

Optical Crossconnects of Reduced Complexity for WDM Networks with Bidirectional Symmetry

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Abstract— One promising approach to provisioning and restoration in long-haul wavelength-division-multiplexing (WDM) networks is to deploy a mesh of optical crossconnects that operate on individual wavelengths. As wavelength-count and traffic demand rapidly increase, however, this approach will likely require high-port-count optical crossconnects that severely strain the capabilities of known device technologies. Thus, it is critical to devise ways to build large crossconnects from a small number of constituent switches, each with reduced port count. We present a general means of accomplishing this for networks, such as current long-haul networks, that demonstrate bidirectional symmetry. We describe a broad class of symmetry-exploiting architectures that yield $N \times N$ crossconnects, both rearrangeably nonblocking and strictly nonblocking, using constituent switch fabrics no larger than $N/2 \times N/2$. By exploiting connection-symmetry, these architectures reduce the number of such $N/2 \times N/2$ fabrics by 30%–50% compared with corresponding fully connected three-stage Benes and Clos switch structures.

Index Terms— Communication switching, multistage interconnection networks, optical switches, wavelength-division multiplexing.

I. INTRODUCTION

NETWORK providers face the need to satisfy user demand both for significantly higher network capacity and for improved reliability. The associated point-to-point capacity needs are now rapidly being met by wavelength-division-multiplexing (WDM) transmission systems; however it has become increasingly important to find new approaches to provisioning and restoration in high-capacity systems. One such approach is to configure optical crossconnects in a mesh topology, with the crossconnects operating on individual wavelengths transporting high-speed signals at OC-48 rates and above. As network demand continues to surge, it is expected that large long-haul offices will within ten years need to provision and restore hundreds of such OC-48's. Providing full reconfigurability via a crossconnect of such a large number of lines requires a switching matrix beyond the capabilities of current technology, both optical and electronic. However, current long-haul networks typically demonstrate bidirectional symmetry in the desired connections, e.g., if input A is connected to output B, then input B is connected to output

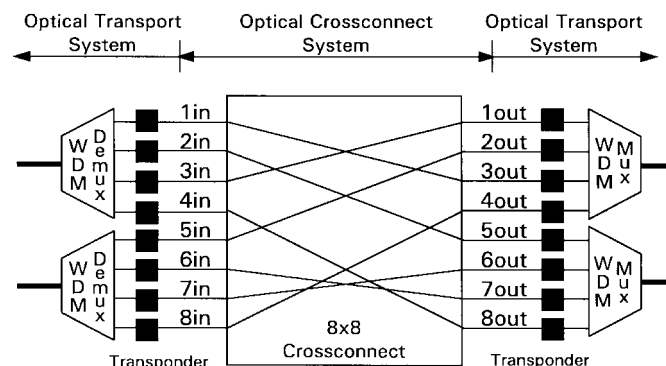


Fig. 1. An example of an 8×8 crossconnect with only symmetric connections established. The crossconnect operates on individual wavelengths delivered by the optical transport systems.

A. By exploiting this symmetry, the complexity of the overall switching matrix can be reduced, as we show below.

We present a symmetric crossconnect architecture for both the rearrangeably nonblocking and the strictly nonblocking cases, where in both architectures, an $N \times N$ crossconnect is constructed from constituent switch fabrics no larger than $N/2 \times N/2$. Partitioning a large switch into smaller component switches is a familiar technique as exemplified by the well-known Benes and Clos architectures that support arbitrary traffic. For the special case of symmetric traffic, we describe architectures that eliminate roughly 30%–50% of the hardware used in three-stage Benes and Clos architectures. The symmetric rearrangeably nonblocking architecture presented here uses one $N/2 \times N/2$ switch while the corresponding fully connected three-stage Benes architecture uses two; the symmetric strictly nonblocking architecture employs two $N/2 \times N/2$ switches while the corresponding fully connected three-stage Clos architecture uses three.

In a fully connected $N \times N$ crossconnect, there are N inputs and N outputs, with the number of possible crossconnect states being: $N \bullet N - 1 \bullet N - 2 \bullet \dots \bullet 1 = N!$. With current optical technology, crossconnects on the order of 32×32 are commercially available [1]. It is thus important to seek ways of accommodating larger port-counts. We do this by limiting the possible connections to those that are symmetric (in so doing, we also eliminate the possibility of connecting input A to output A); Fig. 1 shows an 8×8 switch where all established connections are symmetric. With such a symmetric arrangement, the number of possible crossconnect states is reduced to $N - 1 \bullet N - 3 \bullet N - 5 \bullet \dots \bullet 1$. This product

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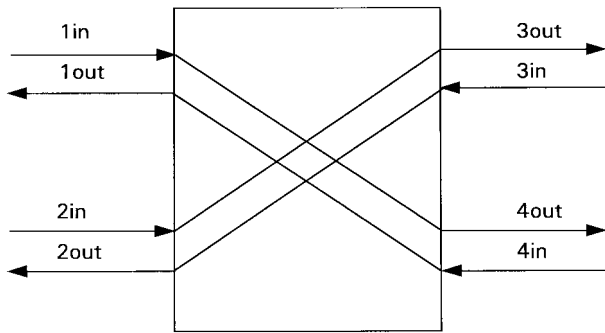


Fig. 2. A 2×2 bidirectional crossconnect in the cross state. Bidirectional pair 1 is connected to bidirectional pair 4, and bidirectional pair 2 is connected to bidirectional pair 3.

satisfies

$$2^{N/2-1} \left(\frac{N}{2} - 1\right)! < N - 1 \bullet N - 3 \bullet N - 5 \bullet \dots \bullet 1 \\ < 2^{N/2} \left(\frac{N}{2}\right)!$$

Since the number of states is bounded above by $2^{N/2}(N/2)!$, it is in principle possible to construct such a switch using $N/2$ 2×2 switches in conjunction with one fully connected $N/2 \times N/2$ switch. The largest required switch matrix is thus $N/2 \times N/2$, not $N \times N$.

II. BIDIRECTIONAL CROSSCONNECTS

In order to satisfy the requirements of a system with bidirectional symmetry, it is convenient to make use of what we will refer to as “bidirectional crossconnects.” Fig. 2 illustrates a 2×2 bidirectional crossconnect in the cross state. The distinguishing feature of a bidirectional crossconnect is that links are switched in pairs. In this example, bidirectional pair 1 is connected to bidirectional pair 4, and pair 2 is connected to pair 3.

To be concrete, such a bidirectional switch could be implemented, for example, by modifying the free-space micromachined matrix switch described in [2]. Each micromirror can be designed to reflect two lines, as opposed to a single line, as shown in the 2×2 example of Fig. 3. Flipping a micromirror to the up position automatically forms a connection between bidirectional links. With the mirrors in the position shown in the figure, the connection pattern of Fig. 2 is realized.

III. REARRANGEABLY NONBLOCKING ARCHITECTURE

An example of a symmetric architecture making use of the minimally required number of switching modules described above (i.e., $N/2$ 2×2 s and one $N/2 \times N/2$) is illustrated in Fig. 4, for N equal to 8. All of the crossconnects in this figure are bidirectional, as defined in the previous section. The links that are paired up in the 2×2 switches at the top of the figure are arbitrary; any pairing works. In order to interconnect links, it is necessary to set the 2×2 switches such that the links to be connected are directed to opposite sides of the $N/2 \times N/2$ switch, and then set the strictly nonblocking $N/2 \times N/2$ switch. We prove below that this can always be

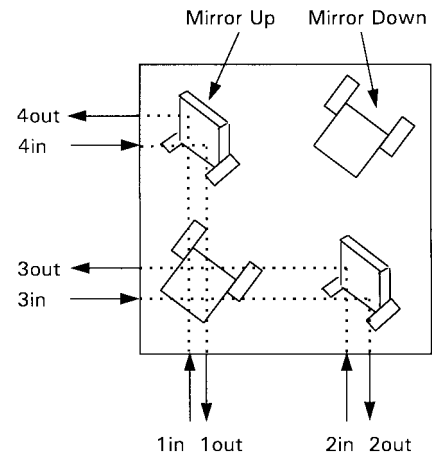


Fig. 3. A 2×2 grid of micromirrors can be used to construct a 2×2 bidirectional crossconnect. The position of the mirrors shown in this figure matches the connection pattern of Fig. 2.

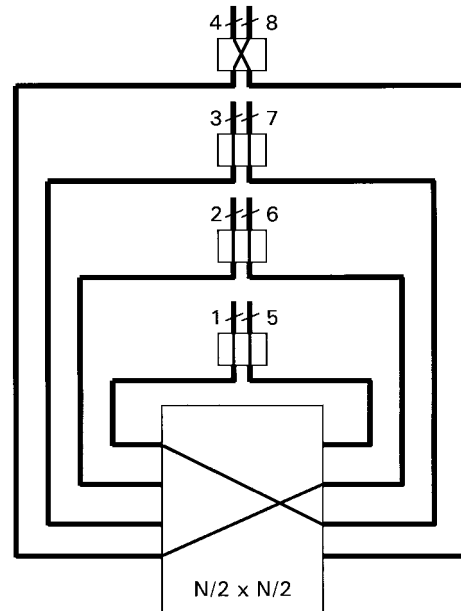


Fig. 4. A rearrangeably nonblocking switching architecture comprised of one $N/2 \times N/2$ switch, and $N/2$ 2×2 s. In this example, N equals 8. Each of the lines in the figure represents a bidirectional link. In this example, 1 is connected to 7, and 6 is connected to 8.

done for any fixed set of desired connections. Fig. 4 shows the connections of bidirectional lines 1 and 7, and 6 and 8.

In a strictly nonblocking architecture, it is possible to add any connection without disturbing any of the connections already established, regardless of the algorithm used for establishing connections. This architecture does not satisfy this condition. For example, in Fig. 4, we cannot add a connection between 4 and 5 without rearranging already established connections. (Lines 4 and 5 are both forced to the “right side” of the $N/2 \times N/2$ crossconnect).

The architecture is, however, rearrangeably nonblocking. In a rearrangeable nonblocking switch, if we know *all* connections that need to be established, then it is possible to find an arrangement that accommodates all connections. The strategy is to avoid a situation where two links that must be connected

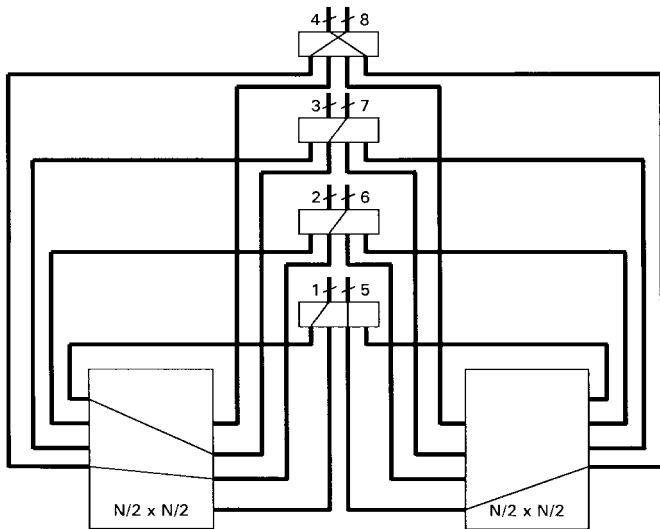


Fig. 5. A strictly nonblocking switching architecture comprised of two $N/2 \times N/2$ switches, and $N/2$ 2×4 s. In this example, N equals 8. Each of the lines in the figure represents a bidirectional link. In this example, 1 is connected to 7, and 6 is connected to 8 using the $N/2 \times N/2$ on the left. In order to connect 4 and 5, the second $N/2 \times N/2$ is needed.

are “forced” to be on the same side of the $N/2 \times N/2$ switch, thus making their interconnection impossible.

For example, the following algorithm can be used to set up the connections. Define a “pair” to be the two links in a given 2×2 switch. For example, in Fig. 4, 1 and 5 are pairs, 2 and 6 are pairs, etc. We will use the superscript “ p ” to indicate a pairing; e.g., $1^p = 5$. The algorithm maintains two sets: set D contains all links that have been successfully connected, and set P contains all links that are not involved in an established connection but whose pair is a member of set D . Any connection is chosen as the first connection to be established; assume it is a connection between links i and j , so that links i and j are placed in set D . i^p and j^p are placed in set P (unless $i^p = j$). Notice that i^p and j^p will be forced to opposite sides of the $N/2 \times N/2$ switch. The next connection to be established should be any pairing involving a link in set P , i.e., i^p or j^p . If there are no links in set P , then any remaining connection can be established. Following this algorithm, where connections are always chosen for the links in set P (if P is nonempty), then there are never more than two links in set P , and these two links will always be forced to opposite sides. Links that are neither in set D nor set P may be directed to either side. Thus, the scenario where a connection must be established between links forced to the same side of the $N/2 \times N/2$ switch can never occur. As an example, if the desired connections are: $1 \leftrightarrow 7$, $2 \leftrightarrow 3$, $4 \leftrightarrow 5$, $6 \leftrightarrow 8$, then the algorithm will add them in the following order: $1 \leftrightarrow 7$, $4 \leftrightarrow 5$, $2 \leftrightarrow 3$, $6 \leftrightarrow 8$.

We compare this architecture to a conventional fully connected three-stage Benes architecture which is also rearrangeably nonblocking [3]. In order to construct an $N \times N$

switch using switches no larger than $N/2 \times N/2$, the Benes architecture uses N 2×2 s and two $N/2 \times N/2$ s. By limiting the switching states to only symmetric connections, we use only 50% of these switches, although each one is bidirectional. Note that in both the symmetric architecture and the Benes architecture, there is a need to provide interconnecting fibers between the switches.

IV. STRICTLY NONBLOCKING ARCHITECTURE

The architecture of Fig. 4 can be modified to produce a strictly nonblocking switch. If a second $N/2 \times N/2$ is added, and the $N/2$ 2×2 s are replaced with 2×4 s, we have the strictly nonblocking architecture of Fig. 5. Consider the connection of bidirectional links i and j . At any given time, both i and j have at least three choices of outputs on their respective 2×4 , directing them to three out of the combined four sides of the two $N/2 \times N/2$ switches. Thus, it must be true that on at least one of the $N/2 \times N/2$ switches, link i can be directed to one side and link j can be directed to the opposite side, thus enabling a connection to be made. This proves that Fig. 5 is strictly nonblocking.

This architecture can be compared to a conventional fully connected three-stage Clos architecture which is also strictly nonblocking [3]. In order to construct an $N \times N$ switch using switches no larger than $N/2 \times N/2$, the Clos architecture uses N 2×3 s and three $N/2 \times N/2$ s [3]. As in the rearrangeably nonblocking case, constraining the system to support only symmetric connections reduces the number of required $N/2 \times N/2$ switches by one.

V. CONCLUSION

By constraining a crossconnect system to support only symmetric connections, the case of chief practical importance in long-haul networks, one can substantially reduce their complexity. Both rearrangeably nonblocking and strictly nonblocking symmetric architectures were demonstrated where $N \times N$ symmetric switches can be constructed using no switch larger than $N/2 \times N/2$. The number of required $N/2 \times N/2$ switches in the symmetric architecture is one smaller than in the respective Benes and Clos fully connected three-stage architectures. Such economies are expected to grow rapidly in importance, as swiftly rising demand makes monolithic $N \times N$ crossconnects either technologically unattainable or economically unfeasible.

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