Design and performance of optical cross-connect architectures with converter sharing

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ABSTRACT

WDM techniques may be used to utilize the large bandwidth available with optical fibers. In the network context, this will allow lightpaths to be configured on demand between the various source-destination pairs using either wavelength-continuous or non-wavelength-continuous paths. Some degree of wavelength conversion capability would be desirable at the network nodes in order to use the network resources efficiently. This paper addresses the architectures that may be used to provide wavelength conversion in an optical cross-connect node where the converters may be shared either in a share-per-link or share-per node basis. Different ways of implementing OXCs with converter sharing using space-switching matrices, delivery-and-coupling switches and various combinations of couplers and filters have been presented. These OXCs are then compared in terms of various features like complexity, expandability, upgradability, degree of wavelength converter sharing and blocking probability performance under different traffic loading.

1 Introduction

Rapid developments in lightwave technology offer the potential of making huge bandwidths available in a single optical fiber. It would be possible to construct multiple-access networks with fiber links of 50 Tbps using the low-loss passband (1200–1600 nm) of optical fibers [1]. The bottleneck to this is typically the much lower speed of the optical-electrical interface. This may however be countered using *Wavelength Division Multiplexing* (WDM) and all-optical switching. By operating a large number of wavelength-multiplexed channels over each optical link in the network, WDM will be able to provide a good utilization of the overall network capacity. The high speeds attainable with each WDM channel will also make it attractive for use in future applications [2-4].

WDM networks may be realized using a wavelength routing mechanism to route different *lightpaths* between

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the various nodes of the network. In this kind of *wavelength-routed network* [5], the intermediate nodes switch optical signals from an incoming link to an outgoing one, preferably without any intermediate optical/electrical conversion. In an *all-optical wavelength-routed network* [6] of this type, an optical cross-connect switch (OXC) performs the routing and switching functions at each node. Note that the OXC is a switch, which will generally be controlled by the management layer while setting up or terminating lightpaths. It would therefore require less frequent and slower reconfiguration than if it were to be controlled by call traffic signaling.

The lightpath, representing the optical layer connection between the source-destination node pairs, can be set up through the intermediate OXCs in either a *wavelength-continuous* (WC or VWP, virtual wavelength path) or *non-wavelength-continuous* (NWC or WP, wavelength path) fashion. In the WC case, the same wavelength is used over the entire lightpath whereas, in the NWC case, different wavelengths may be used in different optical links along the given path. Setting up the lightpath would not only involve selecting the route to be followed but also the wavelengths to be used along the selected route. Various heuristic algorithms may be proposed for doing this—an example of this has been described and studied in [7].

Wavelength conversions at the intermediate nodes is necessary if NWC (WP) lightpaths are to be supported. This, however, would require the OXCs to do wavelength conversion in addition to their switching functions. The OXCs may, in turn, be classified based on their wavelength conversion capability [8]. An OXC without any wavelength conversion capability is called a *wavelength-selective cross-connect* (WSXC) whereas an OXC with full conversion capability (i.e. capable of changing any wavelength on any incoming link to any wavelength on any outgoing link) is referred to as a *wavelength-interchanging cross-connect* (WIXC). Examples of these have been shown in Fig. 1. Note that SSM refers to the space-switching matrix used to switch the optical signals without doing any wavelength conversion. The wavelength converters required have been shown separately.

Given the cost and complexity of wavelength conversion, an OXC with limited wavelength conversion capability may also be used as these have been observed to perform almost as well as WIXCs with full conversion capability [9] in typical network environments. These are referred to as *limited-wavelength-interchanging cross-connect* (L-WIXC). The limitation here is in the number of converters available for changing wavelengths between the inputs and the outputs. In an L-WIXC, a limited number of wavelength converters are shared instead of being dedicated as in a WIXC. The wavelength converters are therefore more efficiently utilized. The number of wavelength converters required can be further reduced with some optimization techniques [10]. Two architectures for L-WIXC are proposed in [11], namely the *share-per-node* and *share-per-link* architectures, as illustrated in Fig. 2. In the share-per-node architecture of Fig. 2(a), any converter from the common pool of C converters may be accessed by any of the incoming lightpath requests by appropriately configuring the $NW \times (NW + C)$ SSM. Only the lightpaths requiring conversion are actually directed to the converters. A second-stage $C \times NC$ SSM is used to switch the converted light paths to the desired output link. The share-per-link architecture of Fig. 2(b) provides a set of converters dedicated for each output link. These may be used only by the lightpaths intended for that link. In terms of sharing efficiency of wavelength converters, share-per-node is the best followed by share-per-link and WIXC the worst. In terms of complexity of switching, WIXC is the least complex, share-per-link comes next and share-per-node the most complex.

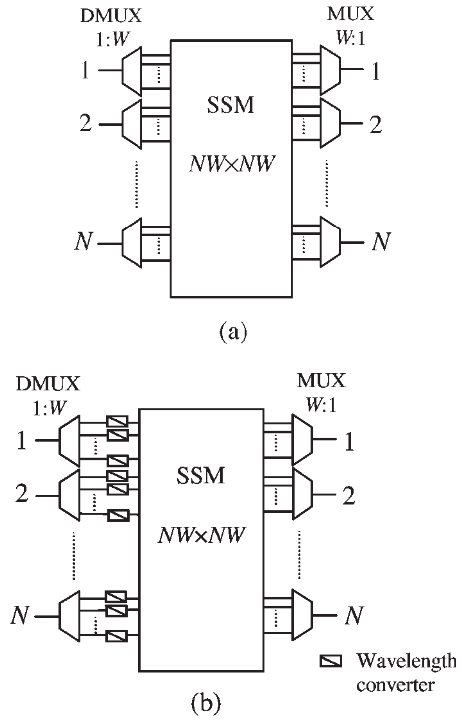


Figure 1: OXC Architectures (a) WSXC (b) WIXC.

Practical implementation of the OXCs often employs multi-stage structures to achieve the required size with less complexity [12-17]. Various OXC architectures have been proposed in these works; however, all of them are suitable for either WIXC or WSXC architectures. In addition, the multi-stage L-WIXCs may impose some restrictions in the sharing of wavelength converters, as in the share-per-link architecture. In this paper, we propose a number of multi-stage L-WIXC architectures and attempt to understand the various tradeoffs and their performance in the wavelength-routed networks.

Section II describes some basic elements for L-WIXCs. In Section III, we point out some issues related

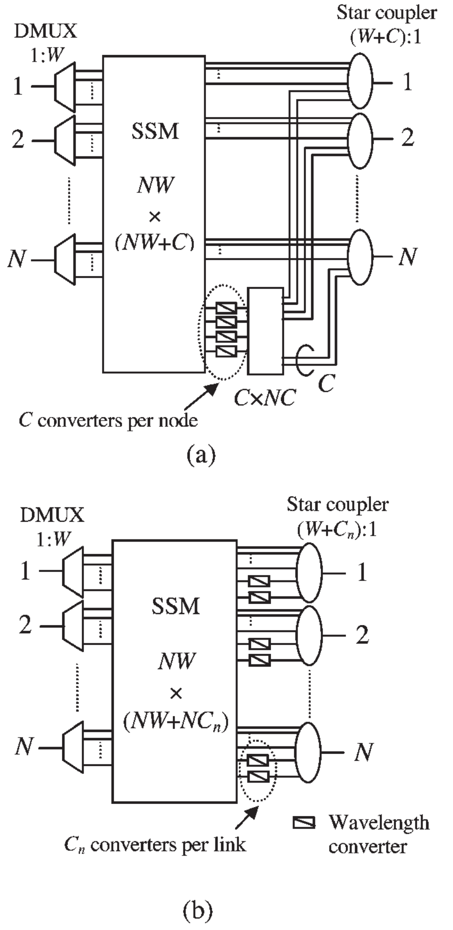


Figure 2: L-WIXC Architectures (a) Share-per-node (SSM-1) (b) Share-per-link (SSM-2).

to the L-WIXC architectures. Section IV presents a wide range of architectures that may be used to design such OXCs. Comparative studies of these and the corresponding simulation results are presented in Section V. Section VI ends the paper with conclusions and some suggestions for future work.

2 Basic Elements in L-WIXC

A basic element of an OXC is the *space switch* used to implement the *space-switching matrix* (SSM). There are a number of technologies available for space-switching in the optical domain, e.g. electro-optic material, interferometer, acousto-optic interaction, thermocapillary effect and micro-eletromechanical system (MEMS), as proposed and studied in [18-23] and large switching matrix can be constructed using basic 2×2 elements.

It is also possible to obtain the space-switching function using a *Delivery and Coupling Switch.* The DCS is based on star couplers and 1×2 switching elements arranged in an array, as shown. This could be a very flexible switch allowing, for example, multiplexing of multiple input signals to a single output [24]. We have shown an example of a $N \times L$ delivery and coupling switch in Fig. 3.

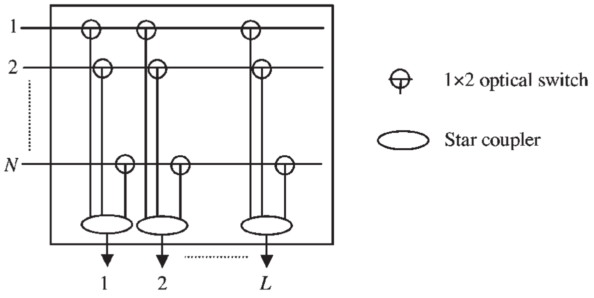


Figure 3: Delivery and Coupling Switch.

The other important element in an L-WIXC will be a wavelength converter to change from one input wavelength to a different output wavelength [25]. It is possible to do this with an *Opto-electronic Wavelength Converter,* which detects the optical signal and then retransmits it at a different wavelength. This has the advantage of doing signal regeneration and will allow considerable flexibility in network control and management. This method may not be preferred in high-speed networks, which would probably like to do *all-optical switching* for high bandwidth operations. One way of doing this would be through an *Optical Gating Wavelength Converter* employing an optical device that changes its characteristics depending on the intensity of the input signal. This change causes a continuous wave signal (called a “probe”) to be modulated with the information in the input signal. This category includes optical cross-gain and cross-phase modulators. *Wave Mixing Wavelength Converters* provide another way of achieving all-optical wavelength conversion. This utilizes the nonlinear interactions between optical signals in a nonlinear optical material to generate a signal at a different wavelength. This includes four-wave mixing based on third-order optical nonlinearities and difference frequency generation based on second-order nonlinearities.

3 Issues Arise from Multi-stage L-WIXC

In an L-WIXC, the degree of converter sharing will be an issue of concern, as the OXC will have only a limited number of converters. It would obviously be desirable to have an architecture where any converter may be used for any lightpath through the OXC regardless of its input and output links. In a practical scenario, this may not however be feasible and different architectures would allow different degrees of converter sharing.

Using standard switching terminology [26], the degree of sharing may be described as being (a) partial sharing, (b) simple full sharing, (c) rearrangeable full sharing, or (d) strict full sharing. An OXC supports *partial sharing* if each converter can be accessed by only a subset of all the possible lightpaths that may connect through the OXC. On the other hand, *simple full sharing* allows any lightpath to access any converter when the OXC does not have any established lightpath connections. If there are established lightpath connections, the existing lightpaths may prevent a new lightpath to access a wavelength converter even though the converter is not being used. With *rearrangeable full sharing,* the arriving request can be assigned a wavelength converter by rearranging the existing connections. *Strict full sharing* gives the greatest freedom in converter access as it allows any free converter to be accessed by any new lightpath connection independent of the state of the OXC.

Upgradability and expandability of the OXC designs would also be an issue of major concern when looking at different L-WIXC architectures. As traffic demands increase, the number of converters required will also tend to increase. An expandable OXC architecture would then be more desirable as it would allow the flexibility of adding more converters to the switch with very few structural changes. Further growth in traffic demand may also eventually require the L-WIXC to be upgraded to a WIXC, i.e. an OXC with full conversion.

4 Architecture of Limited-Wavelength-Interchanging Cross-Connects

We present next various OXC architectures based on space-switching matrices, delivery and coupling switches and combinations of couplers and filters.

4.1 L-WIXCs based on space switching matrix (SSM)

The basic L-WIXCs of this type had been shown earlier in Fig. 2. The L-WIXC with the share-per-node architecture will be referred to as SSM-1 and has been shown in Fig. 2(a). The corresponding share-per-link L-WIXC will be referred to as SSM-2 and is shown in Fig. 2(b). In SSM-1, the incoming channels are separated by the demultiplexers (DMUX). They are then routed by the SSM directly to the proper output (for wavelength-continuous lightpaths) or to the wavelength converters and then to the proper output (for non-wavelength-continuous lightpaths) by a second SSM. A *star coupler* is used instead of a multiplexer because the wavelength of the output from the second SSM is not known a priori. The first stage switching is an $NW \times NW$ SSM and the second SSM is of dimension $C \times NC$, giving a total of $N^2W^2 + NC^2$ cross-points. In addition, there are a total of N $1 \times W$ DMUXs, N $W \times 1$ star couplers. The degree of wavelength converter sharing is strictly full and SSM-1 represents an ideal share-per-node architecture.

The SSM-2 represents an ideal share-per-link architecture. Each output link has a dedicated set of converters that can be accessed by any channel from any input link. This is ideal because any request that involves a particular output link can be routed through any free converter in the dedicated set regardless of the switching state. It only allows partial sharing of wavelength converters. This has

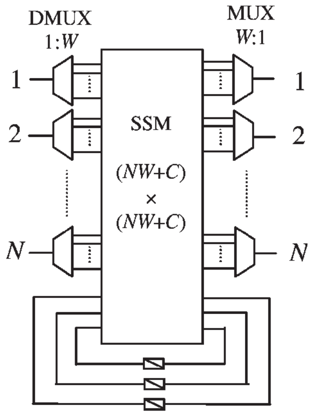


Figure 4: SSM-3 Architecture.

$N^2W^2 + NC_n^2$ cross-points, N DMUXs and N star couplers.

The SSM-3 shown in Fig. 4 is a variant of the SSM-1 architecture using recirculating lines. It uses less number of SSMs than SSM-1 but the size of the SSMs used is larger. As with SSM-1, strict full sharing is possible with this design. The total number of cross-points is $(NW + C)^2$. The switch may use a MUX in place of a star coupler because it is possible to configure the switch so that each output of the SSM corresponds to a fixed wavelength. The MUXs impose lower loss than star couplers and also act as filters to block all unwanted wavelengths from the wavelength converters eliminating the need for additional filters.

In practice, the switching function of an OXC is often implemented in multiple stages in order to reduce its overall complexity. SSM-4, as depicted in Fig. 5, is a multi-stage realization of SSM-1 with strict full sharing of wavelength converters. A combination of star couplers and tunable filters replace the DMUXs so that lightpaths of any wavelength can be routed through any of the M SSMs in order to avoid blocking. The number of SSMs, i.e. M, needed to achieve strictly non-blocking behavior and strict full converter sharing would be at least max

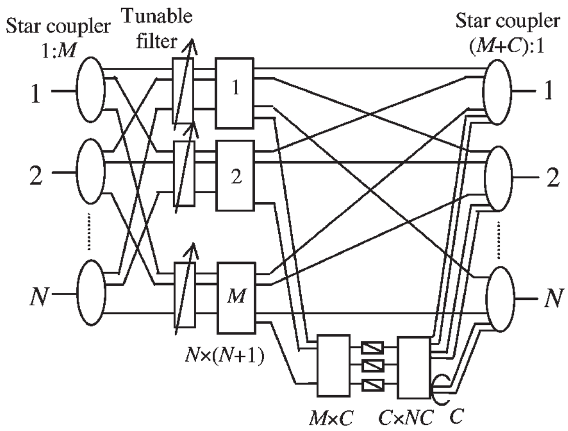


Figure 5: SSM-4 (Multistage) Architecture.

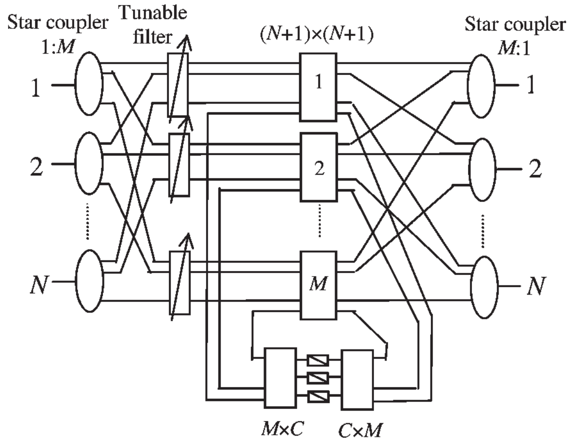
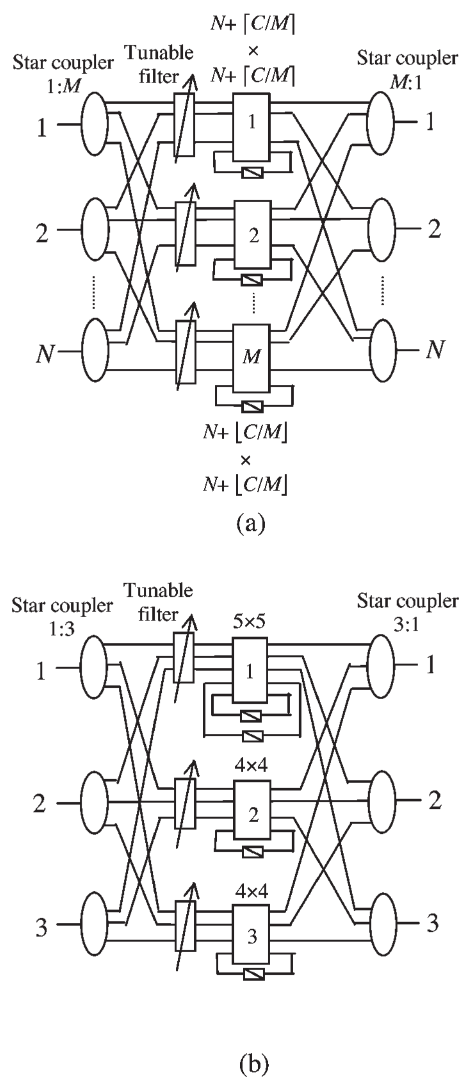


Figure 6: SSM-5 Architecture.

$\{W + C - 1, 2W - 1\}$ following the principle of a three-stage Clos network [26]. By applying a proper routing scheme, it is possible to have an ideal share-per-node architecture with $M = W + C - 1$. This scheme will route the unconverted lightpaths of i^{th} wavelength to the i^{th} SSM. However, if wavelength conversion is needed for a lightpath of the i^{th} wavelength, it will be routed to the wavelength converters through the i^{th} SSM or any of the $(W + 1)^{th}$ to $(W + C - 1)^{th}$ SSMs depending on their availability. It can be proved that there will always be at least one such SSM available. The converted signal on j^{th} wavelength will then be routed to the appropriate output by another SSM. This L-WIXC requires M $N \times (N + 1)$ SSMs, one $M \times C$ SSM, one $C \times NC$ SSM, $2N$ star couplers and NW tunable filters. The SSMs will have a total of $NM(N + 1) + MC + NC^2$ cross-points, $2N$ star couplers and MN tunable filters.

SSM-5 of Fig. 6 is a multi-stage implementation of the SSM-3 architecture. Similar to SSM-3, it is strictly nonblocking with strictly full wavelength converter sharing if $M = \max\{W + C - 1, 2W - 1\}$. The same routing scheme described for SSM-4 is applicable to this architecture. The converted signal on j^{th} wavelength will then recirculate into j^{th} SSM or any of the $(W + 1)^{th}$ to $(W + C - 1)^{th}$ SSMs and be routed to the appropriate output link. SSM-5 consists of $M + 2$ SSMs with a total of $M(N + 1)^2 + 2MC$ cross-points, $2N$ star couplers and MN tunable filters.

SSM-6 is a simplified version of SSM-5 with a smaller degree of converter sharing, as shown in Fig. 7(a). It allows only rearrangeable full wavelength converter sharing. If $M < 2W - 1$, it is possible that no route is available for unconverted lightpaths even though there are common unused wavelengths at both input and output. Therefore, the number of SSMs should be at least $2W - 1$ to avoid blocking of unconverted lightpaths. Let $K = C \bmod M$ (the remainder in the division of C by M), then M SSMs, K of which have $N + \lceil C/M \rceil$ input and output, while $M - K$ have $N + \lfloor C/M \rfloor$ input and output ($\lceil x \rceil$ denotes the smallest integer larger than x and $\lfloor x \rfloor$ the largest integer smaller than x), $2N$ star couplers and NW tunable filters are needed in this architecture. Fig. 7(b) illustrates an example with $N = 3$, $W = 2$ and $C = 4$.



(a)

(b)

Figure 7: SSM-6 (a) Architecture (b) Example.

A multi-stage implementation SSM-7 of a share-per-link architecture is shown in Fig. 8(a). As a share-per-link architecture, the wavelength converters here are partially shared. It has more limitations in sharing the converters than in an ideal case. This is because the maximum number of converters that can be accessed by the lightpaths coming from a particular input port or the lightpaths going to a particular output is limited to C_n. (In an ideal share-per-link OXC, the lightpaths coming from a particular input port would have had access to any required number of wavelength converters, even though this may be limited by the availability of such converters.) Moreover, the lightpaths that need no conversion may also go through the wavelength converters even though this is

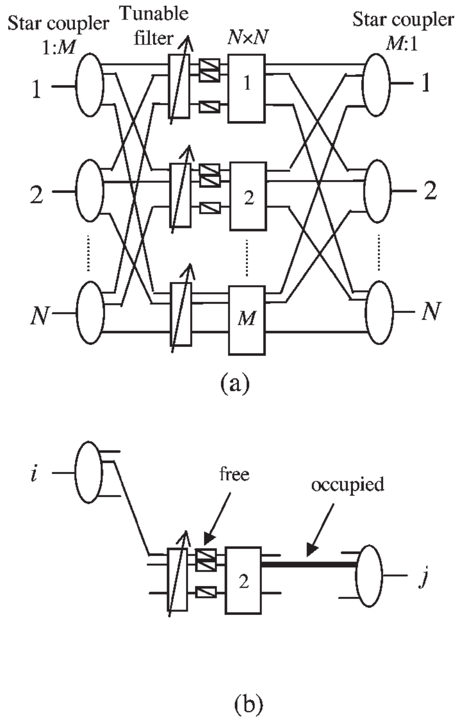


Figure 8: SSM-7 (a) Architecture (b) Link Mismatch.

not required. This wastes conversion resources through *wasteful occupancy.* A routing scheme that avoids routing the unconverted lightpaths to the wavelength converters can be applied to minimize wasteful occupancy. This scheme first searches the SSMs without attached wavelength converters for available routes before any other routes are tried. As in SSM-6, the number of SSMs should be at least $2W - 1$ to avoid blocking of unconverted lightpaths. If a routing scheme is employed such that all the unconverted lightpaths with the same wavelength are routed to the same SSM, only $W + C_n$ SSMs are needed to eliminate the blocking of unconverted lightpaths. Under this scheme, unconverted and converted lightpaths are routed to separate sets of SSMs, and only lightpaths requiring conversion can access the wavelength converters. There is therefore no wasteful occupancy. However, converted lightpaths can still be blocked when *link mismatch* occurs. For example, in Fig. 8(b), the converted lightpath cannot be established because of link mismatch, although wavelength converters are available. Additional wavelength converters can be installed, maintaining exactly the same structure and the architecture, to let this SSM be upgraded naturally to a full conversion capable OXC. This upgradability feature would be a big advantage of this OXC architecture.

4.2 L-WIXCs based on delivery and coupling switches (DCS)

We examine here some L-WIXC architectures using DCS. The first example of this is the DCS-1 architecture of Fig. 9, which supports strict full converter sharing. Those lightpaths from an input link that need conversion can be multiplexed to the $(N + 1)^{th}$ output of the corresponding DCS. The SSM located before each tunable filter selects one of the outputs from the star couplers and feeds it into the tunable filter to single out a particular wavelength. DCS-1 comprises N $W \times (N + 1)$ DCSs, C $N \times 1$ and C $1 \times N$ SSMs, N DMUXs, $3N$ star couplers and C tunable filters.

The second type of DCS-based OXC is shown in Fig. 10. It is similar to SSM-7 but because of the capability of a DCS to connect multiple inputs to one output, W DCSs are sufficient to avoid blocking of the unconverted lightpaths. Note that this is not possible in the SSM-7 architecture. Furthermore, if a wavelength converter is available in this architecture, then any converted lightpath can find its route through the OXC without the link mismatch problem. Wasteful occupancy can be minimized if routing unconverted lightpaths through the wavelength converters is avoided whenever possible. With $W + C_n$ DCSs, this routing scheme will completely eliminate wasteful occupancy.

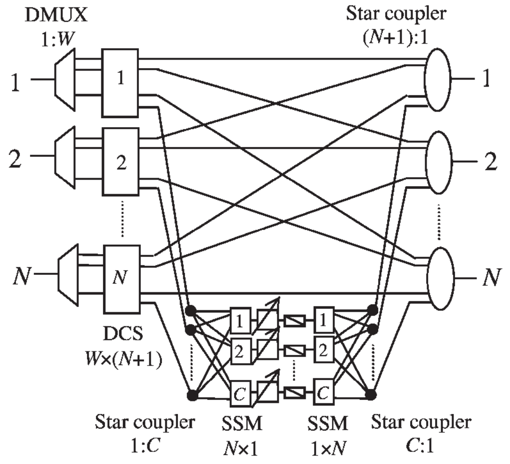


Figure 9: DCS-1 Architecture.

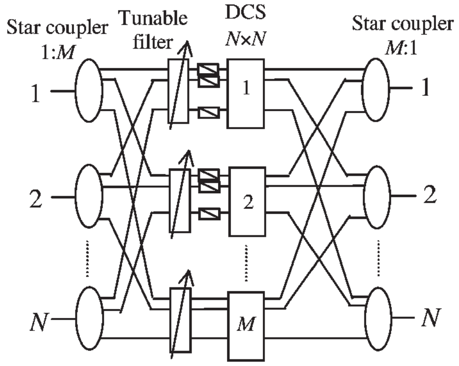


Figure 10: DCS-2 Architecture.

4.3 L-WIXC based on couplers and filters

A combination of star couplers and tunable filters may also be used as a switching element. The CF-1 architecture of Fig. 11 is composed of multi-wavelength selective filters (MWSF), tunable filters and star couplers. A MWSF can select any combination of wavelengths using acousto-optic interaction [27]. The MWSFs will be configured such that signals of the same wavelength are never led to the same star coupler. This limitation makes CF-1 an architecture that only allows simple full sharing of wavelength converters. There are N identical intermediate modules. In each of these modules, only C_n tunable filters are followed by wavelength converters.

In the CF-2 architecture of Fig. 12, the WDM comb from any of the N input links is delivered to every one of the $N \times 1$ SSMs. Each SSM inhibits all but one input comb. The tunable filter at the output of the SSM will then select a channel from the comb. This architecture allows strict full sharing of wavelength converters. For the architectures of Figs. 11 and 12, applying a routing scheme that searches first for routes without wavelength converters when routing unconverted lightpaths will minimize wasteful occupancy. OXCs based on couplers and filters generally suffer from high loss due to the splitting of WDM signals. However, as in the case of the SSM-7 architecture, they offer superior expandability and upgradability compared to the other architectures of the same kind.

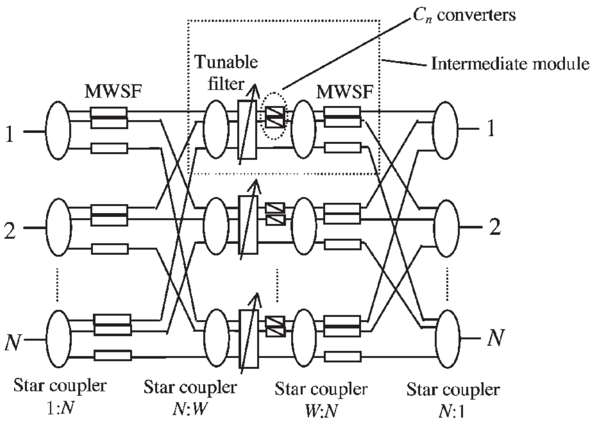


Figure 11: CF-1 Architecture.

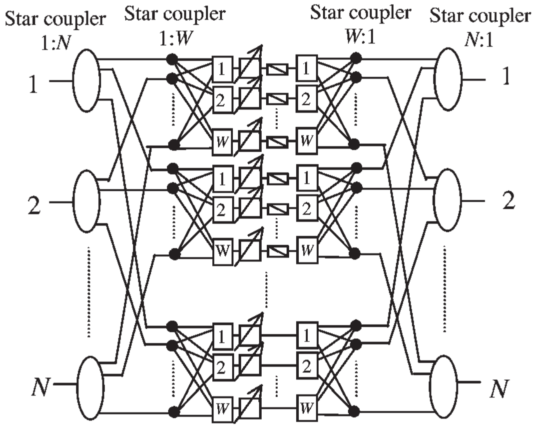


Figure 12: CF-2 Architecture.

5 Comparison of Various L-WIXC Architectures

The hardware complexity of different wavelength architectures may be listed as per their requirements of the basic hardware components, e.g. cross-points in the switches, tunable filters, star-couplers, demultiplexers and multiplexers. We have listed these requirements in Table 1. Given the actual values of N and W, this table may be used to make a comparative study of the relative hardware requirements of each of the L-WIXC architectures discussed earlier. Table 2 gives a summary of some of the key

Designation	Cross-point	Tunable filter	Star coupler	DMUX	MUX
SSM-1	$NW(NW + C) + NC^2$	–	N	N	–
SSM-2	$NW(NW + NC_n)$	–	N	N	–
SSM-3	$(NW + C)^2$	–	–	N	N
SSM-4	$NM(N + 1) + MC + NC^2$	NM	$2N$	–	–
SSM-5	$M(N + 1)^2 + 2MC$	NM	$2N$	–	–
SSM-6	$K(N + \lceil C/M \rceil)^2 + (M - K)(N + \lfloor C/M \rfloor)^2$ $K = C \bmod M$	NM	$2N$	–	–
SSM-7	MN^2	NM	$2N$	–	–
DCS-1	$NW(N + 1) + 2NC$	C	$3N$	–	–
DCS-2	MN^2	NM	$2N$	–	–
CF-1	–	NW ($2N^2$ MWSF)	$4N$	–	–
CF-2	$2WN^2$	NW	$2N(N + 1)$	–	–

Table 1: Complexity comparison of OXC architectures.

Designation	Degree of sharing	Wasteful occupancy	Expandability
SSM-1	strict full	no	poor
SSM-2	partial	no	poor
SSM-3	strict full	no	poor
SSM-4	strict full	no	poor
SSM-5	strict full	no	poor
SSM-6	rearrangeable full	no	poor
SSM-7	partial	yes	good
DCS-1	strict full	no	poor
DCS-2	partial	yes	good
CF-1	simple full	yes	good
CF-2	strict full	yes	good

Table 2: Comparison of OXC architectures.

features of the respective architectures in terms of the degree of sharing that they allow, whether wasteful occupancy is incurred or not and their relative expandability. The SSM-based and DCS-based share-per-node architectures generally require more complex switching than the WIXC. The multi-stage share-per-link architectures, on the other hand, appear very similar to the multi-stage WIXC architectures except that they have fewer converters. This also makes the share-per-link architectures easily upgradable to WIXC, as stated in Table 2. The share-per-node L-WIXCs using couplers and filters require no additional complexity and are generally easily expandable. However, extensive use of couplers imposes a high splitting loss.

The blocking performance of the OXC architectures is studied through simulation. For this purpose, the NSFNET, ARPA2 and a 16-node mesh-torus networks, as shown in Fig. 13 are used as sample networks to generate results. Each edge in the graph represents a bi-directional link that consists of two directed links in opposite directions with 16 wavelengths per directed links (as in [7,11]). The simulation model assumes that lightpath connection requests from the i^{th} node to the j^{th} node arrive from a Poisson process with mean arrival rate λ_{ij}. We also assume that the lightpath request arrival processes of different node pairs are independent of each other. We assume blocking such that a blocked lightpath request will be lost. The holding time for each such connection is exponentially distributed with mean h_{ij}. The traffic intensity (in Erlang) from the i^{th} node to the j^{th} node is given by $\lambda_{ij}h_{ij}$. Note that this allows asymmetrical bidirectional connection between any two nodes, which is quite common with data traffic. Each node has an infinite number of transmitters and receivers. The shortest path between the source and destination nodes is always followed to set up the lightpath. A first-fit wavelength assignment strategy is typically employed. However, the details of the implementation will vary for WIXC, WSXC and L-WIXC.

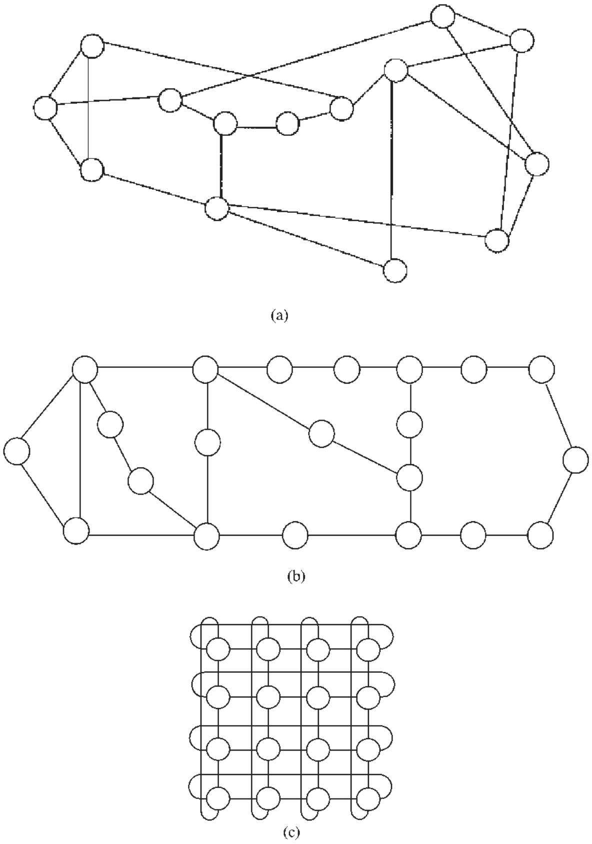


Figure 13: (a) NSFNET (b) ARPA2 (c) Mesh-torus.

To establish a lightpath, a wavelength channel needs to be assigned on each link traversed by the lightpath. For WIXC, the first available wavelength channel in each link is independently assigned to the lightpath. For WSXC, the first wavelength commonly available at each link along the lightpath is assigned. The wavelength converters in an L-WIXC may or may not be available when there is a request for lightpath connection. Because of this, lightpath establishment is more complicated in a network with L-WIXCs, as the availability of a wavelength converter in an L-WIXC is not guaranteed. However, a carefully designed lightpath establishment algorithm can reduce the number of wavelength converters required so that the converters are more efficiently shared. To set up a lightpath in a network with L-WIXCs, a wavelength-continuous path is first tried. If none is available, the first (nearest to the source) L-WIXC with an available wavelength converter is identified and a wavelength-continuous path is sought from the source to the L-WIXC. If this is successful, then a lightpath needs to be set up from that L-WIXC to the destination and this process is recursively applied to assign wavelengths to the lightpath from the source to the destination. This wavelength assignment procedure tends to reduce the number of wavelength converters used in setting up lightpaths even though the result may not be truly optimal. The steps for this are summarized in the following:

1. Make the source node the tagged node *i*.
2. Search for a wavelength-continuous path from node *i* to the destination, If it exists, set up the path.
3. Search for the first node *k* with an available wavelength converter and a wavelength-continuous path from node *i* to node *k*. If this is successful, set up the wavelength-continuous path. If this fails, the request is blocked.
4. Make node *k* the tagged node *i* and go to step 2.

In the simulated networks, an L-WIXC has C_n wavelength converters per link, or equivalently NC_n wavelength converters at a node with N input and N output links.

Fig. 14-16 plots the blocking probability of the simulated networks when SSM-7 architecture is used in the L-WIXCs. Amongst the proposed architectures, SSM-7 is the most restrictive in sharing wavelength converters. Even then, its blocking probability is observed to be close to that using WIXCs with only a small number of wavelength converters. Note that we only show results over a range where the blocking probability is reasonably low as this would correspond to a practical implementation. In fact, two separate factors contribute to the blocking observed. One is *link blocking*, when there is no available wavelength on one or more links traversed by the requested lightpath. The other is *node blocking*, when one or more nodes along the requested lightpath fail to accommodate the required configuration even though there is no link blocking. The latter will happen either because of the lack of wavelength converters at the node or because as routing path through the internal switching structure cannot be found. The results suggest the dominance of link blocking in these networks at higher traffic load. Similar trends are observed in different network topologies. It should be noted that the blocking probability is generally observed to be higher in the ARPA2 network because it requires more number of long lightpaths (maximum 8 hops) which would be more vulnerable to blocking.

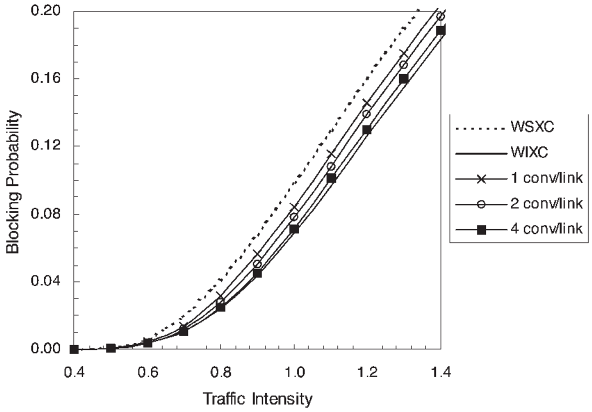


Figure 14: Blocking Probability of NSFNET network (conv/link—converters per link).

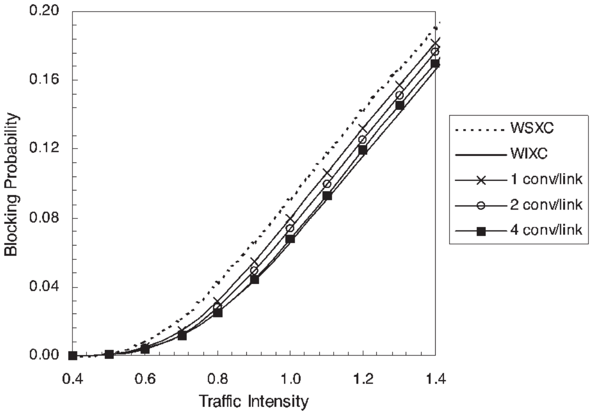


Figure 15: Blocking Probability of Mesh-torus network.

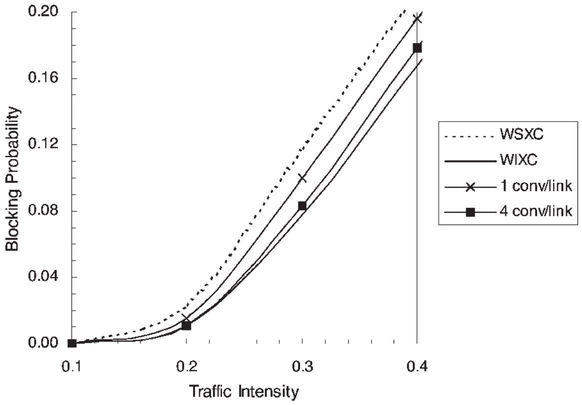


Figure 16: Blocking Probability of ARPA2 network.

In the histogram in Fig. 17, the blocking probabilities of the lightpath requests to the mesh-torus network are shown separately for lightpaths with different hop counts. The results indicate that wavelength converters can indeed improve fairness of access in addition to improving the overall blocking performance. In the network with WSXC, lightpaths with large hop counts are more vulnerable to the wavelength continuity constraint and tend to be blocked more often. Even with a limited number of shared wavelength converters in the L-WIXCs of

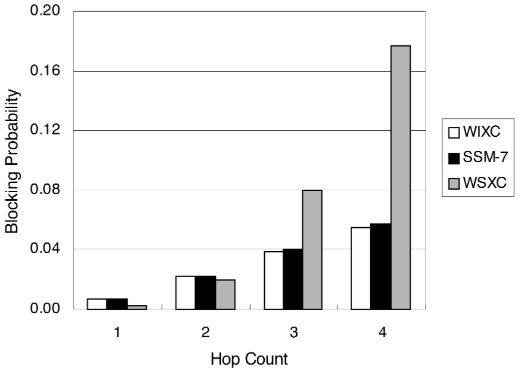


Figure 17: Blocking Probability of lightpath requests grouped according to hop count (4 conv/link, traffic intensity = 0.8).

SSM-7 architecture, fairness of access is significantly improved allowing long lightpaths a better chance to be admitted in the network. The corresponding results for the other architectures have not been shown since similar effects are observed in those cases as well. It should be noted that architectures that show greater flexibility in sharing converters than the SSM-7 architecture would also tend to give better overall results.

In general, the blocking probabilities of L-WIXCs reduce to that of WIXCs as the number of wavelength converters increases. This has been shown in Fig. 18 for the various L-WIXCs considered by us where the number of converters is expressed as a fraction (in percentage) relative to that needed in a WIXC. There is a sharp drop in the blocking probability of each share-per-node L-WIXC at around the 25% fraction of wavelength converters. The decrease in blocking probabilities of the share-per-link architectures, i.e. SSM-7 and DCS-2 is relatively moderate. These achieve a performance comparable to that of WIXC at about the 50% fraction of wavelength converters. Both curves for SSM-6 and CF-2 coincide with each other and with the curve for the ideal share-per-node, SSM-1. SSM-6 ($2W - 1$ SSMs), with its rearrangeable full sharing capability, is comparable to CF-2 in this because the blocking states actually occur very rarely. The drop in blocking probability is observed to be the slowest for SSM-7 because in this case, link mismatch may still prevent the free wavelength converters from being used. On the other hand, the structure of CF-1 requires that two signals with the same wavelength should not be routed to the same star coupler. This causes more blocked requests than the other architectures and therefore the blocking probability of CF-1 saturates at a level higher than the other architectures. However, it outperforms the share-per-link architectures when the number of converters is small because the wavelength converters are shared in CF-1 on a per-node basis. Fig. 19 plots the blocking probability against the number of converters at different traffic loads. The blocking probability decreases as the number of converters increases and saturates beyond certain threshold. At this threshold, link blocking tends to dominate, as the L-WIXCs will have enough wavelength converters to avoid node blocking. The threshold declines with the traffic load on the network.

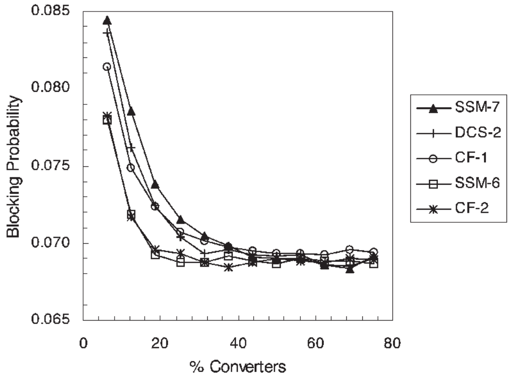


Figure 18: Blocking Probability vs. Fraction of Converters (Traffic intensity = 1).

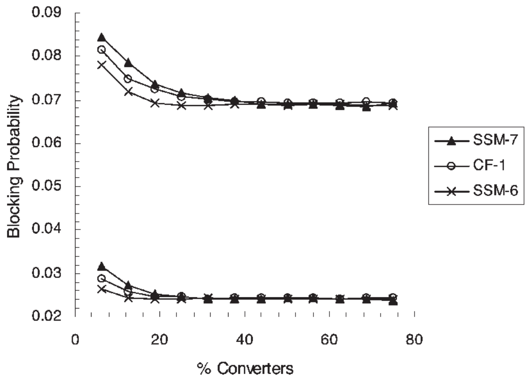


Figure 19: Blocking Probability vs. Fraction of Converters at different traffic load (Traffic intensity = 1).

6 Conclusions

We have addressed in this paper the architecture and performance of wavelength converter sharing in an optical cross-connect (OXC). Wavelength conversion would improve the blocking performance of an OXC by allowing more flexibility in the choice of wavelengths and routes for a lightpath between source and destination nodes. Since wavelength converter utilization is very low in a fully convertible OXC (WIXC), better use of converter resources may be made by allowing the converters to be shared, either in a share-per-node or in a share-per-link fashion. We see that this can indeed be achieved in L-WIXC architectures for converter sharing OXCs leading to efficient usage of the converters.

We have proposed a large number of different architectures that may be used to implement L-WIXCs. These differ in the degree of converter sharing and are implemented in different ways using SSMs, DCS or combinations of couplers and filters. We have studied the performance of the OXCs in terms of complexity, expandability, upgradability, blocking probability, and overall converter utilization. These results have been compared and presented here. Note that it is not possible to pick up any one of the architectures as the one offering the best solution for an L-WIXC to fit all applications. However, by considering the results presented here, a judicious choice may be made. The share-per-node architectures generally utilize the wavelength converters more efficiently than share-per-link architectures. The latter, on the other hand, trade efficiency in exchange for architectural simplicity. It should also be noted that the share-per-link architectures tend to be easy to expand and may also be made to evolve naturally towards a full conversion OXC without actually making any drastic structural changes. The L-WIXCs using couplers and filters are easy to configure in the share-per-node mode of operation.

These are both easily expandable and upgradable but will suffer from relatively high splitting losses.

To further investigate the proposed OXC architectures, the components may be modeled in greater detail to obtain other parameters like the loss, noise, and cross-talk characteristics. Such an analysis will be needed in network design and planning to determine the power budget, receiver sensitivity, and the fiber span amplifier gain and regeneration distance. The main noise effects arise from the accumulation of the amplified spontaneous emission (ASE) introduced by the wavelength converters and amplifiers. Imperfect filtering, on the other hand, would cause cross-talk between the wavelength channels.

Each wavelength conversion technique exhibits its unique characteristics. This allows the design of OXCs that exploits these features. On the other hand, the design of OXCs should be able to overcome the physical constraints of the wavelength converters. For instance, simultaneous conversion of a number of wavelengths using four wave mixing (FWM) or difference frequency generation has been demonstrated though this suffers from a drastic drop in conversion efficiency with the increase of the conversion range. Moreover, the conversion range of a wavelength converter is limited by the tunability of its pump laser in most wavelength converters. L-WIXC design that tolerates limited range conversion while retaining high performance may therefore be necessary.

It has been shown that the L-WIXCs achieve almost the same blocking probability as the WIXCs. Since wavelength converters would be a scarce commodity, it is desired to have a design framework that efficiently places the correct number of converters in each OXC in an optically cross-connected network, given the topology and traffic pattern of the network. In a network designed in this way, each OXC would be equipped with a limited number of converters that are efficiently utilized while at the same time providing the necessary conversion for a satisfactory performance.

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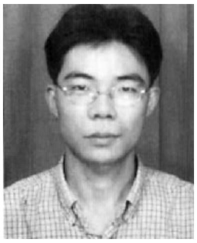

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