Availability of All-Optical Switching Fabrics Used in Optical Cross-Connects

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Abstract - The application of all-optical switching fabrics will be an important breakthrough in avoiding capacity bottleneck caused by electronic-switching in optical networks. All-optical domain of achieved network is characterised by absence of optical-electrical-optical conversions. In this paper, the-state-of-the-art of optical switching fabrics used in optical cross-connect is reviewed. Moreover, availability analysis of those switching fabrics have been examined. Methods for increasing availability of MEMS switches and entire optical network have been shown.

I. INTRODUCTION

Contemporary telecommunication networks demand huge amount of capacity due to the exponential growth of IP traffic. In order to face this problem, considerable research is devoted to design and implementation of optical network layer. One of the main aspirations regarding optical network design is avoidance of capacity bottleneck caused by electronic switching[1]. As single optical fiber can offer transmission capacity of 5 THz, it is important to have adequate equipment that will be able to exploit large bandwidth. Although optical Dense Wavelength Division Multiplexing (DWDM) is providing impressive transmission capacity, extension of optics from transmission to switching is needed. In this context, all-optical switching fabrics play a central role and will be a significant breakthrough in providing huge bandwidth capacities.

Fundamental issue in all-optical switching is supporting efficient and cost-effective transport services for wide range of bandwidth granularities. Multi-granular optical cross-connects (MG-OXCs)[2-4] are supporting optical circuit switching (OCS), optical burst switching (OBS) and even optical packet switching (OPS). Architecture on Demand (AoD)[5] concept of MG-OXC consists of large number of not fully wired optical components, which can dynamically adapt in real time in order to provide the required functionality to satisfy the switching and processing requirements of network traffic. In AoD two optical switching fabrics are used: slow MEMS (*Micro-Electro-Mechanical Systems*) optical switches and fast switches based on SOA (Semiconductor-Optical-Amplifier) or PLZT (*Plumbum Lanthanum Zirconate Titanate*). Those two switching types can support OCS, OBS and OPS. In this paper MEMS switching technologies are reviewed.

The remainder of this paper is organized as follows: Section II and III describe and classifies the optical switching technologies used in optical cross-connects. Section IV explains how the component failure rates were selected. Section V shows the analytical availability calculation for MEMS switches and introduces possible approaches for the usage of internal redundancy. Section VI concludes the paper.

II. OPTICAL SWITCHING TECHNOLOGIES

The basic premise of optical switching is that by replacing existing electronic network switches with optical ones, the need for OEO (optical-electrical-optical) conversions is removed. Advantages of avoiding OEO conversions are significant[6]. First, optical switching technologies should be cheaper, as there is no need for lots of expensive high-speed electronics. Secondly, complexity removal of electronics switching elements should make switching element smaller and more practical to implement. Unfortunately, most solutions for all-optical switching are still under study. As different technologies feature different performance, and optical switching technologies support wide range of applications, it seems reasonable that there will not be one wining solution. Switching technologies differ in their performances (scalability, switching speed, insertion loss, crosstalk, etc.) In this paper MEMS switching technologies will be reviewed.

III. MEMS OPTICAL SWITCHES

MEMS[7-9] are characterized as slow optical switches. They switch data in ms range and can be used for optical channel switching. There are two main approaches to implement MEMS optical switches: 2D and 3D MEMS switches. These technologies differ in terms how they are controlled and on principle they direct light beams. 3D MEMS are preferred when the switch scaling is bigger, because they use less mirrors than the 2D MEMS for same number of input and output fibers.

Both switches have low insertion loss. The main sources of insertion loss are:

- Variation in optical path lengths
- Variation in position and angle of optical beam sent to the output port
- Loss of optical power at the mirror boundary

- Roughness and warping of mirror surfaces

A. 2D MEMS

In this architecture, mirrors are arranged in a cross-bar configuration as shown on Figure 1. Each mirror has only two states: *cross* and *bar*[10]. *Bar* represents state in which light is passed uninterrupted, while in *cross* state light is reflected to one of the output fibers. The binary nature of the mirrors positions simplifies the control mechanism. Control mechanism consists of simple TTL (Transistor-Transistor-Logic) gates and appropriate amplifiers to provide adequate voltage levels to actuate mirrors.

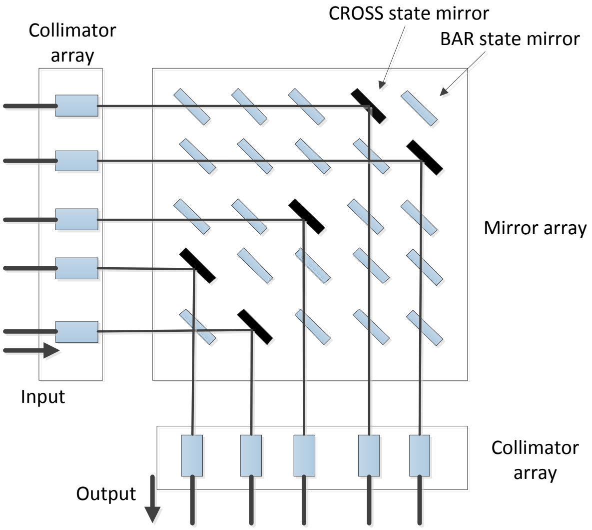

Figure 1. Structure of 2D MEMS optical switch

For an $M \times M$-port switch, a total of M^2 mirrors are required to implement a strictly non-blocking switching fabric. For each input port, an output port to be coupled is determined by selecting the mirror is in *cross* state. For example a 32×32-port switch will require 1024 mirrors. To overcome this exponential increase of mirrors, it is possible to implement alternative approach in which are smaller 2D MEMS combined in multistage switching network architecture. However, this cascades require a lot of complex interconnections between smaller switching modules. Also, the beam propagation distances among ports-to-ports switching are not constant, so the insertion loss is not uniform for all ports. The 2D MEMS find applications in areas of communication networks which require smaller ports sizes. For applications which require bigger ports sizes (over 32) 3D MEMS are used.

At 2D MEMS optical switches, optical path lengths vary according to the selected pair of input and output ports. Variation of optical paths increases as the number of ports increase. To eliminate variation in position and angle of optical beam collimators and mirrors must be precisely aligned.

B. 3D MEMS

3D MEMS switches have mirrors that can rotate around two axes and achieve multiple positions for each of them. In this way it is possible to precisely redirect light to multiple angles, as it is shown on Figure 2. The number of possible angles is at least as the number of input fibers. In this way the maximum number of mirror is 2M, if M is the number of inputs and outputs. Second advantage is that differences in free-space propagation distances among ports are much less dependent on the scaling of the port-count. Number of ports for 3D MEMS can increase to thousand without big loss differences.

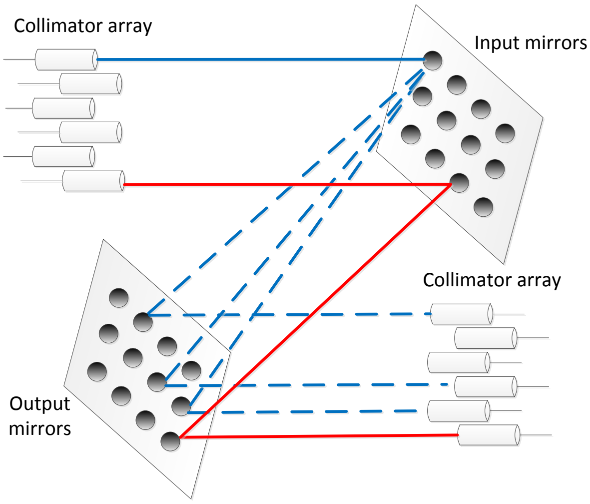

Figure 2. Structure of 3D MEMS optical switch

The light path passes through three sections of the optical switch: the input collimator (device which precisely line up input fibers for better switching performances and low loss), the switching matrix (which contains two mirror arrays) and the output collimator. The switch matrix enables switching time of approximately 20 ms and low optical loss (around 2.0 dB). Each mirror array has big number of individually controllable mirrors (even up to thousand). The input signal passes to the switch matrix where the mirrors are aligned in a way to direct light to the output port.

Optical switches need external components that control appropriate switching behavior. For mirror control cord cards are used. Each cord card controls a set of input and output fibers. For example, one cord card can control 8 input and 8 output mirrors. In case of 96 input and output ports, MEMS must be connected to 12 cord cards. Also, there can exist some spare cord cards for system operation and testing. Optical switch is also controlled by configuration processor, which establishes and maintains connections. Because of the vital role, the processor regularly has its redundant one. If first fails, the secondary processor takes over. On each port optical power can be measured, so it is possible to detect any signal degradation.

IV. COMPONENT FAILURE RATES

The failure rates for optical switches and their components rely on data from several sources. We assume component failure rates are constant. Failure rates are presented in FIT.

TABLE I.
COMPONENT FAILURE RATES

Component	Symbol	Failure rate [FIT]
MEMS mirror	MIR	21
Entire MEMS	MEMS	10 FIT / port
Fiber	FIB	310 FIT/km
EDFA	EDFA	2850

EDFA

The failure rate of node-internal EDFA was taken from [11] and [12].

MEMS mirror

The failure rate was obtained from [13]. Static availability has been experimentally verified for more than two years over 4,000 switch elements.

MEMS optical switch

MEMS failure rate was obtained from [14].

Fiber per km

Fiber failure rate was taken from [15]. It is assumed that a link failure rate per kilometer includes fiber and inline amplifier failures.

V. MEMS AVAILABILITY

The critical part of 2D MEMS optical switch is moving MEMS mirror. Additional assumption is that control electronics is redundant and high available. Possible arrangement could be done by adding additional back loop from MEMS exit to MEMS entry in order to bridge possible failure of a mirror on the “right and up” part of MEMS matrix where primary or spare path are passing through. Path represents connection between input and output fiber. If the 2D MEMS is used to switch redundant component there are two possible paths enabling correct operation. The redundant arrangement is illustrated on a simple example of4×4 2D MEMS, as depicted on Figure 3.

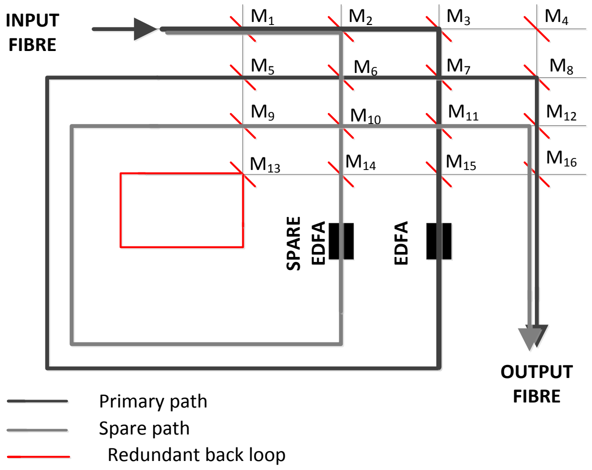

Figure 3. Redundant back loop in the lower left corner of MEMS matrix

In the example an application of Architecture on Demand (AoD) with only one component - Erbium doped fibre amplifiers (EDFA) is assumed. One EDFA is placed on a primary path and spare EDFA is a part of the spare path. Note, another arrangement of components in AoD do not change availability analysis. An assumption is that a failure of any mirror on a path causes the failure of entire path. Mirrors M_1 and M_{16}, as input and output mirrors respectively, are critical switching elements because they have no redundancy. Black line represents primary path between input and output fibres, including eleven mirrors and one EDFA. The spare path is represented by grey line with nine mirrors and the spare EDFA. Redundant back loop connects one output port and one input port in lower left corner, next to the mirror M_{13}. For example, if the mirror M_3 fails, the primary path does not work and it can be switched over to the spare path. In the case the mirror M_2 fails neither primary or spare path cannot be accessed through input port 1. In this case redundant back loop can be helpful connecting additional two ports. Optical signal is redirected down to M_1, through back loop to the mirror M_{15} (for primary path) and to the mirror M_{14} (for spare path). By using the redundant loop there are two additional spare paths which can overcome some failed mirrors.

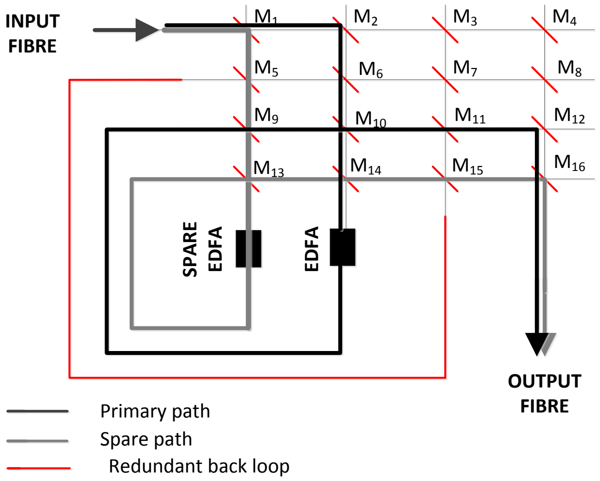

Figure 4. Redundant back loop in upper right corner of MEMS matrix

On Figure 4., redundant back loop is “on the right” of primary and spare path. Primary and spare path passes through fewer mirrors than on Figure 3, but availability isn’t increased because redundant loop uses more mirrors then primary and spare path.

Availability comparison of MEMS with and without redundant back loop is given on Figure 5. Availability performance was calculated by transformation of union of non-disjoint paths through mirrors to the union of disjoint path elements, assuming the union in both cases is the same. The transformation was done by Abraham’s algorithm [16]. If redundancies of mirrors are not used (there are only two paths), better solution is to put all paths in lower left corner because in this case the paths use less mirrors, and there are less chances of a path failure. If redundancy in 2D is used (with 2 additional spare paths), then is a better solution to put the redundancy in lower left corner because additional spare paths and primary path have less mirrors in common.

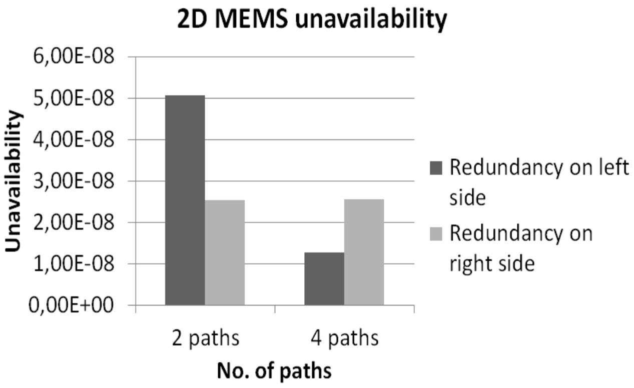

Figure 5. Availability comparison with or without redundant back loop

The $N \times N$ MEMS and eight fibers connecting node A and node B are shown on Figure 6. Each fiber is 20 km long. Logical channel (LCH) represents two-way connection from node A to node B. There are two logical channels (green and red one). Logical connection (LC) is up if at least one logical channel is working correctly, which can be presented through Boolean expression:

$$LC = LCH_1 \vee LCH_2 \qquad (1),$$

where LC, LCH_1 and LCH_2 are true (working path) or false (broken path).

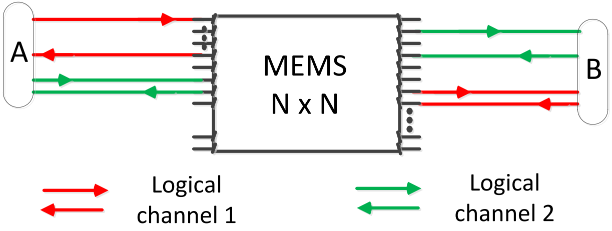

Figure 6. Two logical channels with one MEMS

On Figure 7 is depicted structure consisted of two smaller MEMS ($N/2 \times N/2$) each supporting one logical channel. The availability comparison of these two structures is calculated.

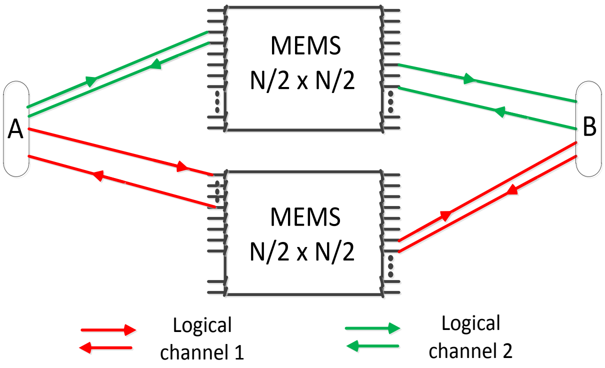

Figure 7. Two logical channels with two MEMS

The availability model of structure with one MEMS is depicted on Figure 8(a) and on Figure 8(b) is shown the availability model of structure with two smaller MEMS.

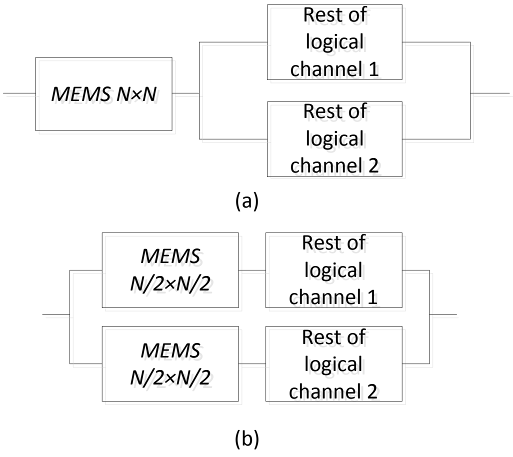

Figure 8. Availability models of case study structure

Unavailability of structure with larger MEMS is $3,84*10^{-5,}$ which corresponds to downtime of approximately 20 minutes per year. The unavailability of the structure with two smaller MEMS is $2,82*10^{-8}$. It corresponds to downtime of 0,014 minutes per year. Usage of two smaller MEMS instead of one bigger MEMS adds redundancy, which increases availability thousand times (Figure 9), while cost increase is much lower.

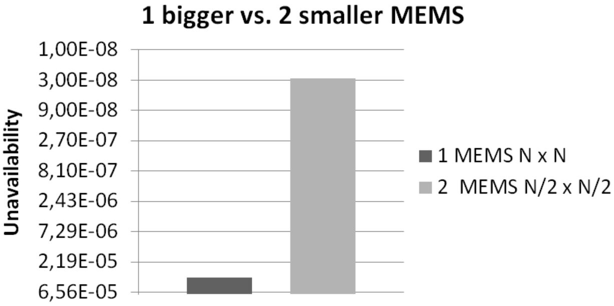

Figure 9. Availability comparison of MEMS structures

VI. CONCLUSION

In this paper, the all-optical MEMS switching fabrics used in optical cross-connects were reviewed. MEMS switches are mature technology for building large optical cross-connects. They offer ability to integrate electrical, mechanical and optical elements on a single chip, which can support switching capabilities with low loss, low cost and crosstalk. MEMS switch data in ms regime, thus supporting optical channel switching. Through this paper availability analysis and possible approaches for availability increase of MEMS optical switches and optical network have been reviewed. It has been shown that 2D MEMS optical backplane can use internal mirror redundancy. One back loop connection can replace some multiple mirror failures. Back loop connection which connects one input port and output port in lower left corner of the MEMS increase availability for 5 times. In the case of 2D MEMS of bigger scale, availability benefit is higher. Usage of two smaller MEMS instead of one bigger can increase availability, as well.

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