing onto the selected output fiber. Multiplexing occurs by optical couplers and, at the OXC output, the signal is amplified by a set of EDFA's. It is to be noted that, at the OXC input, wavelength conversion is set before amplification since wavelength converters based on FWM works more efficiently with a low input signal power [10].

The OXC depicted in Fig. 9 is strictly nonblocking and results in both fiber and wavelength modular, provided that the central star is suitably over-dimensioned. The addition of a new input/output fiber needs an addition of M new filters, $M+1$ new wavelength converters, a new output coupler, and two new EDFA's, while the rest of the OXC remains unchanged. The addition of a new channel per fiber needs an addition of N new filters and wavelength converters, besides a new setting of the wavelength converters in front of the OXC to avoid contentions at the star center. This setting can be done by tuning the semiconductor lasers that provide the optical pumps to the converters without substituting any optical device. Complete add/drop flexibility can be achieved if enough transmitters and receivers are available.

Since no space switching is realized inside the OXC, there are no cross-points. On the other hand, $N(M+1)$ wavelength converters and N tunable filters are required after the first wavelength converter stage. Depending on the wavelength converters type, $N(M+1)$ more tunable filters after the second wavelength converters stage may be required. Moreover, the star coupler needed to multiplex all the input channels is more complex to realize than the star couplers that are present in the OXC's, based on space switching having many more ports.

This kind of OXC based on wavelength switching provides better modularity and a minor complexity with respect to previously analyzed schemes based on wavelength switching. It requires very high performance wavelength converters. As a matter of fact, the maximum conversion interval in this case is $NM\Delta f$, Δf being the channel spacing, while it is only $M\Delta f$ in the case of OXC based on space switching. Moreover, converters able to shift an entire WDM comb are needed.

The last architecture considered in this section is proposed here for the first time and shown in Fig. 10. Such a scheme is quite similar to previous ones. At the OXC input, the incoming WDM combs are properly set in adjacent portions of the optical spectrum by means of the input wavelength converters. Then they are delivered to N star coupler of dimension $(N \times N)$. At any output of a star coupler there is the entire comb of the channels entering the node. Then the system works as in the previous scheme.

This architecture is strictly nonblocking and presents basically the same characteristics of modularity as the previous architecture. However, the single $(N \times NM)$ star coupler is substituted by N smaller star couplers that are easier to realize. The main advantage of this architecture with respect to the previous one is that any upgrading or maintenance of the system can be accomplished without traffic disruption. Furthermore, a few small star couplers are needed instead of one of large dimensions, which is more complex to realize. The number of wavelength converters and tunable filters is the same as the previous architecture.

III. Key Technologies

The scope of this section is to review some of the main enabling technologies for the realization of the OXC archi-

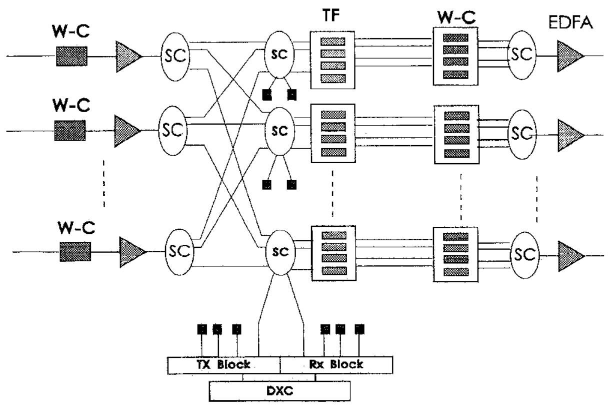

Fig. 10. Optical cross-connects based on wavelength converters as switching elements and using different input star couplers. EDFA: Erbium Doped Fiber Amplifier; TF: Tunable Filter; DXC: Digital Cross-Connect; W-C: Wavelength Converter; SC: Star Coupler.

tectures shown in the previous section. We do not pretend to present a complete review of all the possible technological options or to operate a complete technological comparison. We concentrated on existing technologies, some of them already exploited in commercially available devices, to point out the possibility to realize the considered OXC schemes using devices available today.

Besides passive optical devices technology, which can be considered already stabilized, there are three key devices in this applications: tunable optical filters, optical space switches (crossbar matrices and DCS's), and wavelength converters.

A. Tunable Filters

Two types of filters are mature for the considered applications: Fabry–Perot filters (FP) [11] and acousto-optic tunable filters (AOTF) [12], [13].

Fabry–Perot filters present low losses, easy tunability, large tuning range (more than 30 nm) and are polarization insensitive. Moreover, filters with an optical bandwidth comprised between some hundreds of kilohertz and hundreds of gigahertzs can be realized. However, the roll-off of FP filters is quite slow. This means that the channel spacing must be great enough to not appreciably introduce crosstalk (for example 1 nm for 2.5 Gb/s channels).

Acousto-optic filters have a large tuning range (more than 30 nm) and a good roll-off coefficient. Moreover, these filters can select more frequencies at a time, each being frequency independently tunable. This property can be useful both in designing all optical add/drop multiplexers and OXC architectures based on wavelength switching.

A third type of filter could be employed in the future, based on InP technology [14]. However, for the time being, they are not mature for implementation. Their most important advantage is that they could be monolithically integrated with active optical devices such as lasers, semiconductor optical amplifiers, and wavelength converters. The integration has the considerable advantages of removing the stabilization and coupling problems that are present in the implementations by discrete devices and of lowering the costs.

B. Space Switches

There are, at present, several technologies suitable for the realization of space switching devices. In particular, there are space switches based on $LiNbO_3$ [15], mechanical switches [16], silica waveguide switches utilizing thermo-optic effect [17], switches based on active devices based on InP technology [18], and opto-electronic switches [19], consisting of an array of receivers/transmitters, for the opto-electronic conversions, and of an analog electronic switch matrix.

Among all-optical switches, passive devices, as those based on silica waveguide and thermo-optic effect, are characterized by their losses: these contribute to the overall OXC loss and must be compensated by the EDFA amplifiers. Active switches, as those based on InP technology, can present gains great enough to completely compensate their inner losses. However, these devices add noise to their optical output: this noise is added to the overall noise accumulating along the signal route and affect the receiver performances.

As far as hybrid opto-electronic devices are concerned, at least bit-rate transparency can be obtained by adopting analog electronic devices. However, for low bit rates, this approach could present significant advantages in terms of costs; at high bit rates it seems there is no relevant technological advantage to use this solution instead of all-optical devices.

C. Wavelength Converters

Wavelength converters are key devices to obtain modular and flexible OXC's and, among the considered devices, they are based on the less established technology. This is evident considering that a large number of quite different technological options are available, none of which is today exploited to obtain commercial devices.

We limit ourselves to consider those wavelength converters that can be favorably employed in high speed optical networks and that have been realized at the prototype level obtaining good performances. There are baiscally four different types of device:

1) optoelectronic converters based on the photodetection and re-transmission of the signal on another wavelength (OEC) [20]. This type of device can or cannot be based on complete signal regeneration;
2) converters based on cross-phase modulation (XPM) in semiconductor optical amplifiers (SOA) placed in the arms of an interferometer (generally a Mach-Zehnder or a Michelson interferometer) [21], [22];
3) converters based on four wave mixing (FWM) in SOA's [10];
4) converters based on the second order nonlinearity (SON) in AlGaAs waveguides [23].

Completely regenerative optoelectronic converters prevent the network transparency. On the other hand, signal regeneration, occurring at each node, removes network limitations due to long span transmission occurring in geographical transparent networks.

However, it is possible to realize transparent optoelectronic converters. In fact, they can consist of a photodetector with a front-end, followed by an analog electronic processing and an optical transmitter able to emit the proper wavelength. The device must be designed to work with a very small nonlinear distortion and this is not an easy task, especially when operating on signals with a bandwidth as large as 10 Ghz. Moreover, to obtain the wide tunable converter needed in optical OXC's, a widely tunable transmitter has to be adopted.

The main characteristics of the considered all-optical converters (the last three types) are the high speed, the large conversion bandwidth, and the easy tunability.

In particular, the devices based on XPM present the best conversion efficiency; that is, almost independent of the conversion interval. They can be monolithically integrated with other semiconductor devices, such as the reference laser and, in case, filters based on InP integrated gratings. Monolithically integration, as demonstrated in [22], allows coupling and stability problems that are present when using discrete components to be avoided. XPM devices also have the possibility to provide a signal extinction ratio improvement so they can be favorably cascaded. On the other hand, XPM converters are not transparent to the transmission format since they can process only intensity modulated signals. Finally, XPM converters can be realized in configurations that do not need the use of tunable optical filters.

As far as FWM converters are considered, they can operate with large conversion intervals (up to 20 nm) and can be integrated with other semiconductor devices. They are transparent to the modulation format [24] and, in particular, can convert a whole WDM comb. Moreover, optical phase conjugation occurs during the wavelength conversion providing, if a single conversion is operated inside each OXC, a partial compensation of the transmission impairments caused by fiber dispersion and nonlinear Kerr effect [25]–[27]. Their main disadvantages are the high noise level at their output, the strong dependence of both the conversion efficiency, and the noise level on the conversion interval.

Finally, all-optical wavelength converters based on second order nonlinearity in AlGaAs waveguides can operate with large conversion intervals and attain transmission format transparency allowing the translation of a whole WDM comb. Also, the conversion efficiency almost does not depend on the conversion interval, and the noise added at the optical output is negligible since these converters are based on a passive waveguide. The main impairments of converters based on SON are their low conversion efficiency and the difficult integration with other optical devices used for transmission in the 1.55 mm fiber window. Moreover, in the author's opinion, at the state of the art, these devices are the less consolidated among the considered wavelength converters.

IV. Transmission Performances: Evaluation Model

In order to evaluate the transmission performances of an optical network based on OXC's, a signal path through the network is modeled, as in Fig. 11. The signal originates from the transmitter placed in the first OXC, crosses $K-1$ in-line OXC's, and is detected by the receiver of the last OXC. Thus the path is composed by K fiber links and the total number of

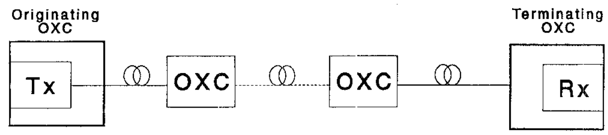

Fig. 11. Model of the signal path through the network.

OXC's in the chain is $K+1$. In the fiber link in-line EDFA's are used when needed.

The main phenomena affecting the transmission performances are:

- amplified spontaneous emission (ASE) noise accumulation;
- fiber dispersion;
- in-band linear crosstalk;
- out-band linear crosstalk;
- nonlinear crosstalk due to four-wave mixing in the transmission fibers.

Other less important transmission impairments are:

- phase-noise introduced by wavelength converters;
- thermal noise of the receiver;
- saturation of the EDFA amplifiers.

In this paper it is assumed that dispersion shifted fibers are used in the network and that passive dispersion compensation is attained by placing a compensating fiber in front of each OXC and, if such is the case, of each in-line EDFA amplifier.

Besides the overall error probability, we consider another performance evaluation parameter: the equivalent OXC noise factor. Such a parameter is defined as $F = S/(G_{\rm OXC} h\nu)$, where S is the spectral noise density of the ASE noise introduced by the OXC, h the Plank constant, and n the optical frequency. While the error probability gives a measure of the overall transmission performances of a signal path through the network, the noise factor takes into account the noise characteristics of the OXC.

In order to evaluate the transmission performances of the network, we have used an analytical model for the evaluation of the error probability at the receiver, located inside the last OXC of the chain represented in Fig. 11. This model gives also the noise factor of each OXC of the chain. For the sake of brevity, it is not possible to describe the analytical procedure adopted for performance evaluation here; however, it is described in detail in [28]. The evaluation of the in-band crosstalk contribution has been accomplished as described in [29].

In the performance evaluation we have considered two conservative assumptions:

1) the crosstalk contributions are considered in the worst case, i.e., any interfering channel originates in the same OXC in where the crosstalk occurs;
2) wavelength conversion always occurs with the maximum conversion interval, in order to consider the worst possible conversion efficiency.

As far as the technology is concerned it is worth noting that:

1) the filters used in the OXC's are assumed to be standard double-stage acousto-optic filters; which allow us to appreciably reduce crosstalk contributions [12];

TABLE I
COMPARISON OF THE ROUTING ABILITY, ADD/DROP FLEXIBILITY, MODULARITY, AND COMPLEXITY OF THE DIFFERENT OXC ARCHITECTURES. RNB: REARRANGEABLY NON-BLOCKING; SNB: STRICTLY NON-BLOCKING; WP: WAVELENGTH PATH; VWP: VIRTUAL WAVELENGTH PATH

OXC Architecture	Blocking	Routing Strategy	Link Modularity	Wavelength Modularity	Add/Drop Flexibility	Cross-Points	Gates	Tunable Filters	Wavelength Converters
Space Switch-1	RNB	WP	NO	YES	M	$M N^2$	$M N^2$	N M	—
Space Switch-2	SNB	VWP	NO	YES	M	$M N^2$	$M N^2$	N M (2 N M)	N M
DCS Switch-1	SNB	VWP	NO	YES	MAX (M N)	$M N^2$	$2 M N^2$	— (N M)	N M
DCS Switch-2	SNB	VWP	YES	NO	MAX (M N)	$M N^2$	$2 M N^2$	— (N M)	N M
Wavelength Switch-1	SNB	VWP	YES	NO	MAX (M N)	M N	M N	N M (2 N M)	N M
Wavelength Switch-2	SNB	VWP	YES	YES	MAX (M N)	—	—	N (1+M) N (1+2 M)	N (1+ M)
Wavelength Switch-3	SNB	VWP	YES	YES	MAX (M N)	—	—	N (1+M) N (1+ 2 M)	N (1+ M)

2) wavelength converters based on SOA are considered and realized using bulk InGaAsP amplifiers; when FWM converters are considered, their geometry is assumed to be optimized to obtain high conversion efficiency as detailed in [30].

Final considerations concern the EDFA gains and the optical bandwidth of the filters. No attempt has been made in order to optimize the performance by a proper adjust of the EDFA gains so the performances can be further enhanced. Moreover, the bandwidth of the selection filter in front of the receiver is assumed to be four times the bit rate. The bandwidth of the filters adopted inside the OXC's is evaluated so that the overall bandwidth of the channel (the cascade of the OXC's crossed in the optical path) is about four times the bit rate.

V. COMPARATIVE ANALYSIS

In this section the different OXC architectures will be compared on the basis of their modularity, complexity, and transmission performances.

The characteristics of the different OXC architectures are summarized in Table I.

Apart from the first architecture, all the others are strictly nonblocking (SNB in the table) and can implement the VWP routing algorithm saving, at the same time, the network transparency if suitable optical devices are used. The first architecture is rearrangeably nonblocking and can realize transparency only if VP routing is implemented.

Considering the modularity, which represents a very important issue, the architectures based on space division switching allow the achievement of only one of the two types of modularity. On the other hand, two architectures employing wavelength switching permit the fulfilment of both link and wavelength modularity. Maximum add/drop flexibility can be achieved by all the considered architectures, but those based on space switching matrices which can add/drop up to M wavelength channels.

Concerning the architecture complexity, it is possible to note that the number of gates which are present in the architectures based on space switching matrices is lower than that relative to the architectures based on DCS's. This figure is counterbalanced by the fact that the architectures based on DCS's can perform optical demultiplexing by static demultiplexers (for example gratings) that are more simple and cheaper than the arrays of tunable filters needed in the OXC's based on space switching matrices.

As far as the tunable filters number is concerned, two numbers are present in the table. The first one refers to the case in which no filter is needed after the wavelength converters; the numbers in brackets refers to the case in which a tunable filter is needed after the wavelength converters. In the case of the last two architectures based on wavelength switching, filters are surely present after the first wavelength conversion stage, since the wavelength converters able to shift an entire WDM comb need a filter. On the other hand, for the second wavelength conversion stage filters may or may not be present.

It is also worth noting that in all the architectures based on space division switching, the number of cross-points increases quadratically with the number of input/output fibers. On the contrary, in the case of the last two architectures, based on wavelength switching, the number of key optical devices (wavelength converters and tunable filters) increases linearly with respect to both the number of input/output fibers and the number of WDM channels per fiber.

A significant indication of transmission performance can be given in terms of the OXC noise factor.

The noise factor of a given OXC architecture depends on the adopted devices and on the OXC dimension; that is, the number of input fibers and channels per fiber.

It is not possible to evaluate the transmission performances for all the described OXC's considering all the possible technologies. Thus, we fixed some reference combinations of bit-rate, number of input/output fibers, channels per fiber,

TABLE II
DESCRIPTION OF THE CONSIDERED SYSTEM CONFIGURATIONS; TO: THERMO-OPTIC SWITCH, DS AO: DOUBLE STAGE ACUSTO-OPTIC FILTERS

Options	C1	C2	C3	C4	C5	C6	C7
Total length (km)	2100	2100	2100	420	420	420	420
Number of OXCs	4	4	4	7	7	7	7
OXC spacing (km)	700	700	700	70	70	70	70
EDFA spacing (km)	50	50	50	35	35	35	35
OXC P_{out} (peak, dBm)	-3	-3	0	-3	-3	-6	-6
Input/output ports	8	8	4	8	8	4	4
Channels per fiber	8	8	4	8	8	4	4
Bit-Rate (Gbit/s)	2.5	2.5	10	2.5	2.5	10	10
Channel Spacing (GHz)	100	100	400	100	100	400	400
Wavelength Converters	XPM	FWM	XPM	XPM	FWM	XPM	FWM
Wav. Conv. (first stage)	FWM	FWM	FWM	FWM	FWM	FWM	FWM
Space Switches	TO	TO	InP	TO	InP	TO	InP
Tunable Filters	DS AO	DS AO	DS AO	DS AO	DS AO	DS AO	DS AO

and technological options. In the selected configurations we evaluate the transmission performances of the different OXC's. In particular, only two types of space switches are considered: space switches based on silica waveguide utilising thermo-optic effect (TO), and space switches based on InP active device technology. Two types of wavelength converters are also considered: wavelength converters based on XPM and on FWM in SOA's, respectively. As far as the system parameters are concerned, the bit-rates of 2.5 and 10 Gb/s are considered.

The gain of the EDFA at the OXC input is selected to assure the right optical power at the wavelength converter input when using XPM converters. In the other cases, the amplifier gain is roughly optimized to achieve the lowest error probability. In all the cases the maximum power at the amplifier output and the maximum amplifier gain are both limited by the amplifier physical characteristics [28]. Typical optimum gain values are between 18 and 35 dB when using FWM converters.

The gain of the EDFA at the OXC output is chosen in order to have the same power level at the output of all the OXC's in the chain. The same power level is also present at the output of each in-line EDFA.

No attempt has been made to optimize the pump and the reference signal power for the FWM and XPM wavelength converters respectively.

A summary of the considered reference configurations is given in Table II. Here the data are divided into two groups: data regarding the path into the network and data regarding the single OXC. It is worth observing that the transmission performance have been evaluated considering two different network paths: a chain of four OXC's, 700 km spaced, and a chain of seven OXC's, 70 km spaced. In the first case, in-line EDFA's are 50 km spaced; in the second case, one EDFA is present in the middle of the link between adjacent OXC's. The first case depicts a signal route in a wide area network, while in the second a signal route in a regional network is represented.

For the sake of brevity, the complete set of parameters used in the calculations is not reported here. They have been taken from the literature and the relevant references are summarized in Table III. The numerical values of some of the most important parameters are also indicated here.

The noise factor F (dB) is reported in Table IV for the seven considered OXC architectures. If the receiver error probability is not lower than 10^{-12}, the corresponding cell in Table IV is shaded. Since the configurations C1, C2 are identical in the absence of wavelength converters (that is, for the first OXC based on space switching), as it happens for C4 and C5, and for C6 and C7, the corresponding cells are merged.

The noise factor results higher for $R = 2.5$ Gb/s than for $R = 10$ Gb/s. This is because, for $R = 2.5$ Gb/s, the OXC dimension is higher, thus the OXC internal losses are greater with respect to the case $R = 10$ Gb/s. While losses are one of the key factors determining F, the optical bandwidth has no impact, since F is defined starting from the noise power spectral density.

The error probability of 10^{-12} is not reached in the considered configurations for two OXC architectures adopting wavelength switching if all the wavelength converters are based on FWM in SOA's. The performances of these OXC architectures can be improved by optimizing the pump power and the channel spacing, especially in the case $R = 10$ Gb/s [8]. This is shown in Table V, where the noise factor is reported for the last two OXC architectures, in cases C2 and C7, assuming a channel spacing of 75 GHz at 2.5 Gb /s and 200 GHz at 10 Gb/s and with a peak optical power at the OXC output of 1 dBm at 2.5 Gb/s and 0 dBm at 10 Gb/s.

TABLE III

References for the Physical Models Adopted to Reproduce the Behavior of the Various Optical Devices Exploited in the Described OXC's and for the Values of the Inherent Parameters. The Values of Some Key Parameters are also Reported in the Table

Device	Physical Model	Parameters	Values of the main parameters
Single mode, dispersion shifted fibre	[31]	[28]	Attenuation : 0.25 dB/km Dispersion : 4 ps/nm/km
Dispersion compensating fiber	[32]	[28]	Attenuation : 0.25 dB/km Dispersion : -50 ps/nm/km
EDFA inside the OXC	[33]	[34]	Maximum gain : 35 dB Maximum output power : 18 dBm Noise factor : 3.8 dB
in line EDFA	[33]	[33]	Works in linear regime Noise factor : 3.8 dB
Acoustooptic filter	[12]	[12]	Double stage standard filters minimum bandwidth 0.1 nm
Switch Matrixes (Thermo-optical)	[35]	[35]	Losses (8x8 matrix) : 10 dB Losses (4x4 matrix) : 3 dB
Switch Matrixes (InP)	[18]	[36]	Internal gain compensates for losses Internal gain (8x8) : 10 dB Internal gain (4x4) : 3 dB Noise factor : 6 dB
DCS (Thermo-optical)	[17]	[17]	Losses (8x8 DCS) : 10 dB Losses (4x4 DCS) : 3 dB
DCS (InP)	-	estimated from [36]	Internal gain compensates for losses Internal gain (8x8) : 15 dB Internal gain (4x4) : 5 dB Noise factor : 6 dB
Converters based on FWM in SOAs	[10]	[30]	SOA length : 1 mm SOA linear gain : 48 dB SOA saturation power : 7 mW
Converters based on XPM in SOAs	[24]	[24]	SOA length : 500 μm SOA linear gain : 28 dB SOA saturation power : 10 mW
IM-DD receivers (2.5 and 10 Gbit/s)	[28]	[28]	Noise factor: 3 dB Load resistance : 50 Ω Temperature : 300°K

TABLE IV

Noise Factors (in dB) of the Seven Considered OXC Architectures for Seven Relevant Network Configurations. The Shaded Box Indicates an Error Probability Higher Than 10^{-12}

OXC Architecture	C1	C2	C3	C4	C5	C6	C7
Space Switch-1	6.15		4.4	8.7		4.8	
Space Switch-2	8.81	8	10.5	11.9	11.5	9	9.9
DCS Switch-1	8	8.3	10.5	12.7	11.9	9	10.2
DCS Switch-2	8	8.3	10.5	12.7	11.9	9	10.2
Wavelength Switch-1	12.1	12.4	13.5	16.4	14.8	13	15.2
Wavelength Switch-2	10.4	31.5	13.5	14.6	33	11.7	28
Wavelength Switch-3	10.5	31.5	13.5	14.7	33	11.8	28

In all the cases reported in Table V, the error probability is lower than 10^{-12}.

It results that these OXC architectures are quite sensitive to the system optimization and the power needed to reach a fixed error probability is higher with respect to the OXC's adopting space switching or converters based on XPM. On the other hand, OXC's adopting wavelength switching and FWM in SOA's are strictly nonblocking and can provide

TABLE V
NOISE FACTOR (IN dB) FOR TWO OXC ARCHITECTURES BASED ON WAVELENGTH SWITCHING, ADOPTING WAVELENGTH CONVERTERS BASED ON FWM IN SOAS. THE NETWORK PARAMETERS ARE REPORTED IN THE TEXT

Options	C2	C7
Wavelength switch - 1	24.4	18.1
Wavelength switch - 2	24.8	18.4

full modularity and transparency to the transmission format.

The best transmission performances are exhibited by the OXC without wavelength conversion that is even transparent to the modulation format. However, it is not link modular and it is only rearrangeably nonblocking.

The other OXC architectures occupy an intermediate position: they have acceptable transmission performances in all the considered cases.

One comparison can be carried out on the ground of the data reported in Table IV: a comparison between the second architecture based on space switching and the architectures based on DCS's. The difference among the transmission performances of these architectures is quite small. In particular, in some configurations the architecture based on space switching matrices exhibits better performances, in other configurations it is outperformed by the architectures based on DCS's. This depends on the different positions in which the wavelength converters are placed in the different OXC's.

VI. CONCLUSIONS

The analysis reported in the presented paper has allowed a comparison among different OXC architectures. It is not possible to determine the best solution for all the cases, because this strongly depends on the considered applications. However, it is possible to derive some indicative conclusions. If the network requirements demand a high modularity level, especially considering the network expandability where link modularity and low complexity are necessary, the OXC schemes based on wavelength switching provide the best figures. The debt that has to be paid is that these architectures present worse transmission performances with respect to the other schemes. The transmission performance penalty is limited if XPM converters are used whenever possible; if FWM converters are used, the penalty is quite high. However, FWM converters allow transparency to the transmission format to be obtained. Furthermore, these architectures demand feasible and reliable high performance wavelength converters.

On the other hand, the OXC based either on space switching matrices or DCS's provide better transmission performances and do not require very high performance wavelength converters at the expense of complete modularity. As a matter of fact, either wavelength or link modularity can be obtained, but not both.

Finally, the best transmission performances can be attained by OXC architectures based on space switching that do not employ wavelength converters. In this case the OXC is only rearrangeably nonblocking and link modularity cannot be achieved.

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