Generalized Space-Equivalent Analysis of Optical Cross-Connect Architectures

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Abstract—Optical Cross-Connects (OXCs) are gaining an increasing importance in high-capacity wavelength-division multiplexing networks. In this work we propose a theoretical approach for the analysis and design of these optical-switching systems. Our method is based on a space-switching equivalent representation which allows to easily classify a general OXC architecture, identify its blocking properties and understand the trade-off between space and wavelength switching-domains. We are going to explain this method and demonstrate its application to some of the best known OXC implementations presented so far in literature.

I. INTRODUCTION

WAVELENGTH Division Multiplex (WDM) networks are evolving nowadays from simple topologies as point-to-point and ring to the general mesh topology. Optical Cross-Connects (OXCs) play a key role in the new-generation WDM networks as optically transparent switching systems, able to manage very high bit-rate data flows.

An OXC must implement the complex functions defined by the WDM Transport Protocol Layer [1], [2]. The most relevant of these in our context is lightpath switching: at an abstract level it is the mapping of an input to an output space/wavelength domain. The time variable is not involved since WDM networks are essentially circuit-switching (lightpath-switching) oriented. However, lightpaths are semi-permanent connections and OXCs are reconfigurable systems on the milliseconds time scale. An OXC must therefore be able to allow any kind of permutations of the inputs to the outputs without generating blocking conditions either in the space or in the wavelength domain. This is the main motivation to study and analyze OXC-architecture connectivity and blocking. The cost of the OXCs has also a very large impact on a WDM-network global cost [3]: complexity and cost reduction should thus be a strong guideline in OXC design. WDM and optical technology offer interesting design options because they allow to combine together in the same architecture switching devices operating on the space domain with devices operating in the wavelength domain.

The analysis of switching architectures operating in a bidimensional domain is not a novelty in the theory of switching: for instance, a large and established body of work has been developed in the past regarding electronic switching in the time and space domain (consider, e.g., TST and SSS switches). However, devices operating in the new WDM network environment are so different from classical electronic equipment that they deserve a separate analysis. This is still a rather unexplored frontier of switching theory. The theoretical model we are going to present is an attempt to give a contribution to this research subject. It is aimed at attaining two objectives: on the one hand it can be used to evaluate the blocking properties of an OXC architecture and on the other hand it can be used to ascertain how the switching function can be distributed between the space and the wavelength domain to reduce complexity. Both these analyses would be quite difficult if performed directly by relying just on the optical implementations: this is why we resorted to a pure spatial equivalent representation. After presenting the model (section II) we will show its application to some of the best known OXC architectures proposed in recent literature (section III) and then discuss the main design features that our model reveals (section IV).

II. SPACE EQUIVALENT MODEL DEFINITION

Figure 1 depicts the general functional scheme of an OXC, in which the various subsystems involved in lightpath switching can be easily identified [4]. We can notice that space switching

![Figure 1. Functional scheme of an optical cross-connect.](image)

of optical channels is one of the core subsystems of the node: it is implemented by means of an optical space switching fabric. The second fundamental subsystem performs wavelength conversion, and it is composed of a pool of wavelength converters. The combination of the space and the wavelength switching
subsystems provides for the nucleus of lightpath switching.

This model is very general and the various OXC implementations proposed by researchers in the last years may include all the subsystems or just a subset of them: OXCs can be classified according to the functional subset they implement. A particular classification criterion, among the several possible ones, subdivides OXCs according to their wavelength conversion capability [5]: Virtual Wavelength Path OXCs (VWP-OXCs) are equipped with at least one full-range converter per switched channel, while Wavelength Path OXCs (WP-OXCs) have no converter at all. The intermediate case of partial conversion (Partial VWP-OXCs) will not be considered in this paper.

A full functionality OXC, as described above, is able to perform switching in both the wavelength and the space domain. We are now going to develop a theoretical approach which allows to build the equivalent of an OXC architecture in the space domain. As we already mentioned, this approach can be very useful to analyze the blocking properties of the OXC architectures, and also to better understand the possibilities and the degrees of freedom that can be exploited in the cost-effective design of OXC architectures.

A. Basic elements and components

Let us consider the basic components of the OXC subsystems that are involved in the lightpath switching function. In a switching architecture operating in both the space and the wavelength domain the following components may be present (SET A):

- Fiber (Input/Output) Termination (IT/OT): it carries a multiplex of optical channels (lightpaths), each one at a given wavelength. The multiplex is characterized by a given wavelength reference-comb which depends on the WDM transmission system.
- Internal interconnection link: it is able to carry either a single-wavelength signal or a WDM multiplex of wavelength signals.
- Fixed wavelength Filter (FF): it selects a single lightpath from a WDM multiplex at a given fixed wavelength and rejects all the others; it is a passive component.
- Star Coupler (SC): an $N \times N$ passive optical device that reproduces in every output the same set of lightpaths which derives from the combination of all the lightpaths entering its inputs. The passive splitter (combiner) is the $1 \times N$ ($N \times 1$) version of the star coupler.
- Wavelength Demultiplexer (WDemux): it separates a multiplex of lightpaths in a set of separate lightpaths, thus performing the conversion of wavelength to space multiplexing domain; it is a passive component.
- Wavelength Multiplexer (WMux): it is the dual of the WDemux, thus performing the conversion of space to wavelength multiplexing domain.
- Fixed Wavelength Converter (WC): it switches the wavelength of an input lightpath to a fixed output value. It can be implemented by various technologies. The most common implementation up to now is opto-electronic: in this case it is often known as transponder.
- Tunable wavelength Filter (TF): it can be tuned at will to select one lightpath out of an input WDM multiplex; the wavelength of the selected lightpath can be anyone of the WDM comb. It can be considered an active device and its cost is higher that that of a FF.
- Tunable Wavelength converter (TW): an active device that switches the wavelength of an input lightpath to any wavelength of a WDM comb. It can be implemented in various ways (all-optical or opto-electronic), but in any case it requires the availability of a tunable laser source. Therefore its cost is higher than that of a WC.
- Optical space Switching Element (SE): it is a $2 \times 2$ (also $1 \times 2$ and $2 \times 1$) active device operating on either a pair of lightpaths or a pair of WDM multiplexed signals (depending on its implementation).
- Optical SNB Space Switching Matrix (SSM): it is a set of SEs suitably interconnected (by internal links) in order to compose an $N \times N$ strictly non-blocking (SNB) optical switching network. It can operate on single lightpaths or WDM multiplexed signals depending on its SEs. The most common topology used to arrange the SEs is the well known cross-bar topology (composed of $N^2$ SEs) [6].

Other special optical devices, such as multi-channel wavelength converters and Delivery and Coupling Switches (DCS) will be introduced later on in section III. Regardless of their physical implementation, these devices can be functionally considered combinations of SET-A devices.

We now define the set of devices that can typically be found in a switching system operating only in the space domain. It is understood that we are considering here the “paradigm” of a “traditional” electronic digital switch, applied to an optical environment.

The basic elements are in this case (SET B):

- Switch inlet (output): it is a port of the switching system able to accept one single signal (lightpath) as input (output).
- Internal interconnection link: as the inlet (output), it is able to carry one single signal (lightpath).
- Switching splitter: an $1 \times N$ active device able to route an input signal (lightpath) from its input to one of its outputs.
- Switching combiner: an $N \times 1$ active device able to select one of the input signals (lightpaths) that is routed to its output.
- Switching element: it is a $2 \times 2$ active device operating on a pair of signals (lightpaths). It can assume the cross or bar state.
- Strictly non-blocking Switching Matrix (SM): it is a set of SEs suitably interconnected (by internal links) in order to compose an $N \times N$ strictly non-blocking switching network. The most common topology used to arrange the SEs is the well known cross-bar topology (composed of $N^2$ cross-points). In the present work when referring to an SM we will implicitly assume it to be a cross-bar.

From the above lists we note that there is not a one-to-one correspondence between elements of the two sets: unlike SET A, SET B does not contain any passive elements. Moreover, the internal links of SET A are multiplexed, while those of SET B are not multiplexed.

B. Mapping rules

The difference between the two sets of components in section II-A is the starting point to find out a way to map an OXC in the space domain.

In this discussion we assume to have on one side a WDM OXC architecture represented in an implementation scheme.
A Lightpath (LP) is the basic traffic unit in an OXC. Each individual signal of the input and output sets of whichever OXC subsystem belongs to a lightpath. In the following development we will consider only OXC subsystems operating on transit lightpaths and we will neglect all the equipment performing lightpath add and drop (transmitters and receivers). This assumption implies that no new lightpath is generated and no lightpath is destroyed inside an OIP subsystem and the correspondence between the inlets and the outlets can be seen as set of connections. However, in a general OIP subsystem two situations can occur:

1. two lightpaths can collide, i.e. two different input signals \( (I_k, u_k) \) and \( (I_l, u_l) \) can be connected to one single output signal \( (O_{k'}, v_{k'}) \)
2. a lightpath can be split, i.e. one input signal \( (I_k, u_k) \) is connected to two output signals \( (O_{k'}, v_{k'}) \) and \( (O_{l'}, v_{l'}) \)

We will show later that some components of SET A can potentially enable such situations.

From the general class of OIP subsystems we can enucleate a class composed of all the subsystems for which the two following rules hold:

- **Collision Free Rule (CFR).** Two lightpaths having the same wavelength can not share a single output link in the optical implementation plane.
- **Lightpath Integrity Rule (LIR).** A given lightpath can never be split into two copies of itself on the output links.

In all the subsystems belonging to this class the correspondence between the sets \( \{ (I_k, u_k) \} \) and \( \{ (O_{k'}, v_{k'}) \} \) is biunivocal, \( K = K' \), and we can write:

\[
\{ (I_k, u_k) \} \leftrightarrow \{ (O_{k'}, v_{k'}) \}
\]

A single index \( k \) can now be used to identify signals both in the input and in the output sets: two connected \( (I_k, u_k) \) and \( (O_{k'}, v_{k'}) \) belong to the same lightpath. In the particular case in which \( K = m \cdot w = m' \cdot w' \) (square subsystem with complete set of inputs), the biunivocal correspondence is a permutation:

\[
\{ (O_{k'}, v_{k'}) \} = \Pi[\{ (I_k, u_k) \}]
\]

By permutation we mean a set of connections such that each input is connected to one single output and viceversa. The expression \( \{ I_k \} = \pi[\{ a_k \}] \) means that vector \( \{ I_k \} \) is obtained by changing the positions of the elements of vector \( \{ a_k \} \). If the subsystem is able to perform all the possible \( K! \) permutations, it is non-blocking. The classical concepts of strictly non-blocking and rearrangeable non-blocking [7] can be therefore readily extended to the bidimensional space-wavelength domain.

Let us now introduce the SEP representation. A OIP subsystem for which LIR and CFR hold is mappable to a SEP space switching matrix. First of all, the input(output) OIP domains have to be mapped on the input(output) SEP domains. To do this, each link connected to the subsystem in the OIP must be characterized by the number of lightpaths which can be multiplexed on it, i.e. by the link mux-factor \( l \). In the worst case, in order to comply with the CFR, \( l = w \) for an input OIP link and \( l = w' \) for an output OIP link. In many cases, however, the structure of the OXC architecture in the OIP guarantees that \( l < w \) or \( l < w' \), as we will show later on. Let us consider for simplicity the case of a regular OIP subsystem in which all the input (output) links have the same mux-factor \( l \). The
SEP set of inlets (outlets) will be composed of $n = m \cdot l_I$ ($n' = n' \cdot l_O$) SEP links which, we remind, are able to carry one single lightpath each. The mapping between the inputs of the OIP subsystem and the inputs $i$ of its SEP representation can be done as follows. A group of $l_I$ consecutive SEP inlets corresponds to each OIP inlet $I$; the elements of the group are numbered with $l_I \cdot i \leq i \leq l_I \cdot (i + 1) - 1$. An analogous mapping is done for the SEP outputs $j$.

A “one-to-one” relation is now defined between the input (output) of each lightpath in the OIP and its input (output) in the SEP. We can now define the basic mapping rule for the subsystems: an OIP subsystem is mapped on a $n \times n'$ SEP space switching matrix if, for each $0 \leq k \leq K$, the latter is able to set up a connection between the inlet and outlet $i_k$ and $j_k$ corresponding to the inlet and outlet $(I_k, u_k)$ and $(O_k, v_k)$ which are connected in the OIP by the former. We can visualize this in a graphical way:

$$
\begin{align*}
\{i_k\} & \leftrightarrow \{j_k\} \\
\downarrow & \\
\{(I_k, u_k)\} & \leftrightarrow \{(O_k, v_k)\}
\end{align*}
$$

The mapping of the OIP subsystem on the SEP switching matrix is based on the concept of functional equivalence: both the switching structures must be able to set up the same set of biunivocal correspondences.

The simple squared OIP subsystem with a complete set of inputs defined above is mapped on a square SEP space switching matrix with $n = n' = K$, performing the permutations \{j_k\} $= \pi\{i_k\}$. If the original OIP system is non-blocking, so must be its SEP image (i.e. it can set up all the possible $K!$ permutations). It will then be strictly or rearrangeable non-blocking according to the properties of the OIP subsystem.

After having clarified the theoretical framework of our approach, let us go back to the OXC. The first subsystem to be considered in the OIP is the OXC as a whole (the “subsystem” actually coincident with the system). Its inlets and outlets are coincident with the Input Terminations (ITs) and the Output Terminations (OTs). We will now make some assumptions to better identify the type of OXCs that we consider in this work. First of all, we will only refer to squared OXCs, i.e. with the same number of OTs and ITs: the ITs and OTs are therefore numbered respectively by $I$ and $O$ with $0 \leq I \leq M - 1$ and $0 \leq O \leq M - 1$. Secondly, all the input and output signals are encoded on a common comb of $W$ wavelengths. This particular set of wavelengths is the comb used in the network for optical transmission over the network fibers, and we can call it the reference WDM comb. In a WP-OXC which is not provided with wavelength conversion devices the reference comb will be the common wavelength comb of all the subsystems as well. In a VWP-OXC, instead, each subsystem can have different wavelength combs. An hypothetical OXC designer can use any set of wavelengths inside the VWP-OXC, but must always comply to the reference comb at the boundaries.

A third assumption we make is that we will consider OXCs which comply with both the LIR and the CFR. These rules hold for all the OXC architectures which do not perform optical channel multicasting at the physical level, i.e. in which an LP entering the switching node can not be transformed into more identical LPs at the OXC outlets. OXCs architectures able to perform multicasting have been proposed, but we will consider them only in a possible future extension of the present work. Since LIR and CFR hold, the number $K$ of lightpaths entering and leaving the OXC will be the same. We further assume that a complete set of inputs is offered to the OXC, and therefore: $K = M \cdot W$.

As a consequence of what we stated above, the OXC sets up biunivocal I/O correspondences, which are also permutations. The OIP representation of the OXC is therefore mappable on the SEP: since each IT and OT carries a multiplex of $W$ lightpaths ($l_I = l_O = W$), it will be mapped on an $N \times N$ space switching architecture, with $N = K \cdot W$, performing the same number of I/O permutations. The mapping between the input and output OIP bidimensional domains and the input and output SEP domains is very simple, and can assume an algebraic form, i.e.

$$
\begin{align*}
i & = I \cdot W + u \\
\downarrow & \\
j & = O \cdot W + v
\end{align*}
$$

We now explain how the OIP and SEP can be used to analyze the blocking features of the OXCs. We have stated that, under the assumptions listed above, an OXC architecture is mappable onto the space domain. If the SEP representation of the OXC can be proved to have certain blocking properties (e.g. to be rearrangeably or strictly non-blocking), given the functional equivalence between the two planes, also the OIP representation will have the same properties. The OIP architectures of the OXC can be decomposed in simple mappable OIP subsystems, whose blocking properties can be easily evaluated. The overall SEP equivalent of the OXC is therefore built as a multistage architecture composed of SEP subsystems of known blocking properties. At this point the classical and well developed theory of the multistage switching systems can be applied to the SEP architecture to ascertain the OXC blocking properties.

Starting from the OIP representation of a given OXC, the first step of the above procedure is the identification of the mappable elementary subsystems. This is not trivial. The LIR and CFR rules are defined for the inputs and the outputs of an OIP network. Therefore, the fact that the OIP overall architecture of an OXC is mappable onto the space domain does not imply that all its subsystems are mappable as well and comply with the LIR and the CFR.

Let us now develop an analysis to identify the most common elementary OIP mappable subsystems, starting from the devices of SET A. For the sake of conciseness, in the following of this section we will omit some of the formal details of each mapping.

The first component we consider is the OIP transparent optical space switching matrix. This device operates only on the space domain, regardless of the of the wavelengths of the lightpaths. Its OIP representation is characterized by $m$ and $n'$ inlets and outlets; the input and output wavelength domains are obviously coincident ($w = w'$). Since there is no wavelength operation, LIR and CFR are always respected. In the simple square case with a complete set of inputs ($K = m = n'$) the biunivocal I/O correspondence can be represented by the following notation: \{(O_k, v_k)\} $= \{(I_k, u_k)\}$, where \{I_k\} $= \pi,\{i_k\}$ and...
$\pi_s$ is a permutation. If the matrix can perform all the possible $m!$ permutations, then it is non-blocking in the space domain, and it can be rearrangeable or strictly non-blocking according to its internal structure. In all the examples that will be analyzed in Section III the OIP SSM are all strictly non-blocking in the space domain.

For what stated above, a SSM is always mappable on the SEP on an $n \times n'$ space switching matrix. Since a transparent SSM can not perform wavelength filtering by definition, the input mux-factor must be equal to the output mux-factor ($l_I = l_O = 1$). Therefore: $n = l_I \times m$ and $n' = l_O \times n'$. At this point, particular care must be taken to the blocking properties. In fact the lightpaths that are multiplexed on an OIP inlet are switched together as a bundle towards a common OIP outlet. This implies that if $l > 1$ the SEP equivalent matrix is blocking. Therefore we can state that if an OIP SSM is non-blocking in the space domain, this does not necessarily implies that it is non-blocking in the space and wavelength domain. In the particular case in which OIP inlets are not multiplexed ($l = 1$), instead, the SEP equivalent of a SSM is non-blocking and therefore also the SSM is non-blocking. In this case, the mapping between the input (output) OIP domain and the input (output) SEP domain is $i = l$ ($j = O$), and the biunivocal I/O correspondence in the SEP in the complete-input square case ($K = m = m'$) is

$$\{j_k\} = \pi_s[\{i_k\}]$$

where $\pi_s$ is exactly the same permutation of the OIP equivalent.

Let us consider now an array of $m$ tunable wavelength converters. They can be regarded as an OIP subsystem having $m$ OIP inlets and $n' = m$ OIP outlets, $w$ input and $w'$ output wavelengths. Since there is no space switching operation, LIR and CFR are always respected, and therefore, in principle, the SEP mapping is possible. However the direct mapping of a wavelength converter array, according to the mapping rules, would lead to an array of simple SEP links, which is a trivial and useless representation.

Another OIP component is the $m$-input passive combiner, which corresponds to an OIP subsystem with $w' = w$ and $n' = 1$. For this component the CFR does not hold and therefore it is not mappable onto the SEP.

The OIP subsystem composed by the cascade of an array of $m$ tunable wavelength converters and an $m$ input passive combiner, unlike the two latter subsystems, has a very interesting SEP mapping. For this subsystem the LIR always holds. Provided that $w' \geq K$, the CFR can be enforced by suitably configuring the wavelength converters so that the wavelengths of all the $K$ lightpaths entering the combiner are different. It becomes therefore mappable on an $n \times n'$ SEP space switching matrix. The OIP subsystem has $m$ inlets with mux-factor $l_I = 1$ and one single outlet on which at most $l_O = K$ lightpaths can be multiplexed, then $n = m$ and $n' = K$. In the simplest case, $m = K$ (complete input set) and we choose the minimum possible value of $m$ which is $w'$. The biunivocal I/O correspondence in the OIP must associate a different wavelength to any different OIP inlet. The mapping between the input (output) OIP domain and the input (output) SEP domain is $i = l$ ($j = v$). Therefore, the biunivocal I/O correspondence in the SEP is

$$\{j_k\} = \pi_w[\{i_k\}]$$

where $\pi_w$ is a permutation. If the array is composed of full-range converters (a signal can be converted to any possible $v$, regardless of its input wavelength $i$), then all the possible $K!$ permutations can be set up and the SEP matrix is non-blocking. By SEP mapping we have therefore proved that a passive combiner cascaded to an array of TWs is non-blocking in the space and wavelength domain. In particular, if the converters can be tuned independently from each other, the subsystem is also strictly non-blocking.

The dual OIP subsystem of the previous one is composed by the cascade of an $m$ output passive splitter and an array of $m$ tunable wavelength filters. With a reasoning similar to above it is possible to show that, while the individual mapping of the two stages is impossible or meaningless, taken together they form an optical mappable subsystem. This time the LIR must be enforced by suitably configuring the TFs and the SEP equivalent space switching matrix has $n = K$ inlets and $m$ outlets, which, in the simplest case where $m$ is chosen equal to the TF range $w$, becomes a $w \times w$ matrix. If the TF array is composed of (independently tunable) full-range devices, then the matrix is (strictly) non-blocking.

In a given OXC architecture, the arrays of tunable wavelength converters are not always directly connected to passive couplers as well as passive splitters are not always directly connected to arrays of tunable filters. Before passing to the space-equivalent plane we can however perform intermediate logic transformations on the OIP representation of the OXC. The arrays of TFs and TWs can in many situations be “moved” towards the passive elements by rearranging the OIP representation without changing the connectivity and functional properties of the OXC: this allows to create subsystems which can then be mapped onto the SEP. The situations we are referring to are the following: a) a passive splitter is connected to a transparent space-switching matrix, which is connected to a TF array; b) a TW array is connected to a transparent space-switching matrix, which is connected to a passive combiner. The sought mappable subsystems can be composed by exchanging the positions of the matrix and the TW or TF array in the overall OIP architecture. This transformation can be made without altering the OXC blocking properties, i.e. by obtaining a functionally equivalent OIP architecture. In the following we will show the proof of this statement only for the TF array and in a special case, being understood that the proof for the TW arrays is quite similar and the extension to the most general case is possible.

Let us consider then an OIP subsystem $S_1$ composed by an array $A$ of $m$ wavelength converters, operating on a common I/O set of $w$ wavelengths, connected to a matrix $B$, which is an $m \times m$ transparent SSM, with I/O mux-factor equal to 1. Then let us consider a subsystem $S_2$ composed of $B$ connected to $A$.

Theorem 1: The two OIP subsystems $S_1$ and $S_2$ defined above are functionally equivalent, provided that the array is composed of full-range wavelength converters which can be tuned independently from each other.

Proof: First of all we shall note that the LIR and CFR hold both in $S_1$ and $S_2$, since they hold separately for the array $A$ and the SSM $B$. Therefore the I/O correspondence is biunivocal both in $S_1$ and $S_2$, and thus we can assume the two subsystems to be crossed by a common set of $K = m$ lightpaths, identified
by the index \( k \).

Let us consider \( S1 \). \( A \) performs the conversion between the input set of wavelengths \( \{ u_k \} \) and a given set \( \{ u'_k \} \). \( B \) performs a preassigned permutation \( \pi_s \) in the space domain. The I/O correspondence of \( S1 \) is therefore: \( \{ (O_k, u_k) \} = \{ (I_k, u'_k) \} \), where \( \{ I_k \} = \pi_s(\{ I_k \}) \). Let us label the converters of \( A \) with an index \( 0 \leq a \leq m \), according to the index \( l \) of the \( S1 \) inlet to which they are connected. The converter \( a \) performs the conversion between the input wavelength \( u_a \) and the prefixed output wavelength \( u'_a \).

Now let us consider \( S2 \). In order to be equivalent to \( S1 \), this subsystem must set up the same I/O correspondence. \( B \), being transparent, can perform the same space-domain permutation as it does in \( S1 \), regardless the fact that lightpaths now have different wavelengths. The converters of \( A \), however, have to be retuned. In fact the converter \( a \) in \( S2 \) must perform a conversion between the wavelengths \( u_{b_a} \) and \( u'_{b_a} \). Here, \( b_a \) is the \( a \)-th element of the vector \( \{ b \} = \pi_s^{-1}(\{ a \}) \). \( \pi_s^{-1} \) is the inverse of the permutation performed by \( B \), such that \( \pi_s^{-1}(\pi_s(\{ a \})) = \{ a \} \).

Since by hypothesis converters are full-range and independent the retuning is always possible. Figure 4 represents a simple case of the swapping operation defined by this theorem.

III. SPACE-EQUIVALENT MAPPING OF MULTISTAGE OPTICAL-CROSS-CONNECT ARCHITECTURES

After introducing the space-equivalent plane representation we can show how it can be practically applied to OXC architectures taken from literature. For each of them, after showing its OIP representation, we obtain its SEP representation describing the mapping procedure. Then we analyze the blocking properties of the network in the SEP representation and on this basis we can ascertain whether the OXC is rearrangeable (RNB) or strictly non-blocking (SNB).

The blocking properties of the OXCs we are going to show are of course already well known in literature. However we developed the following examples mainly to show how a common and general method of blocking property analysis can be applied in the space-wavelength switching domain. The mapping operation leads to identify a basic structure common to all the architectures we have considered, which appear very different from each other when compared in their optical implementations. When mapped on the space equivalent plane they all result to be full-connection multistage switching systems [7], a general class which comprises networks such as Clos, cross-bar and cross-bar tree. Beside those presented here, other OXCs with full-connection multistage SEP architectures have been analyzed in ref. [10].

Many authors have proposed simplified OXCs which switch the incoming lightpaths only in the space domain [8], [4], [9], rather than performing wavelength conversion. These architectures will not be considered in this paper. However finding the SEP mapping of this kind of OXCs is quite easy because it can be proved that a WP-OXC having \( M \) ITs and OTs and \( W \) wavelengths per termination is equivalent to a set of \( W \) parallel \( M \times M \) switching matrices, mutually unconnected, each one operating at one single wavelength. Let us therefore apply the SEP analysis to VWP-OXCs.

The first group of VWP-OXCs we are presenting includes full-connection multistage architectures that are strictly non-blocking, as their space-equivalent analysis indicates. We recall that strictly non-blocking for an OXC means that a new connection defined both in the spatial and wavelength domains can always be set up without disrupting the other connections. All the architectures of the first group are represented in their OIP and SEP in figure 5, except when explicitly indicated otherwise.

The first OXC we analyze (OXC #1) has been proposed by Ken Ichi Sato [11], [4]. It is entirely based on switching in the space domain with fixed-output wavelength converters. The mux-factor of the OIP links is 1 thanks to the input wavelength demultiplexer and no star couplers are employed. Therefore its SEP representation is very straightforward. The OXC is strictly non-blocking. The number of SNB switching matrices in the three stages is \( M, 2W - 1, M \) and the matrices dimension are \( W \times (2W - 1), M \times M, (2W - 1) \times W \). The Clos condition for non-blocking in the strict sense regarding a generic three stage network [7] is \( r_2 = p + q - 1 \), where \( r_2 \) is the number of matrices in the central stage and the matrices of the first and third stage have dimensions \( p \times r_2 \) and \( r_2 \times q \), respectively. Therefore the Clos condition is satisfied in our case, since

\[
r_2 = 2W - 1 = p + q - 1 = W + W - 1
\]

An alternative implementation of OXC #1 has been also proposed (figure 6) [11], [4] which we call OXC #2. In this case the matrices of the third space switching-stage have been replaced by a set of passive star couplers. The fixed-output WC have been replaced as well by a set of ‘prefixed’ (i.e. placed right at the output of the input wavelength demultiplexers) tunable WCs. We can prove that this implementation is equivalent to OXC #1 by showing that their SEP representation are coincident. To do this we apply theorem 1 and move the WCs in a postfix position after the last stage: this is possible as the first and second space switching stages make up together a single transparent switching-matrix. The outputs of this matrix are connected in groups of \( 2W - 1 \) to the \( M \) output star-couplers, each one of which can accept at most \( W \) active inputs at non-coincident wavelengths, due to the CFR. Therefore each subsystem composed of \( W \) TWs and a coupler is mapped in the SEP...
Fig. 5. OIP and SEP representation of the SNB OXC architectures analyzed in the text.
representation on a $2W - 1 \times W$ space switching matrix. In conclusion we find again the SEP representation of OXC #1.

In our investigation we found also another group of OXCs that we do not consider in detail here, whose SEP representation is a multistage Clos network, based on a special optical device which is called Wavelength Interchanging Device (WID) [12], [13]. The various versions proposed in literature comprise 3 and 5 stage Clos networks and the general $x$ stage Clos architectures.

Many authors have proposed OXC architectures based on the Delivery and Coupling Switch (DCS). A $L \times Q$ DCS operates as a set of $L \times Q \times 1 \times 1$ star couplers preceded by a set of $Q 1 \times L$ transparent switching matrices. In particular authors of ref. [9] proposed the architecture that we will call here OXC#3. WCs are prefixed to the DCS: the CFR can be applied a first time to the CFR to the DCS inner star couplers: each of them can carry $W$ non-interfering LPs. The network is SNB. In fact the following condition is verified [7]

$$d = W = \min_{r_{ij}} = W$$

(1)

We are now presenting an OXC architecture (OXC #4), the implementation of which is based on a quite different concept compared to the others previously described. OXC #4 [9], [14] is represented in the OIP in figure 5. In this OXC all the switching functions are performed in the wavelength domain by means of a double set of fixed WCs and a set of tunable filters. The space domain structure of the network is extremely simple, consisting of just a large star coupler. The basic concept underlying this OXC is that each input LP is mapped on an internal set of $W \times M$ wavelengths and then mapped again on the transmission wavelength set at the appropriate output termination. The mapping of OXC #4 on the SEP is quite simple. The network structure obtained is a $W \times M \times W \times M$ cross-bar tree [7] inserted between the $M$ input WDemuxes and the $M$ output WMuxes. The two stages of the cross-bar tree are composed of $W$ switching splitters and switching combiners having, respectively, a fan-out and a fan-in of $W \times M$. They are interconnected by an EGS interstage pattern [7]. It is of course a SNB network. A particular aspect of this OXC is that the input wavelength-converters operate on WDM multiplexed signals, i.e. on a group of lightpaths simultaneously. This is possible only by employing all-optical wavelength-converters based on the wave-mixing phenomenon (multi-channel wavelength converters). Such devices are currently under study.

Other OXC implementations have been proposed where switching is partially performed in the wavelength and partially in the spatial domains, though double wavelength conversion is not required. One of these is OXC #5 [15]. In this architecture shown in figure 5 we can move the tunable filters and the WCs in front of the space switching matrices, applying theorem 1. We obtain the SEP network shown in figure 5, where the space switching function of the added matrices plays the same role of the tunability of the filters and the converters. More precisely the first stage corresponds to the set of filters: each input link may be sent to only one of the $M$ output OTs due to the LIR. The central stage corresponds to the application of the CFR to the tunable WCs. Due to the buddy property [7] of the interconnection stage between the second and the third stage in the SEP representation, the tunable WCs can be subdivided in $M$ groups each one connected to one OT. The interconnection stage is in fact a shuffle connection pattern [7]. We can further note that the matrices of the central stage are arranged in a shuffled order compared to the OTs they are connected to. The resulting overall network in the SEP is therefore a cross-bar tree with one intermediate switching stage of $M^2 W \times W$ matrices. The outer stages are composed of $M \times W$ switching splitters and combiners with fan-out and fan-in equal to $N$. Each input has access to $M$ central matrices. It is SNB since the size of the intermediate stage matrices is such that from each IT all the OTs can be reached, thus complying to the condition reported in ref. [7].

Also architectures that are rearrangeable non-blocking in the space-wavelength domain can be analyzed by our approach. Recall that the setup of a new connection in a rearrangeable non-blocking network can require the switching rearrangement of existing connections. As an example, let us consider the OXC scheme proposed by the same authors of OXC #3 [9]. It is reported in figure 7 and is called OXC #6. It requires a first stage of $M$ sets of $W$ tunable filters, a middle stage of $W \times M \times M$ space switching matrices and a final stage of $M$ sets of $W$ tunable WCs. The SEP representation (figure 7) can be readily found by applying theorem 1. The resulting space equivalent architecture is a three stage RNB Clos network. In fact the Slepian-Duguid theorem [7] is satisfied, i.e.

$$r_2 = W = \min_{r_{ij}} = W$$

(2)

IV. OXC-ARCHITECTURES QUANTITATIVE COMPARISON

In the previous section we have shown how similar architectures in the SEP correspond to very different optical implementations: an OXC with given blocking properties can be implemented in the OIP in a more or less wavelength-switching-intensive way (less or more space-switching-intensive). Which option is the best depends upon many factors concerning the device technologies, e.g. relative cost, loss, noise, integrability, etc. In this section we intend to present a quantitative compari-
son between OXCs exploiting the space-equivalent model. Our architectural analysis is device-technology independent, and it is therefore quite difficult to be too specific: the detailed characteristics of each implementation can be found, on the other hand, in the corresponding original papers. However our model allows to point out general guidelines which can be useful especially to design novel architectures.

Let us introduce some parameters to characterize an OXC in the SEP and the OIP. As usual, the OXC has $M$ ITs and OTs and operates on $W$ wavelengths. In the SEP we call $\Sigma$ the total number of switching points, obtained by summing the switching points of all the SMs; a $Q \times I$ SM gives a $\Sigma$ contribution of $QL$. We will call $\Sigma_s$ ($\Sigma_t$) the number of switching points deriving from the mapping of space-switching (tunable wavelength-switching\(^2\)) devices ($\Sigma_s = \Sigma_s + \Sigma_t$). $\Sigma$ and $\Sigma_s$ are reported in table I for all the OXC architectures analyzed in section III. The parameter $\rho = \Sigma_s / \Sigma_t$ in the third column gives an idea of the trade-off between space and wavelength switching measured in the SEP. Architectures entirely based on space (OXC #1) and wavelength (OXC #4) switching are immediately identified. In OXC #3 the switching function is evenly divided between the two domains. For OXC #2 and 6 $\rho$ increases with the spatial size $M$, while for OXC #5 it depends only upon $W$.

In the OIP, the OXC optical-hardware is characterized by the following parameter: $O_s$ is the number of optical switching elements composing the SSMs ($Q \times L$ SSM gives an $O_s$ contribution of $QL$); $O_t$ is the number of tunable wavelength devices ($\text{TFs and TWs}$) and $O_f$ counts the fixed wavelength devices ($\text{FFs and WC}$). From our model we could clearly show how the optical implementation has been exploited in many cases to simplify the OIP structure compared to the SEP. Let us define $\eta_s = \Sigma_s / O_s$ and $\eta_t = \Sigma_t / O_t$. These two parameters measure the “efficiency” of the optical implementation in terms of hardware requirement compared to an hypothetical electronic implementation of the same SEP architecture. From table I we notice first of all that the tunable wavelength devices, when employed, are at least equivalent each one to $W$ SEP switching points. In many cases an additional gain-factor $M$ is obtained for $\eta_t$. Moreover the implementation of OXC #3 and 5 is very efficient in terms of space-switching hardware ($\eta_t$). It can be shown that $\eta_t > W$ and $\eta_s > 1$ are attainable thanks to the employment of the passive splitters, having a higher optical loss as a drawback.

Finally, we would like to attempt a cost comparison. The per-channel complexity index in the SEP, $C_{SEP} = \Sigma / MW$, is reported in table II.

Cost evaluation in the OIP, being totally technology-dependent, is far more complicated. Therefore, the comparison we are going to propose must be considered as a very rough rule-of-thumb evaluation. Let us make the simplified assumption that tunable and fixed wavelength devices have all the same unit-cost and that this is $\alpha$ times the cost of a single SE. The total per-channel OIP cost is thus $C_{OIP} = [O_s + \alpha (O_t + O_f)] / MW$. Figures 8 and 9 represent $C_{SEP}$ and $C_{OIP}$ of the OXCs we have analyzed evaluated with: $W = 8$, a number of fiber-ports scaling from 2 to 20 and a value of $\alpha$ which seem realistic for current

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
OXC # & $\Sigma$ & $\Sigma_s$ & $\rho$ & $\eta_s$ & $\eta_t$ \\
\hline
1 & $(2W - 1)(2MW + M^2)$ & $(2W - 1)(2MW + M^2)$ & $\infty$ & 1 & - \\
2 & $(2W - 1)(2MW + M^2)$ & $(2W - 1)(MW + M^2)$ & $1 + \frac{W}{2MW}$ & 1 & $2W - 1$ \\
3 & $2M^2W^2$ & $2M^2W^2$ & 1 & $M$ & $MW$ \\
4 & $2M^2W^2$ & 0 & 0 & - & $2MW$ \\
5 & $2M^2W(2 + W)$ & $M^2W$ & $\frac{MW}{2MW + M^2}$ & 2 + $W$ & $\frac{2M^2W}{2MW + M^2}$ \\
6 & $MW(2 + W)$ & $M^2W$ & $\frac{MW}{2MW + M^2}$ & 1 & $W$ \\
\hline
\end{tabular}
\caption{Quantitative comparison of OXC architectures - A.}
\end{table}
WDM networks carrying lightpaths modulated at 10 Gbit per second. The most noticeable and unexpected outcome of the comparison is that OIP complexity can vary very different from SEP. For instance in some conditions rearrangeable architectures as OXC #6 can have equal or higher OIP cost than strictly non-blocking ones, such as OXC #3, 4 (for M > 10) and 5. OXC #4 results to be very scalable in the space domain, since its cost is independent of the number of fiber-ports. However, being entirely based on wavelength-switching, it is very sensitive to α and it can be cost-effective only when wavelength-device technology cost is of the same magnitude as optical-SE cost. The best performing architectures in all conditions tend to be those in which the switching function is evenly shared among the space and the wavelength domains (i.e. OXC #3).

V. CONCLUSIONS

We have presented a method enabling the analysis of various characteristics of the OXC architectures by mapping the space-wavelength switching domain on a purely spatial domain according to simple rules. This approach has led us to discover interesting properties of full-connection multistage OXCs and of their optical implementation by comparing them on the basis of their common fundamental structure. The model we propose, when suitably refined and adapted to real technological conditions, can become a useful tool in OXC design.

REFERENCES


