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Design and Analysis of a Multicasting and Fault-Tolerant Optical Crossconnect for All-Optical Networks

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Abstract. This paper proposes an optical crossconnect (MFOXC) architecture that supports multicasting and fault tolerance. First, a tap-based and two splitter-based MFOXC node architectures are presented for wavelength routed all-optical networks. Compared to the existing optical crossconnects, the proposed MFOXC node not only performs multicasting efficiently but also improves reliability significantly. The MFOXC introduces a new feature (fault tolerance) and keeps the multicasting capability. It can be used at some critical points in a network to improve the overall reliability and multicast performance. Furthermore, the probability of maintaining fault free operations has been investigated for both MFOXC architectures. We present our evaluation results with a commonly used reliability measure, the mean time between failures (MTBF). Finally, we have proposed the cost and the sensitivity analysis for these MFOXC structures. The cost model and the sensitivity analysis show that the cost reduction in different components has various different impacts on the total cost of a MFOXC architecture. It can help us to know which component dominates the total cost and how to make a decision to choose among different MFOXC structures. The simulation results show that (1) the decrease of 75% in the cost of the $N \times N$ switch will result in the reduction of 20% in the total cost of the tap-based MFOXC, (2) the 1×2 switch has a big impact on the cost of the splitter-based MFOXC structures, and (3) the variation in the cost of the splitter does not introduce significant disadvantage to the type II splitter-based MFOXC structure.

Keywords: wavelength routing, fault tolerance, multicast, all-optical networks, wavelength division multiplexing

1 Introduction

As the internet traffic continues to increase exponentially, a wavelength division multiplexing (WDM) network with terabits per second per fiber becomes a natural choice as backbone in the next generation optical internet. This results in the introduction of wavelength routed all-optical networks (WRAON) [1]. For a WRAON, circuit switching is preferred since the optical technology for implementing the intermediate node buffering, header recognition and processing, which are indispensable for packet switching networks, is not available yet [2–3]. In such a system, network failures could interrupt a large number of communication sessions in progress, such as voice and data. As a result, the design of a WRAON must incorporate mechanisms to protect against potential failures, such as node failures, link failures, channel failures, and optical switch failures.

On the other hand, multicasting (for one-to-many or many-to-many communications) is important and increasingly popular on the Internet (IP over WDM). For a WRAON, the optical crossconnect (OXC) plays an important role to realize switching. The OXC supports point to point connections which has been intensively investigated [4–6], and point to multipoint (multicasting) connections [7–11] because a lot of future broadband services are multicasting ones.

For WDM multicast, a (optical) switch needs to have the light splitting capability in order to be able to multicast data in the optical domain. To realize optical multicasting, one can utilize optical power splitters. A power splitter is a passive device used to distribute the input signal to all outputs; thus providing multicasting in the optical domain without buffering. The inevitable power loss requires the deployment of amplifiers to compensate for the splitting loss. In addition, cross-connects which are able to satisfy all

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the different multicast demands must be equipped with a splitter for every wavelength on every input fiber link.

Several OXC structures where proposed to support multicasting [7–11]. Five classes of multicasting OXC exist. First, a star coupler with inherent multicasting capability is used to construct a class of OXC [7]. But wavelength converters and tunable filters are required to work in a large wavelength range. Second, two-stage splitters and one-stage combiners are used to construct another class of OXCs [7–8]. Third, a splitter-combiner switch that has inherent multicasting capability is employed to construct another class of OXC [9]. Fourth, a splitter-and-delivery switch (SaD) is proposed to build OXCs [10]. Fifth, a tap-and-continue switch (TaC) [11] is also built to form OXCs with zero power splitter. All these OXCs support multicasting. Note that switches with spilitting capability are usually more expensive to build than those without. Due to this reason, many researchers selectively let the switches in a network have splitting capability [12], which means that only a subset of the switches in a WDM network supports light splitting. These researches all focus on designing an OXC with multicasting capability, but without fault tolerance.

The fault-tolerance is one of the most important measures in optical quality of service (QoS). Hence, in order to achieve protection against failures, spares must be provided for the corrupted traffic to be restored. It is also desirable that these failures should endeavor to be handled within the optical network layer, rather than by higher layers. With the advent of WDM techniques, it is possible to provide redundancy by means of spare wavelengths (channels) and switches. Several simple failure restoration techniques for WDM mesh networks have been proposed in Armitage et al. [13], Baroni et al. [14], Miyao and Saito [15], Crochat and Boudec [16], Caengem, et al. [17], Dighe et al. [18], Shiragaki and Saito [19]. These researches all focus on designing failure restoration techniques, but without taking the OXC structure into consideration. In addition, the impact on network reliability and cost of the development of the optical transport layer, optical networking, and optical networking elements are an active area of investigation. The OXCs are envisioned as elements that can improve network reliability. The other parameters in terms of modularity, fanout capability, and power distribution are very important for designing the network. Therefore, in this paper we will propose a series of multicasting and fault-tolerant optical crossconnect (MFOXC) architectures and compare them in terms of modularity, fanout capability, power distribution, reliability, and cost sensitivity.

The rest of this paper is organized as follows. Section 2 introduces the basic architecture of the MFOXC. Two different types of MFOXCs will be presented. We also compare them in terms of modularity, fanout capability, and power distribution between the tap-based MFOXC and the splitter-based MFOXC. Section 3 describes the reliability model and requirements for analysis. Section 4 proposes the reliability evaluation and cost analysis for different MFOXC architectures. Section 5 concludes this paper.

2 Node Architecture

2.1 Architecture

Fig. 1 shows a WDM all-optical network employing wavelength routing, which consists of OXCs interconnected by optical links. Each OXC node includes a workstation $(A, B, \ldots, E)$ and an optical switch $(1, 2, \ldots, 5)$. Each link is assumed to be bidirectional and consists of a pair of unidirectional physical links.

An optical crossconnect is a device capable of routing a wavelength on an input link to any output link. However, two input links with the same wavelength cannot be routed simultaneously onto an output link, e.g., the link from node D to node C in Fig. 1. If there are m wavelengths on each link, the OXC may be viewed as consisting of m independent optical switches, one for each wavelength as shown in Fig. 2.

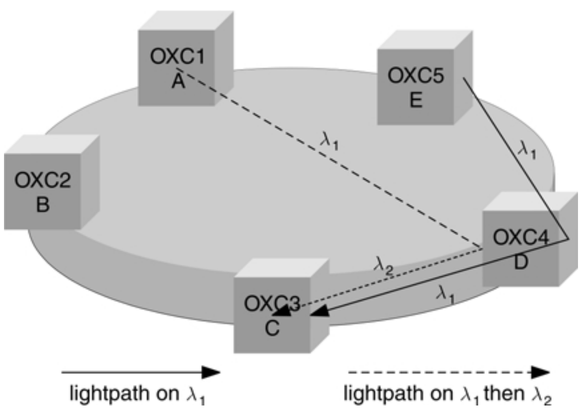


Fig. 1. A WDM network with OXCs interconnected by fiber links.

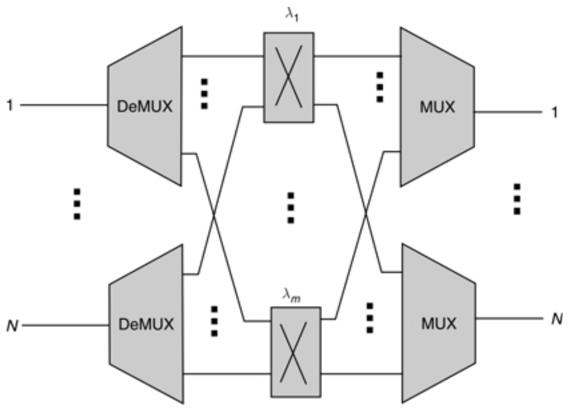


Fig. 2. An OXC without wavelength converters.

Each optical switch has N inputs and N outputs where N is the number of input/output links. There are no optical-to-electrical (O/E) and electrical-to-optical (E/O) conversions, and hence no buffering is needed at the intermediate nodes in these all-optical networks.

The effect of wavelength converters on the signal quality bas been investigated by adding converters to the OXC. Wavelength converters are often desired in the OXC to make the network management much easier and reduce the blocking probability because of their signal regeneration and noise reduction capabilities [20–22]. Fig. 3 shows an OXC with wavelength converters. The drawbacks of the wavelength converter include not only the added higher cost and complexity to the system, but also the single fault problem. If the central optical switch is faulty, the whole OXC will fail if no redundancy is provided at the node level. In addition, the crosstalk problem can be serious if the number of wavelengths is large. In contrast, the OXC without converters in Fig. 2 can tolerate a single fault in an optical switch. This is because any nonfaulty optical switch can replace a faulty optical switch and the resulting OXC can still be functioning with all the wavelengths except the wavelength used by the faulty optical switch. As for fault tolerance capability, an OXC without converters is superior to an OXC with converters. But for network performance (in terms of wavelength reuse), the reverse is true. For designing a highly reliable MFOXC in this paper, we adopt the MFOXC architecture without wavelength converters. In the following we will propose two different types of MFOXCs, tap-based and splitter-based.

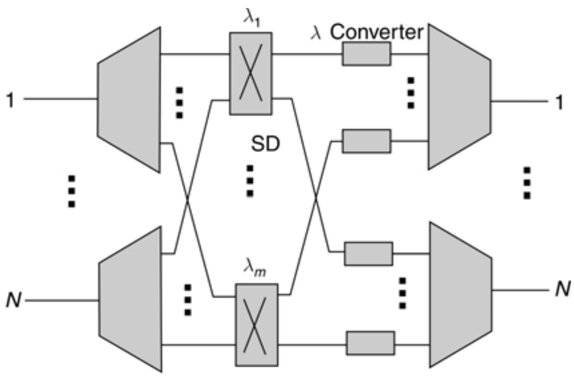


Fig. 3. An OXC with wavelength converters.

2.1.1 Tap-based MFOXC

Fig. 4 shows an implementation of an $N \times N$ tap-based MFOXC. The tap-based MFOXC is an OXC with multicasting and fault tolerance capability, which uses wavelength-dependent optical switches (or mechanical switches). It uses a set of tap-and-continue modules (TCMs) on the right side of Fig. 4(a). In the TCM1 shown in Fig. 4(b), an extremely small fraction of the input signal P_{in} (e.g., (1/1000) P_{in} [23]) is tapped and forwarded to the local station. The remaining power of the order of 99.9% is switched to the other $(N-1)$ outputs. The tapping device used is fully programmable so that the tapped signal power is determined by the signal to noise ratio (SNR). To switch the signal to any of the $(N-1)$ outputs, Fig. 4(c) shows that the tapping devices (Tap) are used to implement the TCM4. A $1 \times N$ TCM module has $\lceil \log_2 N \rceil$ stages where stage i has twice the number of taps compared to stage $(i-1)$. Fig. 4(d) shows an example of a TCM8. An input signal is tapped in using a tapping device. A small fraction of the signal power is directed toward the local station, while the rest continues to a multistage network of taps. By controlling the voltage on these taps, an input can be connected to any output port(s). Hence, the TCM8 module can support multicasting traffic in the optical domain by controlling the voltage on these taps. For example, a multicasting session with destinations 1, 4 and 5 shown in Fig. 4(d) can be achieved by controlling the voltage on TCM1 and TCM4. The destinations 1, 4 and 5 have the signal power distribution 25%, 25% and 50%, respectively and all other nodes do not consume power. Therefore, this architecture saves extra power consumption when a node is not a destination.

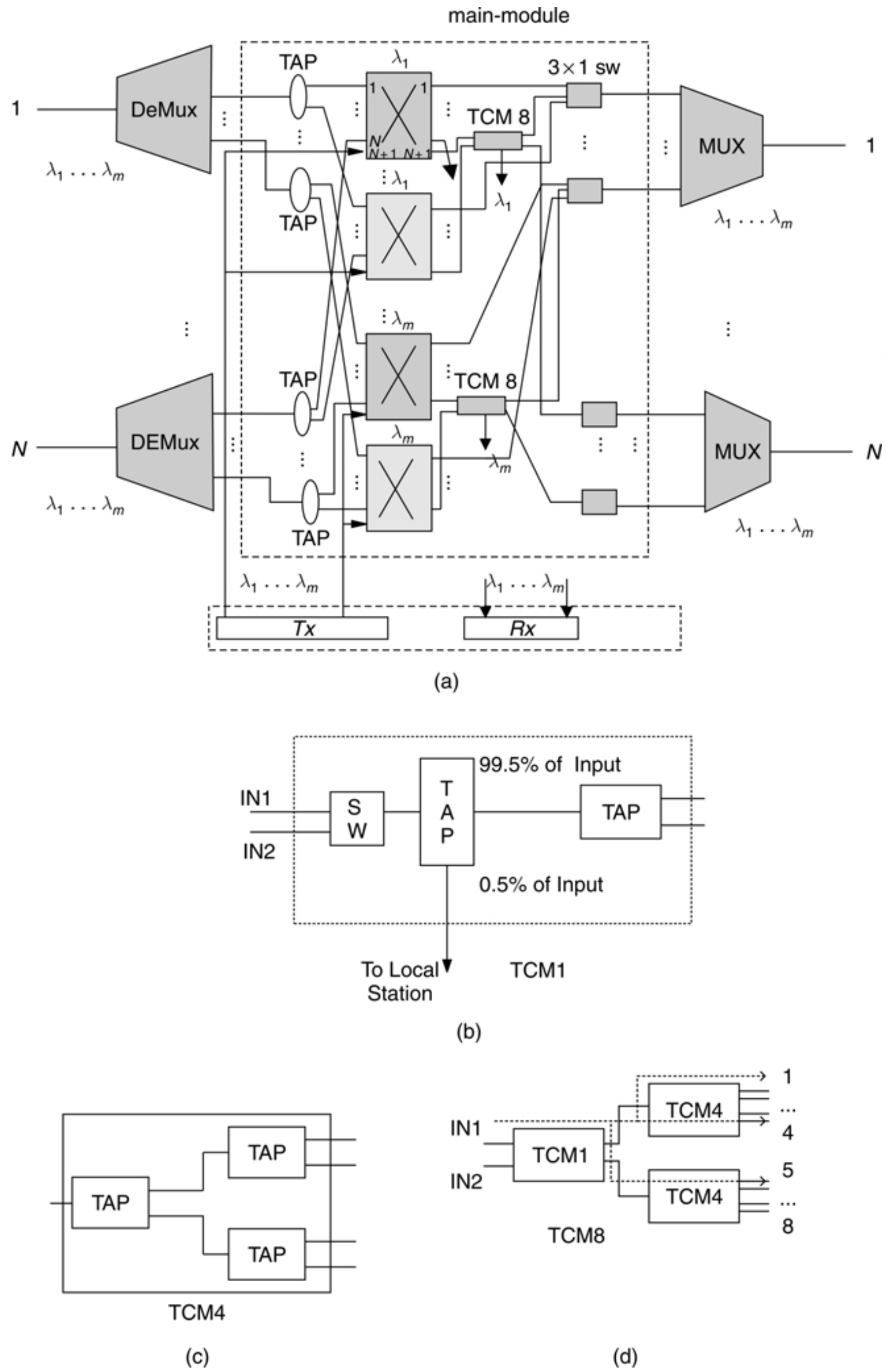


Fig. 4. (a) Structure of a tap-based MFOXC, (b) TCM1 module, (c) TCM4 module, (d) TCM8 (with $\lceil \log_2 N \rceil$ stages).

In order to improve the fan-out capability of the multicast, the MFOXC needs to increase the level of TCM modules. The power distribution is limited in our design. For example, the power distribution in 8(16) destinations is about 12.5% (6.25%) of the original source power. If the limitation of power distribution is exceeded, we need to add some extra optical amplifier. The optical loss can be compensated with optical amplifiers (e.g., EDFA (erbium doped fiber amplifiers) or SOA (semiconductor optical amplifiers)) properly distributed in the MFOXC (not shown in the figure).

On the other hand, the 2×1 SW element shown in Fig. 4(b) and the 3×1 SW element shown at the right side of Fig. 4(a) are used to select the alternative port of switch for normal operation, fault tolerance, or multicasting.

The TAPs shown at the left side of Fig. 4(a) are used to select switches in the MFOXC. A small fraction of the signal power is directed toward the fault tolerant switch, while the rest continues to a normal switch. The benefit of a tap is that all the signal power is directed toward the normal switches in normal operation mode. Only little signal power is transferred to the fault tolerant switch. However, if the normal switch is faulty, by controlling the taps, the signal power is directed toward the fault tolerant switch. Because this behavior occurs in the optical domain, no other restoration in the higher level needs to be considered. It is also desirable that failures should endeavor to be handled within the optical network layer, rather than by higher layers.

In addition for routing and switching signals, the MFOXC also serves as a source and sink of traffic in the network by an array of multi-wavelength transmitters and an array of multi-wavelength receivers, respectively. The source (sink) is the start (end) of a connection. Each inbound link and outbound link has its associated receiver (Rx) and transmitter (Tx), respectively. The bottom of Fig. 4(a) shows that each Tx or Rx is realized by an array of multi-wavelength transmitters or an array of multi-wavelength receivers, respectively. Each optical switch is extended with one additional port to support inbound link and outbound link for multicast. The resulting MFOXC has $2N$ optical/mechanical switches with $(N+1)$ inputs and $(N+1)$ outputs as compared to N inputs and N outputs in Fig. 2.

2.1.2 Splitter-based MFOXC

The splitter-and-delivery (SaD) is a cross-connect with multicast capability that was proposed in Hu and Zeng [10]. A cross-connect consists of a set of SaD switches (see Fig. 5(a)) for each wavelength. A SaD switch consists of an interconnection of power splitters, optical gates (to reduce the excessive crosstalk), and photonic switches. Fig. 5(b) shows the organization of a cross-connect based on the SaD switch. In addition to the SaD switches, demultiplexers (multiplexers) are used to extract (combine) individual wavelengths. In the following we will propose two types of splitter-based MFOXC.

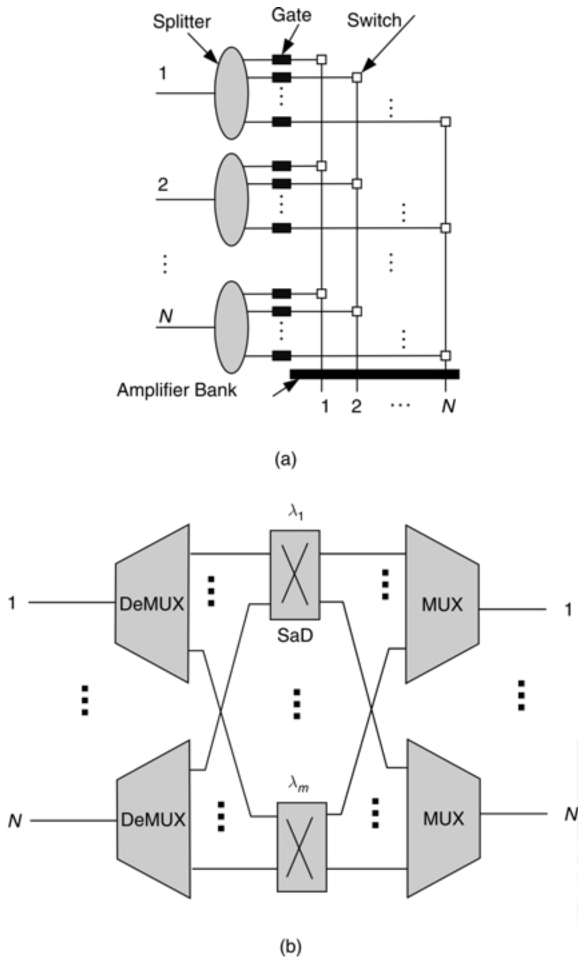


Fig. 5. (a) An SaD switch, (b) an $N \times N$ optical cross-connect based on the SaD.

Type I

Fig. 6 shows an implementation of an $N \times N$ splitter-based MFOXC. Its architecture is based on the SaD switch. In order to achieve robustness on the splitter for reliability, we duplicate the splitter on each SaD switch. In Fig. 6(a), a fault tolerant and multicasting (FTM) module is proposed. The input lightbeam is initially transferred to one of the branches by controlling the SE. Each branch is split into n branches and connects to a switch. Hence, any input of the splitter can be connected to any output branch.

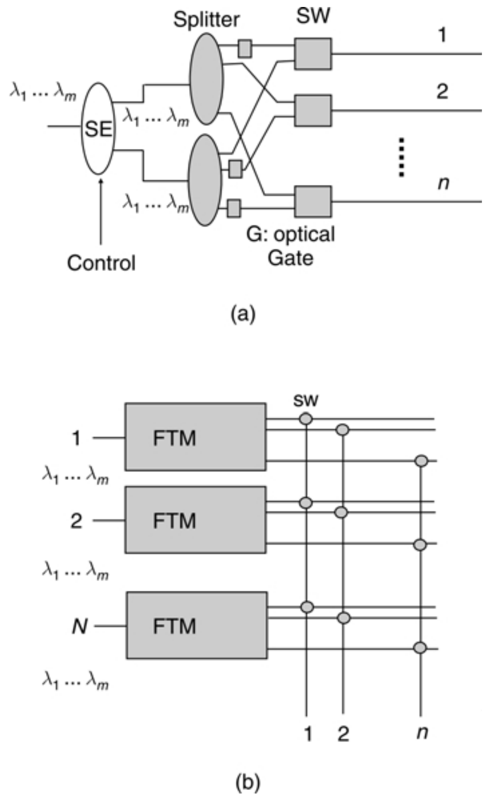


Fig. 6. (a) An FTM module based on SaD, (b) an FTM SaD switch.

Fig. 6(b) is a switch module equipped with N FTM modules and 2×1 switches. Each branch is switchable to an associated output by a 1×2 switch. Therefore, any input can be connected to none, one, several, or all the output ports. This features a multicasting capability.

To implement the FTM module, four types of components, i.e., two splitters, optical gates, 2×1 SW, and a 1×2 SE are integrated on a silicon board using planar silica waveguide technology [4–6]. The structure shown in Fig. 6(b) not only has the advantage of integration for mass production, but also supports the modularity of splitter-based MFOXC.

Type II

Fig. 7 shows an alternative implementation of an $N \times N$ splitter-based MFOXC. Its architecture is very similar to that of tap-based MFOXC. The main difference between these two architectures is the splitter-to-n (SPn) module shown in Fig. 7(b) and the switch element (SE). The former is equipped with a $1 \times N$ splitter to be as a light-splitter in order to support multicasting in the optical domain. The latter is for selecting switches to operate for fault tolerance. Owing to the power spreading of light splitter, the optical loss is assumed to be compensated with optical amplifier (e.g., EDFA or SOA) properly located in the MFOXC (not shown in the figure). The SE can be realized using a photonic directional coupler with electronic control [24]. By controlling the SEs and the switches, the input can be connected to any output port(s). Hence, the SPn module can support multicasting traffic in the optical domain by controlling these SEs and switches.

2.2 Further Discussion

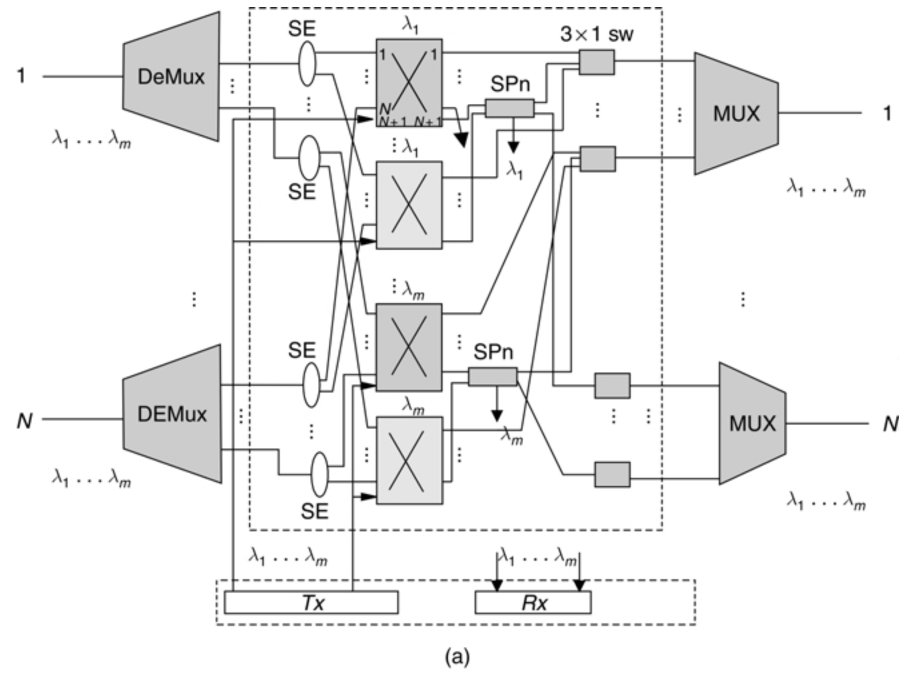
In this section, we compare the multicast parameters in terms of modularity, fanout capability, and power distribution between the tap-based MFOXC and the splitter-based MFOXC.

2.2.1 Modularity and Expansion

It is desirable that an MFOXC has a modular structure and is expandable to allow new fibers (fiber modular) and wavelengths (wavelength modular) to be added to keep pace with the future evolution for the multi-wavelength optical transport network. There are two kinds of expanding methods. One is to increase the number of fibers and wavelengths only by a few. The expanding method is straightforward without changing the layout of the original MFOXC. Large scale devices, e.g., an $(N + N1) \times (m + m1)$ switch and an $(m + m1) \times 1$ multiplexer are used as anticipated. The other is that the number of wavelengths and fibers are increased significantly. Take Fig. 8(a) for example. If N is expanded by K times, where K is an integer, the original MFOXC is consider as a main module (as shown in Fig. 4(a)). K main modules are connected by a common junction [26]. On the other hand, if the fiber bandwidth is increased by K times, it is obvious that the channel spacing will become denser. The original multiplexers must be replaced. The remainder of the original MFOXC is unchanged and regarded as a main module. K main modules are connected together by the new multiplexers and $1 \times K$ splitters, as shown in Fig. 8(b). All the expanding operations as described above do not reduce the multicasting capability of an MFOXC.

2.2.2 Multicast Fanout Expansion

Tap-based MFOXC: Fig. 4(c) shows the tapping devices (Tap) that are used to implement a TCM4 to



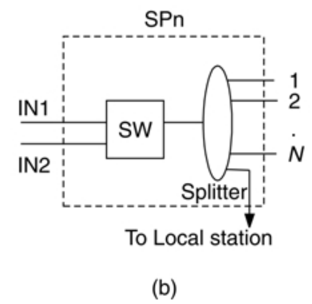


Fig. 7. (a) Structure of a splitter-based MFOXC, (b) $1 \times N$ splitter-to-n module.

support multicast. An $1 \times N$ TCM module has $\lceil \log_2 N \rceil$ stages where stage i has twice the number of taps as stage $(i-1)$. Hence, an $1 \times N \times K$ TCM module has only $\lceil \log_2 NK \rceil$ stages.

Splitter-based MFOXC type I: The expanding method is straightforward without changing the layout of the original architecture. A larger scale device switch and multiplexer are used.

Splitter-based MFOXC type II: Fig. 7(b) shows the splitting devices are used to implement the SPn module to support multicasting. An $1 \times kN$ SPn module, shown in Fig. 9, consists of a $1 \times k$ splitter and k $1 \times N$ splitter modules.

2.2.3 Power Distribution

Power is one of the most important quantitative measures in optical networks. For successful deployment of optical networks this measure needs to be considered at the design phase.

A. Tap-based MFOXC

Fig. 4(d) shows an example TCM8. An input signal is tapped in using a tapping device. A small fraction of the signal power is directed toward the local station, while the rest continues to a multistage network of taps. By controlling the voltage on these taps, an input can be connected to any output port(s). Hence, the TCM8 module can support multicasting traffic in the

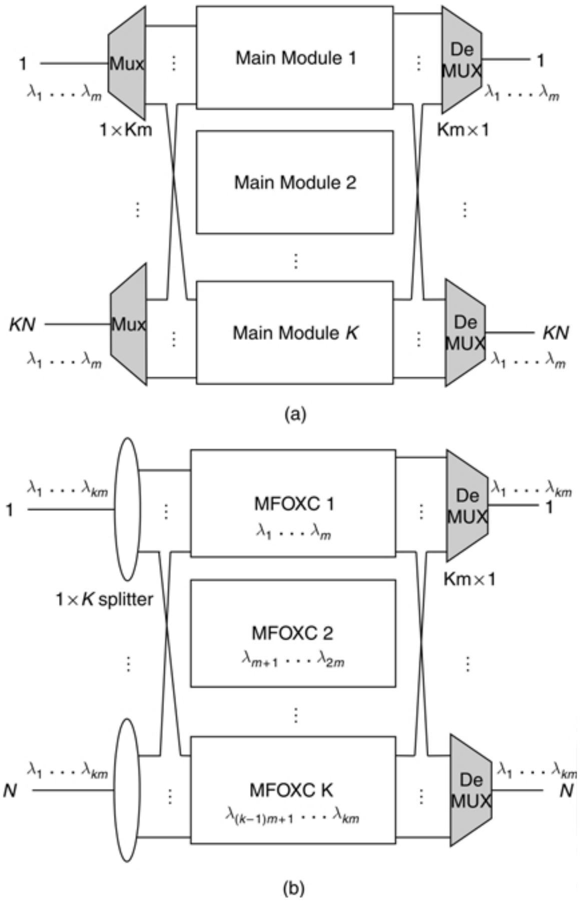


Fig. 8. (a) Expanding method to increase the number of fibers by K times. (b) Expanding method to increase the number of wavelengths by K times.

optical domain by controlling the voltage on these taps. For a multicasting session with k destinations $(k < N)$, it can be achieved by controlling the voltage on the TCM1 and TCM4. The k destinations have at least a $1/k$ signal power distribution and the other

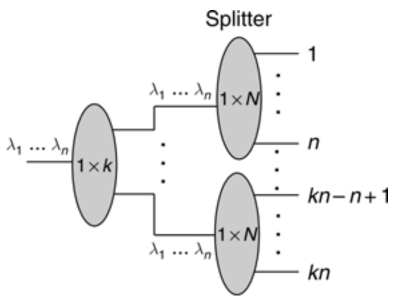


Fig. 9. A $1 \times kN$ splitter-to-kn module.

nodes do not have any power consumption. For example, a multicast session with destinations 1, 4 and 5 has a signal power distribution 25%, 25% and 50%, respectively (fanout = 8). Hence, this architecture can be easily cascaded without extra optical power amplifiers by designing the network topology appropriately.

B. Splitter-based MFOXC

The power splitter is a passive device used to distribute the input signal to all outputs. Hence, for a multicast request in MFOXC, all the outputs have the same power distribution. In other words, the power loss depends on the fanout of a splitter instead of a multicast group. For example, a multicast session with destinations 1, 4 and 5 has the same signal power distribution 12.5% (fanout = 8). Compared with the tap-based MFOXC mentioned above, the cascading capability is poor.

3 Reliability Modeling

3.1 Reliability Requirements

The appropriate downtime allowance for an optical crossconnect is not easy to determine. One reason is the lack of a uniform definition of OXC. In general, component reliability values may come from field data, data from vendors, estimates, and guesses. Field data and vendor data are generally acceptable for system reliability calculations. Because some of the switch technologies are new, estimates and guesses of the component reliability data are necessary for estimating the system reliability. The reliability data of the components that compose the OXCs were obtained from vendors [25]. The appropriate components and their FIT values are listed in Table 1.

We present efficient reliability evaluations for the OXC, tap-based MFOXC and splitter-based MFOXC, respectively. In our analysis, we assume that the components are defect-free initially. For the operating system there must be a method of detecting a failure and a technique for system recovery from faults. Furthermore, we assume that each component has an exponentially distributed lifetime (i.e., the failure rates for system components are time-independent) and the component failure duration is short relative to the time between failures, and that times between failures and the duration of the component failures are

Table 1. Failure rates.

Component	Symbol	Failure Rate
1 : 2 splitter	β_S	50 FITs
1 × 2 switch	β_{SE}	50 FITs
Tap	β_{Tap}	50 FITs
Tunable Tx	β_{TT}	745 FITs
Tunable Rx	β_{TR}	470 FITs
WDM couple (8)	β_{WDM}	360 FITs
Transmitter	β_T	186 FITs
Receiver	β_R	70 FITs
Optical gate	β_{gate}	40 FITs
16 × 16 switch matrix	β_{OM}	1000 FITs
Wavelength converter	β_{Conv}	2000 FITs
8-wide MT connector	β_{MT}	200 FITs
1FIT = 1 failure/10^9 h		

independently distributed. Our calculations are based on failure rates given in Table 1.

The first step in performing a reliability analysis is to obtain a definition of the system architecture from both the functionality and the reliability perspectives. A graphical representation of the architecture such as the reliability block diagram is very helpful in providing a precise and usable description of the reliability structure of the system. The reliability block diagram is based on the functionality of the system and is a method of representing the effects of all possible configurations of working and failed components on the functioning of the system. The reliability block diagram is obtained from the definition of the system failure. Each block in the diagram represents either a component or group of components that has two states: working or failed.

3.2 Reliability Function

The reliability function $R(t)$ is the probability that a component (system) will survive until t (i.e., a failure occurs after t)

$$R(t) = P(X > t) = 1 - F(t)$$

where X is a positive, continuous random variable, called lifetime, describing the duration time of failure-free operation and $F(t)$ is a lifetime distribution. The reliability function can also be seen as a probability of failure-free operation during a specified period of time 0 to t.

For a series system, the probability that the system operates at instant t is a product of the probabilities that all of the components (units) are functioning at the instant t. Thus

$$R(t) = \prod_{i=1}^{n} R_i(t).$$

To calculate the system reliability function, it is necessary to determine the reliability functions for all components. For exponentially distributed component lifetimes and component failure rates $\beta_1, \ldots, \beta_n$, the reliability function for a series system becomes

$$R(t) = \mathrm{e}^{-(\beta_1 + \beta_2 + \cdots + \beta_n)t} = \mathrm{e}^{-\beta t}.$$

For a parallel system, the probability that the system operates at instant t is the probability that at least one component operates at instant t. In the case of active redundancy, it is obtained that

$$R(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)].$$

4 Reliability Evaluation and Cost Analysis

4.1 Optical Cross-Connect Architecture

We first consider two optical cross-connect architectures, with and without wavelength converters, as illustrated in Figs. 2 and 3, respectively. We consider the connection of eight wavelength channels on one specific input link with one specific output link. A system failure occurs when one or more wavelength channels are lost due to the failure of system components.

Fig. 10 presents the reliability block diagrams derived for the OXC architectures shown in Figs. 2 and 3. The diagrams are based on the functionality of the OXC nodes and are obtained from our definition of system failure. In Fig. 10, the failure rate for each

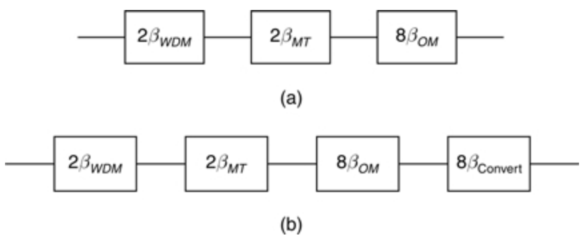


Fig. 10. Reliability block diagrams for (a) OXC without wavelength converters and (b) OXC with wavelength converters.

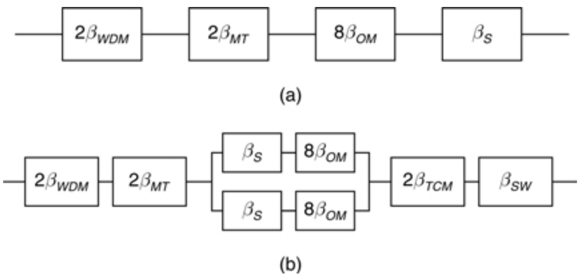


Fig. 11. Reliability block diagrams for (a) tap-based OXC and (b) tap-based MFOXC.

block is indicated (for description of the symbols and their values, see Table 1).

4.2 Tap-based MFOXC

Fig. 4 shows an implementation of an $N \times N$ tap-based MFOXC. The tap-based MFOXC is an OXC with multicasting and fault tolerance capability. Fig. 11(a) show the reliability block diagram derived from Ali and De [11]. Fig. 11(b) presents the reliability block diagram derived from our proposed MFOXC architectures shown in Fig. 4. The diagrams are based on the functionality of the OXC nodes and are obtained from our definition of system failure. In Fig. 11, the failure rate for each block is indicated.

4.3 Splitter-based MFOXC

Fig. 6 shows an implementation of an $N \times N$ splitter-based MFOXC. Its architecture is based on the SaD switch. Fig. 12 presents reliability block diagrams derived for the MFOXC architectures shown in Figs. 5, 6 and 7, respectivity. In Fig. 12, the failure rate for each block is also indicated.

4.4 Results and Discussion

There are a variety of measures and functions of reliability that can be derived using the reliability block diagram and the failure rates of components and taking into account maintenance principles. In this paper, we consider the following:

1. Mean time between failures (MTBF).
2. Reliability function, i.e., the probability of error-free operation until t.

The reliability function becomes important when one has to determine the probability of failure-free operation during a specified period of time (e.g., 10 or 20 years). For example, network operators may change some equipment after 10 or 20 years of operation due to, for example, the development of new technology. In such cases, they may require a high probability of error-free operation of this equipment during this time period. Numerical results for the considered OXC nodes are shown in Table 2.

The results presented in Table 2 show that, from a reliability point of view, (1) an OXC without converters is superior to an OXC with converters. (2) the MFOXC has better performance in terms of

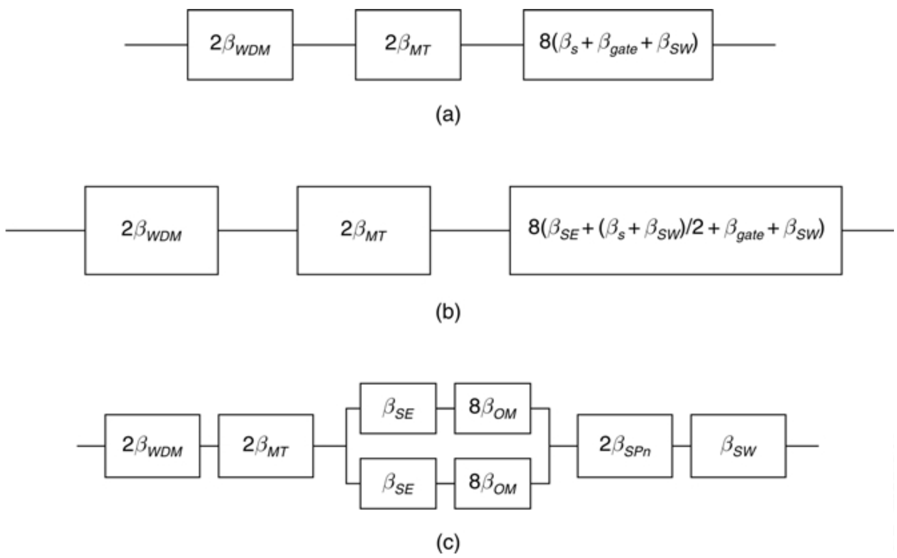


Fig. 12. Reliability block diagrams for (a) SaD switch OXC, (b) splitter-based type I MFOXC and (c) splitter-based type II MFOXC.

Table 2. Reliability results for a 16 × 16 OXC.

	OXC Without Wavelength Converters	OXC With Wavelength Converters	Tap-Based OXC [11]	Tap-Based MFOXC	Splitter-Based OXC [10]	Splitter-Based MFOXC TYPE I	Splitter-Based MFOXC TYPE II
MTBF (year)	12.4	5.7	12.4	19.97	18.8	22	20
MTBF (hours)	1.09×10^5	0.5×10^5	1.09×10^5	1.75×10^5	1.65×10^5	1.93×10^5	1.8×10^5
$R(t = 10$ years)	69%	25%	41%	71%	51%	72%	71%
$R(t = 20$ years)	40%	19%	23%	38%	25%	47%	41%

MTBF and reliability, and (3) the splitter-based MFOXC has better performance than the tap-based under the same reliability requirement.

Fig. 13 shows the reliability functions in different OXC structures. It is of interest to note that the splitter-based MFOXC, tap-based MFOXC, and OXC without wavelength converter have better performance in reliability than those without fault tolerance (FT). On the other hand, the tap-based MFOXC has almost the same reliability with the splitter-based type II. To sum up, we can conclude as follows: (1) the reliability of an OXC without wavelength converters is better than that with wavelength converters. In this case, wavelength converters could improve resource

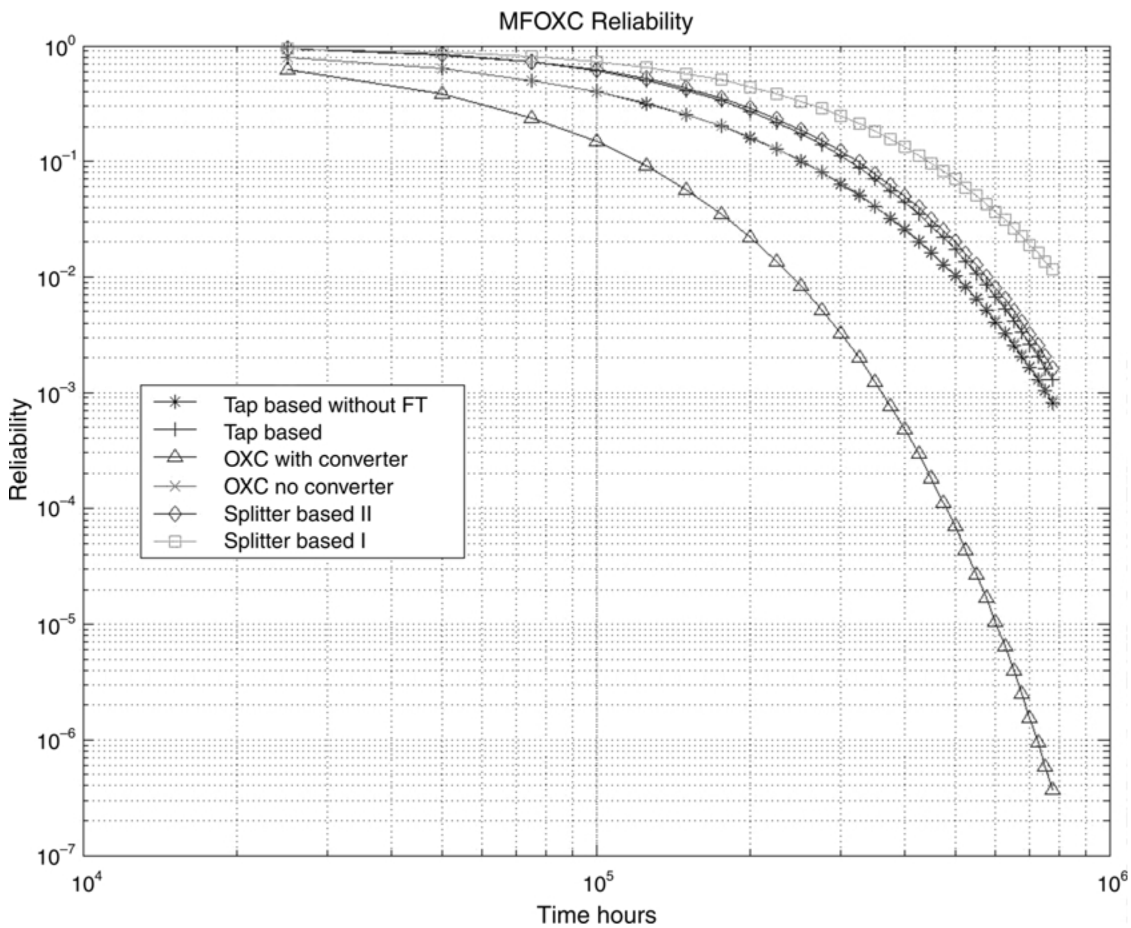


Fig. 13. Reliability for different OXC architecture.

Table 3. Reliability results for a 32×32 OXC.

	Tap-Based MFOXC	Splitter-Based MFOXC Type I	Splitter-Based MFOXC Type II
MTBF (year)	7.6	9.9	7.8
MTBF (hours)	0.67×10^5	0.87×10^5	0.69×10^5

utilization (in term of wavelength reuse), but not for reliability. This is trivial due to the fact that the wavelength converter is a complicated component. From the reliability point of view, an OXC without converters is superior to an OXC with converters. (2) Compared to the traditional structure, the proposed MFOXC node not only has the advantage of multicast capability but also improves the reliability with fault tolerance capability. (3) The reliability of the splitter-based MFOXC is better than that of the tap-based.

Indeed, we investigated the influence of capacity expansion on the reliability of the MFOXCs considered here. Increasing the capacity will affect the reliability of MFOXC. Table 3 shows the evaluation results for a 32×32 OXC. The FIT value for a 32×32 switch matrix is estimated to be 3125 (from the reliability data received for 16×16 matrices [25]).

Comparing Table 2 with Table 3, the MTBF of tap-based OXC in Table 2 is about three times higher than that of a two times larger OXC in Table 3. This is due to the FIT value for a 32×32 OXC is about three times higher than that for a 16×16 OXC. On the other hand, the degradation of reliability for splitter-based OXC seems not significant, i.e., the capacity expansion does not significantly degrade the reliability of the splitter-based MFOXC. As a consequence, from the reliability point of view, we can find out that the splitter-based MFOXCs are attractive and more robust for large switching nodes.

4.5 Cost Analysis

However, the implementation cost is still a dominating factor in optical crossconnect. Generally speaking, the cost of a system is proportional to that of individual component. The component cost depends on the process of fabrication. Since the more complicated the fabrication process is, the less the reliability (the larger the FIT value) will be. Hence, we assume the cost of a component is proportional to the FIT values.

Some of the key design results are presented in Table 4. The total costs are normalized and expressed relative to the conventional OXC architecture. The major cost components modeled in this analysis included MUX, DeMux, $N \times N$ switch, Splitter, Tap, 1×2 switch, optical gate, and MT connect. However, the cost of fiber was not included. The cost of each component was derived by considering the current FITs to estimate the component cost assumptions used. From Table 4, we can observe that the splitter-based MFOXC has the lowest cost, and about 20% (11%) less than the tap-based MFOXC.

In Table 4, we find the splitter-based (type II) only uses a $1 \times N$ Splitter with respect to $2N$ in type I. Because the large number of splitters in a multicast cross-connect has the negative implications of difficult and expensive fabrication, the type II splitter-based MFOXC is a better choice than the type I.

Fig. 14 shows the relative cost component breakdown based on the four major categories: standard OXC, Tap-based, splitter-based type I, and splitter-

Table 4. Cost analysis results for a 16×16 OXC with eight wavelengths.

	Standard OXC	Tap-Based MFOXC	Splitter-Based MFOXC (I)	Splitter-Based MFOXC (II)
DeMux (360x)	N	N	N	N
MUX (360x)	N	N	N	N
Switch NXN (1000x)	M	$2m$	0	$2m$
Splitter $1 \times N$ (550x)	0	0	$2N$	1
Tap (50x)	0	$(2N-1)m$	0	0
1X2 SW (50x)	0	$(2m+1)N$	$2mN$	$(2m+1)N$
Optical Gate (40x)	0	0	mN	N
MT connect (200x)	2	4	4	4
Costs	19 920x	54 320x	47 840x	42 910x
Normalized Total Costs	1	2.7	2.4	2.15

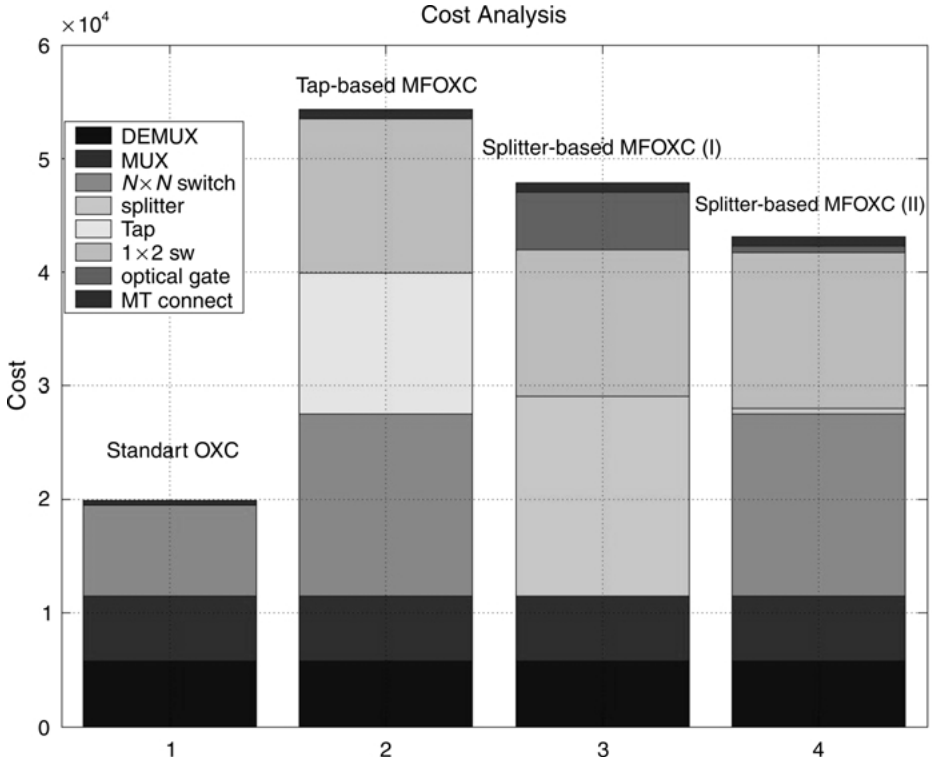


Fig. 14. Breakdown of the relative component costs.

based type II. All values in the figure are relative to the conventional standard OXC. As shown, the $N \times N$ switch costs account for from one-fourth to almost one-third of the total cost in the tap-based and the splitter-based type II OXC. Furthermore, the 1×2 switch costs account for about one-third of the total cost in all types of MFOXC. The tap costs account for about one-fourth of the total cost in the tap-based MFOXC.

Moreover, in order to keep pace with the future advancements, a detailed sensitivity analysis was carried out for the main cost components to evaluate how the relative costs of the different technologies would change if the cost assumptions were not correct. The cost sensitivity analysis can help us to know which component dominates the total cost and how to make a decision to choose among different MFOXC structures.

The $N \times N$ switches, tap, and 1×2 switch have a large impact on the cost of the tap-based MFOXC. Therefore, they are considered first. As shown in Fig. 15, the decrease of 75% in cost for the component tap, $N \times N$ and $1 \times N$ switch results in the decrease of the total cost about 15%, 20% and 18%, respectively in the tap-based MFOXC. On the other hand, the increase of 75% in cost for the component tap, $N \times N$ and $1 \times N$ switch results in the increase of the total cost of about 18%, 22% and 20%, respectively in the tap-based MFOXC. Hence, the $N \times N$ switch has the largest sensitivity in cost ($-$ 20% and 22%).

A sensitivity analysis is also performed for the splitter-based MFOXC. In Fig. 14 the $N \times N$ switches, tap, and 1×2 switch have a large impact on the cost of the type II splitter-based MFOXC. On the other hand, the splitter and 1×2 switch dominates the cost of the type I splitter-based MFOXC. As shown in Fig. 16, the type I MFOXC is more sensitive to the change in the splitter cost than the type II MFOXC. This fact shows that the larger impact to the total cost that the splitter has on the type I structure. The variation in the cost of the splitter does not introduce significant disadvantage to the type II splitter-based MFOXC structure. However, the component 1×2 switch has almost the same sensitivity to cost on both splitter-based MFOXC structures.

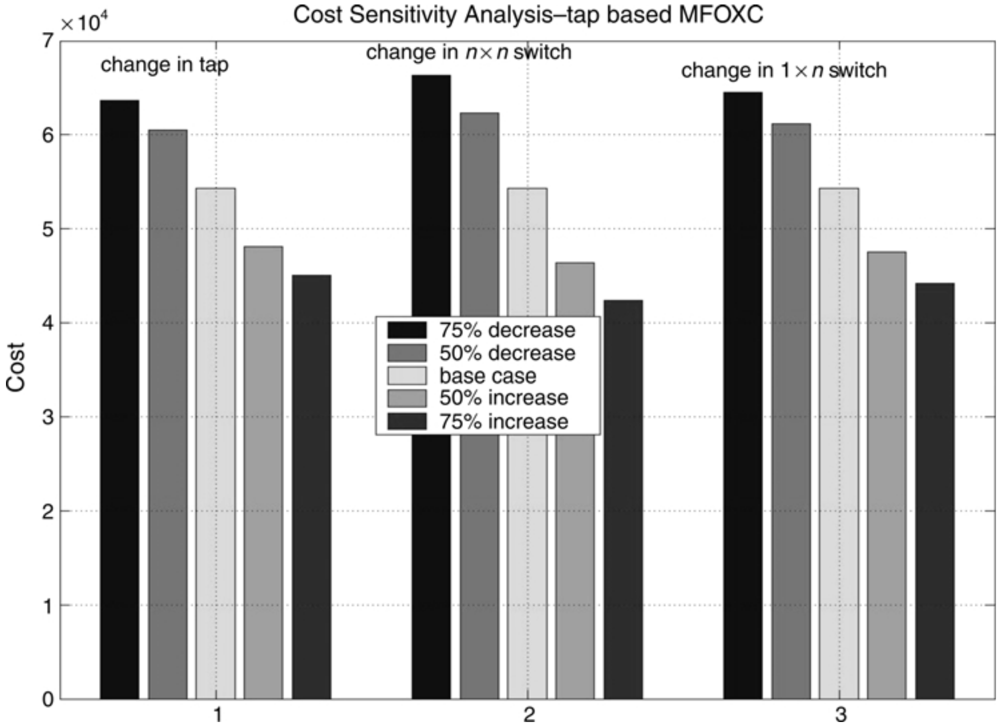


Fig. 15. Cost sensitivity analysis for the tap-based MFOXC.

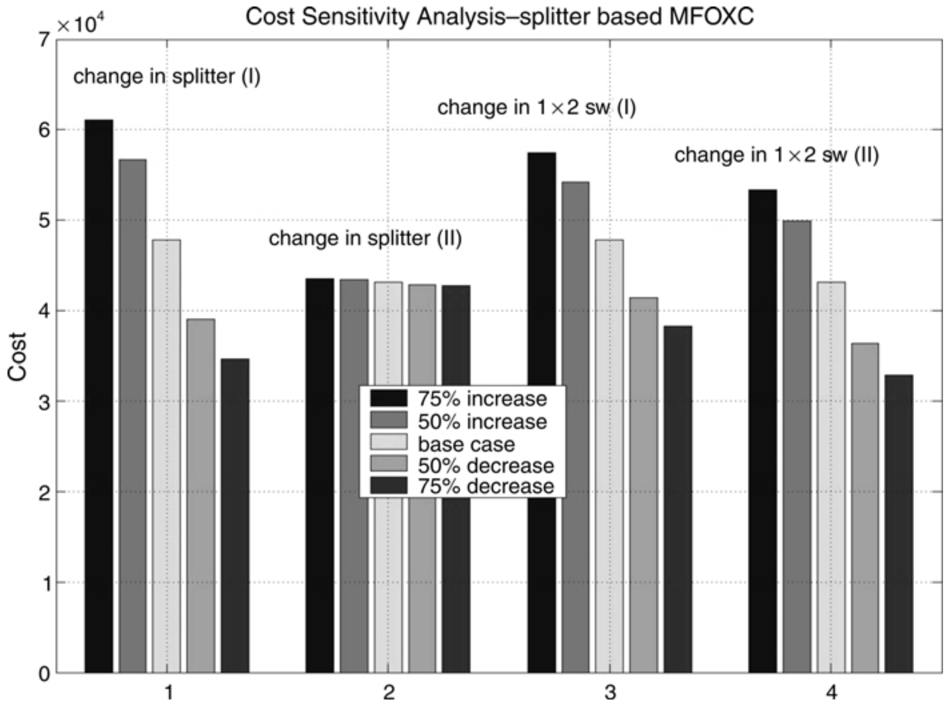


Fig. 16. Cost sensitivity analysis for the splitter-based MFOXC.

5 Conclusions

We have proposed several multicasting and fault-tolerant optical crossconnect (MFOXC) architectures. First, a tap-based and two splitter-based MFOXC node architectures were presented for wavelength routed all-optical networks. The tap-based MFOXC is an OXC with multicasting and fault tolerance capability, and uses wavelength-dependent optical switches. It uses a set of tap-and-continue modules (TCMs). The benefit of a tap is that all the signal power is directed toward the normal switches in normal operation mode. Only little signal power is transferred to the fault tolerant switch. However, if the normal switch is faulty, by controlling the taps, the signal power is directed toward the fault tolerant switch. Second, a splitter-based MFOXC architecture based on the SaD switch was proposed. In order to achieve robustness on the splitter for reliability, the splitter on each SaD switch is duplicated. An alternative implementation of an $N \times N$ splitter-based MFOXC is very similar to that of the tap-based MFOXC. The main difference between these two architectures is the splitter-to-n (SPn) module. Compared to the traditional optical crossconnect, the proposed MFOXC node not only has the multicasting capability but also improves its fault tolerance capability. It can be used in some critical points in a network to improve the reliability and multicasting performance.

We also proposed two different conditions for the modularity and multicast fanout expanding. They are arranged in the wavelength or fiber modular layout. Therefore, the expansion is simple if the MFOXC is expanded by allowing only a few fibers and wavelengths added. The expanding method is quite different if the number of fibers and wavelengths is increased significantly. The original MFOXC is regarded as a main module and a few main modules are connected together. All the expanding operations do not destroy the fault-tolerance property and multicasting capability.

We also performed the reliability evaluations for the OXC, the tap-based MFOXC, and the splitter-based MFOXC. We first consider two optical cross-connect architectures with and without wavelength converters, respectively. The simulation results suggest that the reliability of an OXC without wavelength converters is better than that of an OXC with wavelength converters. We also evaluated the reliability of the tap-based MFOXC and the splitter-based MFOXC. Compared with the tap-based/splitter-based OXC without fault tolerance, the proposed MFOXC node not only has the advantage of multicasting capability but also improves the reliability and the fault tolerance capability. From the reliability point of view, the splitter-based MFOXC has better performance than the tap-based under the same reliability requirement. Therefore, it is attractive and robust for large switching nodes.

Finally, the cost model and the sensitivity analysis results show that the cost reduction in different components would have different degrees of impact on the total cost of the MFOXC architectures. For the tap-based MFOXC, the total cost is sensitive to all the critical components variations in cost. The cost decrease of 75% in the component $N \times N$ switch will result in the decrease of the total cost of about 20% in the tap-based MFOXC. The 1×2 switch has a larger impact on the cost of the splitter-based MFOXC structures and the variations in the cost of the splitter do not cause significant disadvantage to the type II splitter-based MFOXC structure.

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