Reliability of Optical Crossconnect Systems

by

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Abstract

Optical crossconnect (OXC) systems are essential part of the next generation mesh-based core optical networks. Among various switching technologies, micro-electro-mechanical systems (MEMS) has proven itself as the leading choice for realizing large port count OXC switch fabrics. Although much effort have been reported on the development of large port count MEMS-based switch fabric, the reliability of the OXC systems must also be carefully considered in order to achieve a survivable optical network. In this thesis, our studies on the reliability issues in MEMS-based large scale OXC system focus on two parts: 1) lifetime and operational economic of switch fabric for different switch fabric architectures, and 2) connection
availability as a function of switch fabric’s port failure rate.

For the first part, we discussed the two major arrangements for an switch fabric, which are the monolithic switch fabric and the modular switch fabric, and we compare several important reliability parameters between the two arrangements, including the average number of replacements, the average number of forced service interrupts and the operational economic of OXC system over its service lifespan. Connection availability is then investigated for unprotected and protected OXC systems. It is shown that by employing the protection scheme, connection availability can be significantly enhanced even at relative high port failure rate (> 5,000 FIT).

Finally, we propose and experimentally demonstrate a highly scalable 1:1 protection switching scheme for enhancing connection availability in MEMS-based OXC systems. Such scheme employs a low-cost laser transceiver in conjunction with 2x2 switches to facilitate efficient inter-port communication, rapid execution of the restoration procedures against port failure and other network functions such as connection verification.
Chapter One
Introduction

Along with the entering of the new millennium, dramatic changes have been brought to the telecommunications industry. A remarkable revolution in information services was overtaking our society where communication is no longer confined to narrowband voice signals. The Internet and the services it brings along trigger a paradigm shift in data-oriented traffic and an exponential growth in number of users. What was once a voice network growing at 8 percent per year is now a data-centric network growing at more than 30 percent per year [1]. The development of high capacity optical networks and its components becomes the topic of research all around the world.

1.1 Optical Network and OXC Systems

Optical fibers, compared to twisted pair copper wire, offers many advantages such as large bandwidth, light weight, flexible, and immunity to electromagnetic interference. Early optical transmission is on a point to point basis and since the first light-wave system is established in 1970s, the optical network grows at an endless pace. Wavelength division multiplexing (WDM) technique, in which multiple wavelengths are transmitted over a single fiber, can be applied to further increase the capacity.
Optical crossconnect (OXC) is the key element that enables the next generation optical mesh network. An OXC may be seen as a non-blocking switch with multiple input and output fibers carrying network traffic. The basic function of the switch is to enable the signal on any one of the input fibers to be redirected to any one of the output fibers in the manner configured by the users. OXCs are capable of handling complex mesh topologies with large numbers of wavelengths. An OXC can also provide several key functions in a large network, such as automatically provisioning lightpaths, protection against fiber cuts and equipment failures, providing visibility to the performance parameters of a signal at intermediate nodes.

1.2 Optical Switch Technologies

Although the term “optical” is used, an OXC system can internally use either an optical or an electrical switch fabric (SF). Most OXC systems used in today’s networks rely on electronic SF. Optical signal is converted into electrical domain via photodetection before switching. The signal is then routed through the electrical SF, followed by an extra stage of electrical-to-optical conversion which transforms the signal back into optical domain at the output of the system. Not only does this optical-to-electronic-to-optical (OEO) conversion require costly components such as high-speed photo detectors, laser diodes, and high-speed electronic amplifier circuits
for each single port of the OXC system, the fundamental problem with the electronic SFs is that they do not scale well to large port counts. This is because of the fixed switching capacity of the electronic SF which results in reduced port count as data rate increases.

On the contrary, optical SFs or all-optical SFs performs switching by simply altering the propagation direction of the optical signals. The expensive OEO conversion is eliminated from the system. Switching by optical SF is therefore transparent to bit rate and protocol of the signal. The absence of OEO conversion also translates to lower power consumption [2].

Various technologies have been proposed for realizing all-optical SFs. These include thermal bubble generation in planar waveguides-based switches developed by Agilent Technologies [3], liquid crystal switches [4], electro-optic/thermo-optic switches [5-6], and two-dimensional micro-electro-mechanical systems (MEMS) switches [7]. However, all of these technologies suffer from limitations such as polarization dependency and or scalability limitations. The largest SF achieved by using these technologies is 32×32 in port count. With today’s number of wavelength in WDM or DWDM transmission exceeding 16 wavelengths in a single fiber, technology for building large port count all-optical SF must be developed.

In terms of scalability, footprint, manageability, and cost, 3-D MEMS has
proven itself as the leading choice for realizing large port count SF [7-10]. 3-D MEMS SF typically consists of lens arrays, fiber arrays, and miniature mirrors arrays fabricated on silicon substrate. The tilt angle of each mirror can be adjusted continuously by various methods of actuation, as shown in Fig. 1.1.

By using these micro-mirrors, input light beams are steered to the appropriate output ports to perform the switching function.

![3-D MEMS switching architecture](image)

Figure 1.1 Illustration of 3-D MEMS switching architecture [9]

1.3 Reliability in MEMS-Based OXC Systems and Thesis Outline

In the development of OXC systems, efforts have been focused on the design and fabrication of these MEMS-based SFs. Reliability issues of OXC systems have not been carefully studied. These seemingly challenging task due to the short history
and hence lack of MEMS mirrors reliability data must be understood in order to deploy OXC systems in survivable optical networks.

Figure 1.2 Generic OXC system architecture

Figure 1.2 shows a generic architecture of an OXC system. A signal comes into the system through the input linecard which consist of connectors, photodetectors, various electronics and other sensing devices to enable monitoring functions. After the linecard, the signal goes to the OXC’s SF where signals are switched to its desired output. Finally, the signal is output from the OXC through the output linecard.

In chapter two of this thesis, we analyze the lifetime and the operation economic of the SF at various SF port failure rates. The impact of adding overbuild port to SF is also calculated. Two different SF configurations, monolithic and modular SF, will be investigated. In chapter 3, we propose and experimentally a novel 1:1 protection switching scheme against connection outage in OXC system due to port failure in SF.
The enhancement in connection reliability introduced by such protection scheme is then analyzed in chapter 4 where Markov modeling technique is employed to compare protected and unprotected OXC systems. Conclusion and future work is presented in chapter five finally.
Chapter 2
Monolithic Switching Fabrics and Modular Switching Fabrics

2.1 MEMS Switch Fabric

As the number of wavelength in DWDM system increases, building large port-count all OXC has emerged as a major technical challenge. As mentioned in chapter one, micro-electro-mechanical systems (3-D MEMS) appears to be the leading technological choice for realization of such SF when stringent requirements such as scalability, optical insertion loss and switching time are considered. In this chapter, we describe two different SF configurations namely, monolithic and modular SF. We investigate the reliabilities of these two fabric configurations in particular, we study the impact of overbuild port on overall fabric lifetime. The fabric lifetime is related to number of in-service replacement for the fabric and therefore carries important implications of OXC system operational cost for network operator.

2.2 Monolithic MEMS Switch Fabrics

In earlier stage of MEMS-based SF development, a widely adopted approach is to make use of large monolithic MEMS mirror array [7-10]. The arrangement is
schematically shown in Fig. 2.1 and is typically referred as monolithic SF. The SF consists of two MEMS mirror arrays, input/output fiber bundles, and input/output lens array. Each switch port is composed of one fiber and one lens, and is associated with one mirror in the mirror array. The optical signal from an input port is collimated and shone on the associated mirror. The tilt angles of this mirror in both rotational axes are adjusted, and the signal is directed to the mirror in the second mirror array that corresponds to the desired output port. The tilt angles of the second mirror are then adjusted to route the optical signal to the output lens/fiber.

![Figure 2.1 Illustration of a monolithic 3-D MEMS switch fabric [9]](image)

Although the monolithic SF consists of fewer components and simplifies the packaging complexity, it suffers from several drawbacks. First, yield of components is a major concern due to the scale of each port involved and the stringent optical
alignment tolerance (e.g. center-to-center spacing in fiber and lens array). Poor component yield leads to increased per-port cost and limited port count. Secondly, as the massive monolithic fabric is manufactured and assembled as a whole, the initial installation cost is very high even if only a limited number of ports are needed at the starting stage. Third and most importantly, in the scope of the thesis, the monolithic SFs are rigidly and permanently assembled. Therefore, there is no flexibility in component repair or in-service replacement. Failure situations can result in the entire fabric replacement at a very significant cost and also cause massive connection interrupt on functional ports.

2.2.1 Reliability Modeling

Figure 2.2(a) display a general model for a single-port connection with MEMS mirror. Here, we assume the use of controller is necessary for precise tilt angle control of each mirror such that optical insertion loss is kept at minimum. In practice, the controller can be implemented by using commercially available digital signal processor (DSP) and each DSP typical control 16 or 32 mirrors in a time-division-multiplexed manner [11].
Figure 2.2 (a) General model for a single port connection with MEMS mirror in monolithic switch fabric. (b) Equivalent reliability block diagram for the model of a monolithic switch fabric. Each DSP controls multiple single ports. All DSPs are connected to the OXC system controller.

The equivalent reliability block diagram is shown in Fig. 2.2(b). Only one half of the SF is shown (input or output) because of the symmetry of the configuration. Each block in Fig. 2.2(b) has its own failure rate, which is often expressed in FIT (failure in $10^9$ hours). Fiber, lens, and mirror of each port are bundled together to represent single port failure rate $\lambda_p$ (See Appendix A). Also included in $\lambda_p$ but not shown in Fig. 2.2(b) are the failure rates of electronics used for generating the mirror’s actuation voltage and sensing the mirror’s tilt angle. $\lambda_{DSP}$ is the failure rate of the controller in form of the DSP. In this reliability block diagram, there are two failure mechanisms. The first one is contributed from $\lambda_p$ and corresponds to a single port failure event. The second component is contributed from $\lambda_{DSP}$ and corresponds to a cluster failure event. Since each DSP controls a group of mirrors, failure of a
DSP leads to failure of all ports in the associated group.

**N-out-of-K redundancy**

When failure occurs within the SF, either a single-port or a cluster event, it must be repaired or replaced in order to maintain the number of port and therefore maintain the switching capacity throughout certain service lifespan. Since the monolithic SFs do not have the flexibility of in-service repair or replacement, overbuild ports are commonly added to reduce the chance of complete SF replacement during service. In other words, an $N \times N$ SF often carries $K \times K$ ports ($K > N$) to accommodate potential port failures such that the fabric maintain a scale of at least $N \times N$ at the end of service lifespan.

Reliability-wise, such SF can be modeled as a parallel structure having **N-out-of-K redundancy**. The SF composed of $K$ independent identical single port element, of which any $N$ of them must be functional for overall SF qualification. We assume they are all active from the beginning of service lifespan such that the redundant elements are also subject to failure. As a result, the maximum allowable number of failures is $F = K - N$. For example, if we want to have 256x256 OXC system which carries 256 light traffics with 16 overbuild ports added to the SF, the SF will have 272x272 ports when being installed. Once a failure occurred among one
of these 272 ports, the available ports are down to 271 ports. Since the SF is required to maintain a minimum of 256 traffic lines at one time, single port failure does not lead to repair or replacement directly. However when number of failed ports exceeds the number of overbuild ports, the SF cease to satisfy the minimum requirement of accommodating 256 communication lines. Therefore, a repair or replacement is needed to restore the desired 256 available ports. For monolithic OXC system, this repair denotes a replacement of the entire switch fabric.

2.2.2 Analytical Calculations

In this section, we derive the reliability function \( R(t) \) and the system life time distribution function \( F(t) \) of the SF. These two functions are essential in calculating the number of replacement needed within the service lifespan and the impact on such replacement by introducing overbuild ports.

First of all, we assume each port in the SF is independent and identical. They all have the same constant exponential failure rate \( \lambda_p \). A single port’s reliability \( R_p(t) \) is defined as the probability that the port remain functional at time \( t \) (Assume all activities stat at \( t = 0 \) ), the reliability function can be written as

\[
R_p(t) = e^{-\lambda_p t} \tag{2.1}
\]

Similarly, a cluster’s reliability \( R_{DSP}(t) \) is also defined as the probability that a
DSP and its related control circuitry will remain functional throughout time $t$, such that no failure port on this cluster is due to the malfunction of the DSP. With a constant exponential failure rate, $\lambda_{DSP}$, the cluster reliability function is:

$$R_{DSP}(t) = e^{-\lambda_{DSP} t}$$  \hspace{1cm} (2.2)

### 2.2.2.1 System Reliability

As mentioned in the previous section, with the overbuild ports, the monolithic SF system forms an $N$-out-of-$K$ reliability model. The system reliability probability, $R_{sys}(t)$, which is the probability of at least $N$ of $K$ successes, is governed by the Binomial Probability Law:

$$R_{sys}(t) = P(x \geq N) = \sum_{x=N}^{K} \binom{K}{x} \cdot R_p(t)^x (1 - R_p(t))^{K-x}$$  \hspace{1cm} (2.3)

where $x$ is the number of functional ports.

However, one must also take the cluster failures into account. If a SF system has $k$ DSPs and each DSP controls $q$ individual single port mirrors, then we have $k \times q = K$ ports in total on the SF.

Therefore, if we have $K = k \times q$ ports in total and $N = n \times q$ is the required number of ports for system success, we could derive the analytical result for the system's reliability:
\[ R_{sys}(t) = P(x \geq N) = \sum_{y=n}^{k-q} \sum_{x=N}^{K-q} \binom{K - y \cdot q}{x} \cdot R_p(t)^x (1 - R_p(t))^{K-x} \cdot \binom{k}{y} R_{DSP}(t)^y (1 - R_{DSP}(t))^{k-y} \quad (2.4) \]

In equation (2.4), the result can be interpreted as two parts contributing to the system reliability. One part is

\[ \sum_{y=n}^{k} \binom{k}{y} R_{DSP}(t)^y (1 - R_{DSP}(t))^{k-y} \]

Clearly, this part also follows a binomial probability law, represents the probability for each number of DSPs remains functional in the system. The number of success DSPs is varied from the minimum required number, \( n \), to the total DSP number, \( k \).

Based on these cluster failure situations, the second part is added to justify the overall system success probability.

\[ \sum_{x=N}^{K-q} \binom{K - y \cdot q}{x} \cdot R_p(t)^x (1 - R_p(t))^{K-x} \]

The second part here represents the success probability for each number of single ports remains functional after different cluster failure scenario. The probability is calculated by considering all possible number of functional single ports varying from the minimum required number, \( N \), to the total number of working single ports.
after the different cluster failures, that is \( K \cdot y \cdot q \).

### 2.2.2.2 Number of In-Service Replacement

When network operators install OXC systems in their networks, one of the most important parameter is the average number of replacement the OXC system within a specified period of service lifespan. This number determines the operating cost of the network.

The following example illustrates situations for the replacement: An OXC system using monolithic SF is put into operation and is functioning at time \( t = 0 \). When the SF fails (i.e. number of functional port is less than the required number \( N \)), it is replaced by a new SF of the same type, and restored to an “as good as new” condition. When this SF fails, it is again replaced, and so on. Assuming the replacement time is negligible. This kind of process is called an ordinary renewal process. The events of replacements are called renewals, noted as \( N(t) \), while the time intervals between consecutive events are called renewal periods. For more detail about Renewal functions, please refer to [Appendix A].
Figure 2.3 illustrates the relationship between renewal periods and number of renewals. The SF is having a sequence of renewal periods which is the system lifetimes, $T_1$, $T_2$, $T_3$, ..., between each replacement. These lifetimes are independent and identically distributed random variables with the same continuous distribution function:

$$F_{sys}(t) = P(T_i \leq t) \quad \text{for} \quad t > 0, i = 1,2,...$$ \hspace{1cm} (2.5)

and density function:

$$f_{sys}(t) = P(T_i = t) \quad \text{for} \quad t > 0, i = 1,2,...$$ \hspace{1cm} (2.6)

From the physical meaning of $f_{sys}(t)$, we know that this system life time density function is also the system failure density function. Thus, it can be directly derive
from the system reliability $R_{sys}(t)$ which we have in the previous section.

The failure density function can be found by differentiating reliability, $R_{sys}(t)$, with respect to time:

$$f_{sys}(t) = -\frac{dR_{sys}(t)}{dt} \quad (2.7)$$

Therefore, the distribution function $F_{sys}(t)$ is

$$F_{sys}(t) = 1 - R_{sys}(t) \quad (2.8)$$

Therefore, the expected number of replacement for a certain working period $T$ can be calculated by applying the renewal theory and is expressed in form of renewal function $W(T)$:

$$W(T) = E(N(T)) = \sum_{r=1}^{m} F_{sys}^{(r)}(T) \quad (2.9)$$

where $F_{sys}^{(r)}$ denotes the $r$th convolution result of $F_{sys}(t)$. (eg. $F_{sys}^{(2)}(t) = F_{sys}(t) * F_{sys}(t)$)

By numerically solving equation (2.9), the expected number of replacement with the service lifespan $T$ can be obtained.
2.2.3 Simulation

In addition to the analytical derivation in section 2.2.2, computer-aided discrete-event simulation has also been adopted to emulate the real case situations for a monolithic SF put into action. We use a simulation program to model the single port and the cluster failures. Subsequently, the simulated number of in-service replacement for the monolithic SF can be obtained.

In our discrete-event simulation, the modeled system evolves over time by a representation in which the state variables change instantaneously at separate points (countable number of points) in time. These points in time are the ones at which an event may occur. The events can either be a single port failure or a cluster failure. They are modeled as instantaneous occurrences and the SF’s state variables changes as the total number of failed ports accumulates.

Figure 2.4 illustrates the flow of the discrete-event simulation. A SF with \( K \geq N \) is in concern. At beginning of this simulation, an event list is generated. In the list, an exponentially generated failure time is given to each of the individual ports and DSP groups accordingly to their respective failure rate \( \lambda_p \) and \( \lambda_{DSP} \). After these future events along the time axis are determined, the simulation started with the next-event time-advance approach.
Figure 2.4 Flow chart of the discrete event simulation

The simulation clock is initialized to zero when the program starts and the clock is advanced to the time of first future events in the list, at which point the state of the SF is updated to account for the fact that an event has occurred, such that we update the total number of failed port and check if it exceeds the maximum allowable failures. If the system runs out of overbuild ports, a replacement routine is carried out. Else, the simulation clock is advanced to the time of the next most imminent event
and the state of the system is updated. This process of advancing the simulation clock from one event time to another continues until eventually the stopping condition is satisfied. In our case, the stopping condition is the end of service lifespan. Since all states changes in our simulation occur only at event times, periods of inactivity are skipped over by jumping the clock from event time to event time. The program logs down all the system behaviors such as number of port failed, number of replacement made. The simulation runs for more than a hundred thousand times to obtain the ensemble average of each of the interested parameters.

2.2.4 Results

Our study is to find out reliability parameters for the SF and therefore evaluate the feasibility and performance of applying the proposed optical SF into real life telecom applications. These reliability parameters include operational cost, maintenance frequency and service quality for establishing network connections. Average number of fabric replacements leads to answer for all of the above mentioned aspects. As a result, we have concentrated our discussion on the various results for the average replacement numbers.

In the analysis and simulations we mentioned in previous sections, we have made various assumptions. First, the system lifespan is assumed to be twenty years.
The reason is that twenty years is an established common requirement for telecommunication equipments. Any equipment is expected to be functional for the twenty years of time to fulfill the industry standards. Therefore, the target working period for all our calculations and simulations is twenty years of time. Secondly, the cluster failure rate, $\lambda_{DSP}$, is assumed to be a constant. Based on the proprietary vendor communications for each individual component in the DSP controller group, including the digital signal process (DSP), complex programmable logic device (CPLD) and field programmable gate array (FPGA), we are able to estimate a constant failure rate of FIT = 125. This cluster failure rate is only the hardware failure rate while the software failure rate for the digital processors is not considered. Finally, we assume each DSP controls 16 MEMS mirrors. This is typical time division multiplexing (TDM) channel capability for commonly used low cost DSP in MEMS system.

2.2.4.1 Failure Behavior

Figure 2.5 shows the output of the simulation program. Three cases have been plotted in this graph, each represent a probability distribution of the monolithic system at a particular single port failure rate. This result is obtained by logging down all the system status in each simulation and use the ensemble average of 100,000
executions to evaluate each of the parameters.

![Graph showing probability distribution](image)

Figure 2.5  Probability distribution of number of replacement for monolithic system. Assume 256x256 SF, 20 years of lifespan

In this graph we can see the number of fabric replacement in the period is a stochastic variable based on the single port FIT rate. From the distribution we could calculate the average number of fabric replacement which is approximately at the peak value of each distribution. When port failure rate increases, such peak is shifted to the right-hand side indicating an increase in the number of average replacements. We can also see the variance of the replacement numbers is relatively small.

2.2.4.2 Average Number of Replacement

From the analysis, we understand that the average number of replacement is depending on the FIT rate of components in the SF. As we discussed in the previous
section, components such as DSPs and other control electronics are commonly available and their failure rate is properly studied, so we could make assumptions on the cluster failure rate and many other components. However, the MEMS mirror itself is a relatively new device and no reliability data is carefully measured. As a result we leave the single port FIT rate as a variable and investigated the performance of the switch fabric at different MEMS FIT rate.

Figure 2.6 shows the relationship between single port FIT rate and the average number of fabric replacements in a 256×256 monolithic SF. In addition, three lines are plotted in the graph, each representing the SF with different number of overbuild ports. Therefore, we could evaluate the impact of the overbuild ports by comparing their required number of in-service replacements.

First of all, we can see all three lines increases nearly linearly with the single port FIT rate. For the no overbuild port case, average number of replacement raises so sharp that even at a very low single port FIT rate of 1000, the SF requires 40 replacements during its service lifespan. Clearly, such no overbuild monolithic system is not applicable in real life applications as the number of services, replacement cost, and overall downtime will be unacceptable.
Figure 2.6  Relation between single port FIT rate, $\lambda_P$, and the average number of fabric replacement for 256×256 monolithic switch fabrics

By adding 16 overbuild ports, the average number of replacement required drops dramatically. When single port failure rate equals to 1000 FIT, the overbuilt SF only requires two replacements. For the 32 overbuild ports case, the number of replacements keeps dropping by almost another half showing that the providing overbuilds is essential to the reliability performance of monolithic SF.

Figure 2.6 also shows both the analytical result from the renewal process calculations and the discrete event simulation result. We can see the two results accurately confirm each other, indicating that our simulation technique is correct and accurate in emulating the real life situations of the SF put into action.
2.2.4.3 Number of Overbuild Ports

If we keep adding more and more overbuild ports, the reliability keeps increases in the sense that the average number of replacements keeps decrease. However, large number of overbuild ports generates new problem in the overall performance of a SF.

Firstly, from Fig. 2.6 we can see that when we adding the first 16 overbuild to the SF, the improvement is dramatic, but when we add 16 more the improvement is much smaller. This trend continues that when we try to add more and more overbuilds, the improvement is getting smaller and smaller. However, the cost of overbuild is more and more significant. First of all, adding lots of overbuild ports would increase the size of the monolithic components especially the MEMS mirror array. This will drive the already poor component yield even poorer. Thus, leads to a significant increase in the per-port cost, making the SF less cost-effective. Furthermore, SF with a large number of overbuild ports in fact worsen the problem of its expensive initial cost. All of these factors limits the number of overbuild ports in a SF and the optimal number of overbuilds can only be determined when we could accurately evaluate the overall failure rate of the entire SF.
2.3 Modular Switching Fabrics

To cope with challenges monolithic SF are facing, namely the limitation on port count due to poor component yield rate, high initial cost and most importantly the lack of in-service replacement flexibility, modular optical SF architectures are proposed.

![Diagram of a single port modular MEMS SF](image)

Figure 2.7 Schematic of a single port modular MEMS SF [11]

Figure 2.7 illustrates the arrangement of a modular SF. In this SF, switch ports are distributed among a number of identical modules which resembles necessary circuits and mechanical structures to enable modular installations. Each of these switch port units is composed of fibers, lenses, and a stand alone MEMS mirror. The optical signal from input port is firstly directed to the MEMS mirror. The MEMS mirror will change its tilt angle such that the signal is shone to the target output port.
through the common dome lenses and folding mirrors in the SF. The tilt angles of the
text side MEMS mirror are then adjusted to route the optical signal to the output
lens/fiber. Associated angle sensing scheme is incorporated into each port. They are
responsible for minimize the extra alignment lost introduced by the module
installation mechanics.

The modular SF realizes a number of distinct benefits. First, there is no port
yield bottleneck since each port is built and optimized individually. Secondly, high
startup cost can be avoided by adding individual modules to the system gradually
instead of installing the whole SF as in a monolithic approach, realizes the
pay-as-your-grow cost structure. More importantly, modular system can allow
in-service installation and replacement of individual modules, giving flexibility to the
system operator to repair components and replace module while not causing massive
connection interrupt on functional ports. That is when the SF has failed ports,
replacement of the entire SF is not needed, only the module with the failed ports is
replaced. When we have $N$-out-of-$K$ redundancy, we could pick the module with the
most number of failed ports to replace once we run out of overbuild-ports.
2.3.1 Reliability Modeling

Figure 2.8 (a) Single port model for modular switch fabric (b) Reliability block diagram for modular switch fabric

Figure 2.8(a) displays a general model for a single-port setup in modular SF. A modular SF is composed of a number of identical switch modules. Each module contains a number of ports. Each port consists of fibers, a MEMS mirror, lenses, and an associated angle-sensing scheme. Reliability wise, a modular OXC switch structure is quite similar to a monolithic one. We still consider the reliability elements including single port reliability with its failure rate $\lambda_P$ and DSP group reliabilities with its failure rate $\lambda_{DSP}$. In modular model, we added a new tier of failures event which is the modular failures with its failure rate $\lambda_{MOD}$. Module failures are not occurred in monolithic cases but only in modular structure. It is
because to realize the modular architecture, extra components and circuitries must be
installed, such as the angle-sensors, MEMS angle controllers, and various
mechanical parts in order to maintain the relative alignment between the module and
the SF chest. As switch ports and DSPs are mounted on these modules, if any of
those abovementioned components has failed, all ports on this module will not be
functional any more.

2.3.2 Simulation

Because of the replacement mechanism mention in the previous section, the modular
structure has infinite states when we try to describe its relationship between failed
ports and replacement. After each module replacement, the number of failed ports on
that particular module is a random variable leaving the functional ports after each
replacement undetermined. This forms a random process as number of replacement
increases. Although we can numerically solve the simpler cases, as the size of the SF
increases, this random process is very difficult to be modeled by analytical equations.
Therefore, in the study of modular SF, only simulation is carried out to find out the
system reliability.

The simulation technique similar to the monolithic system is applied to this
modular system. They are all follow the discrete-event simulation method and
next-event time advance mechanism. The program flow and basic routines are the same except the repair and replacement procedures are differently handled for the two systems.

In monolithic system, once the system run out of overbuild-ports, a whole new monolithic SF replaces the failed one so that the system restored to its initial state. However, in the modular system, a different repair mechanism is adopted. When the number of overbuild ports cannot accommodated the failed ports, the module with the most number of failed ports was selected and replaced by a new one. The simulation is again ended when simulation clock reach the desired equipment lifespan.

2.3.3 Results

In this modular section, all results are obtained from the simulation as we mentioned previously. We have used the same criteria to evaluate the modular system as we did in the monolithic SF studies. Similar assumptions are made on the component failure rates and the system lifespan of twenty years is assumed. One important assumption for this part is that we assume the modular failure rate is relatively small in comparing to the DSP group failure rate such that we can focus our comparison between modular and monolithic SF on the difference of replacement mechanisms.
The impact of increased per-port failure rate for modular SF is discussed in the later discussion part.

2.3.3.1 Failure Behavior

![Probability distribution of number of replacement for modular system](image)

Figure 2.9 Probability distribution of number of replacement for modular system. Assume 256x256 switch fabric, 20 years of system lifespan

Figure 2.9 is the output of the modular simulation output. We can see the failure behavior of modular system by observing the probability distribution of the number of modular replacement. Again the graph shows the probability distribution for three distinct cases, each with a different single port failure rate. The number of replacement in the lifespan forms a shape closed to normal distribution. The average number of modular replacement can be calculated as the expectation of the
distribution and the average number is approximately at the peak of the distribution. The variance of the replacement numbers is relatively high than in the monolithic cases. As a result, when we studying the average number of modular replacement, we should bear in mind that the real life situations for a modular SF is easily underestimated if we only look at the average because of the large variance of the modular failure behavior.

2.3.3.2 Average Number of Replacements

Figure 2.10 shows the relationship between single port FIT rate and the average number of fabric replacements in a 256×256 modular SF. Again three overbuild cases is plotted in the graph to evaluate the impact of overbuild ports in the modular SFs.

In Fig. 2.10, we can once again see that all three lines increases nearly linearly with the single port FIT rate as in the monolithic discussion. However, one thing we should notice is that the average replacement numbers is much larger than in the monolithic system. This is because these average replacement numbers represent modular replacements. For each replacement only a module is replaced instead of replacing the entire SF.
Figure 2.10  Relation between single port FIT rate, $\lambda_p$, and the average number of fabric replacement for 256×256 modular switch fabrics

For the no overbuild port case, we can see a same performance as in the monolithic SF where average number of module replacements raises sharply as the single port failure rate increases.

With 16 overbuild ports, the replacement number required cut down to one fourth of the previous case. For the 32 overbuild ports case, the number of replacements keeps dropping by almost another half. Although the impact of the overbuild ports does not generate as much impact in this modular system, we can still see the great importance of adding overbuilds to the system reliability performance.
2.4 Comparisons between Monolithic and Modular Switch Fabric

Number of replacements reflects the number of service needed for in-service equipment during its lifespan, the more replacement required, the more frequent maintenance must be take place to restore a failed connection. Such maintenance action costs connection interrupt to the user and operational cost to the system operator. In Fig. 2.11 below, we first compare the total number of replacement needed of the two SF arrangements and evaluate performance between the monolithic and modular SF.

![Graph showing comparison of number of replacements between monolithic and modular systems](image)

Figure 2.11  Comparison of number of replacement between Monolithic and Modular system. Assume 256×256 switch fabric
In Fig. 2.11, we can see the number of replacement in both monolithic and the modular SF cases. For the no overbuild case, modular and monolithic SF requires the same number of replacement. This is easy to understand; when the SF has no overbuilt, any single failure will require a replacement to fix the failure in order to keep the desired number of connections.

For overbuilt cases, modular SF requires a much larger number of replacements. This is due to the different replacement mechanism. Under monolithic system, one replacement will restore the SF back to the initial state, repair all the failed ports. In the contrast, the replacement in modular system only repairs a number of failed port on a particular module, leaving some failed port un-repaired. Therefore, modular system may require more frequent replacement than the monolithic system. If each of these replacements takes several hours to be carried out, the total down time of a modular SF will be around 6 times higher than the monolithic SF and the system operator will need to carry out the maintenance more frequently if they choose to use a modular SF.

When we associate the number of replacement with the replacement cost, we can see the other side of the coin. In monolithic system, each replacement represents the installation of a new SF which is identical with the initial installed one in order to restore the system back to its functional state. That means, for monolithic system,
one single replacement will cost the amount of another initial cost. In other words, if
the system requires only one repair during the operation period, the total cost is the
double of its initial cost of installing the first switching fabric.

It is not the case in the modular approach. Modular design allows flexibilities in
doing the in-service repair and replacement. When a replacement is need for the
modular system, only one module with the most number of failed ports are replaced.
The cost for each replacement is equal to the cost of each module. For a 256×256
modular SF divided into 16 modules, each of them only costs one sixteenth of its
initial cost.

Consequently, Fig. 2.12 clearly indicates the significant advantage from
modular switch when comparing total operational cost for operating both switches in
twenty years of lifespan. Particularly, when there is no overbuild ports protection, the
advantage is huge. Although the modular switch architecture may increase the
per-port cost comparing to the monolithic one, the advantage of modular structure is
still significant.
Figure 2.13  Comparison of total cost between Monolithic and Modular system for different number of overbuild ports. Assume 256×256 switch fabric, modular system has the same building cost as monolithic system.

Another important aspect should be considered is the service quality of the two systems. This can be evaluated by investigating the forced service interrupt generated by the in-service replacement. A forced service interrupt happens when the in-service replacement is carried out. Some connections on the functional ports will be affected during the replacement and we call it a forced service interrupt. More frequent forced service interrupt indicates the poorer quality of service. For a monolithic system, whenever a replacement is needed, all the ongoing traffic on the entire SF must be interrupted. However, in a modular system, a replacement only happens on a particular module, so only those traffic on that module is affected.
Figure 2.13  Comparison of number of forced service interrupt caused by replacement between 256×256 Monolithic and Modular system for different overbuild ports.

Figure 2.13 shows that each SF arrangement is again having a huge difference in the number of forced service interrupts. We can see the modular system beats the monolithic once again in the service quality point of view.

From the above comparison on the total operational cost and the forced service interrupt, clearly we can see when the single port failure rate is high, the modular SF have an absolute advantage in the analysis. However, as we mentioned previously, modular SFs generally have a higher per-port cost than monolithic fabric because of its extra circuitry and sensing components. When single port failure rate is low, the difference between the two arrangements in the operational cost or the number of forced interrupt is not big. As a result, modular fabrics' higher per-port cost and its
extra modular failure possibility put itself into disadvantage against the monolithic structure.

2.5 Summary

In this chapter, we have studied the two available OXC SF arrangements. One is the monolithic approach and the other is the modular one. We have evaluated the both system from its total number of required replacements, total operational cost and also the forced service interrupt. In the study, we understand that introducing overbuild ports is essential to the overall reliability of the SF. In both arrangement, overbuild ports do give a significant improvement in their reliability performance.

Due to the different replacement mechanism, modular SFs have larger number of replacement, but lower replacement cost and fewer forced service interrupt. The optimal choice between a monolithic SF and a modular SF is still controversial. If the MEMS failure rate is low, monolithic SF provides a more reliable service as it needs less number of replacement, but at high component failure rates modular SF has its advantages in the operational cost and forced service interrupt measurements.
Chapter Three
Protection Switching in OXC Systems

3.1 Protected OXC System

In Chapter 2, we have studied the impact of port and cluster failure rates on SF’s operational economy. When a connection is established through the OXC system, restoration and protection schemes against such failure are inevitable to order to achieve survivable optical networks. To improve overall OXC system reliability, redundant SF can be employed in OXC system. Such arrangement is called protected OXC system. Several protection schemes have been demonstrated for OXC systems [13-15]. For example, the use of 3-dB coupler for bridging the optical signal through two SF has been reported in [13]. While the scheme requires only passive optical components, it requires reconfiguration of the connection matrix during the protection switching operation which is undesirable because 1) it causes interruption on functional connection, an 2) it requires long protection switching time, 3) it complicates the already-challenging servo-control mechanism for mirror’s tilt angle in 3-D MEMS SF.

In this chapter, we propose and experimentally demonstrate an efficient and scalable protection scheme for large port count MEMS-based OXC. A unique feature
of the proposed scheme is the addition of a low-cost laser transceiver on each bi-directional switch port which 1) enables direct communication between input and output ports so that restoration can be rapidly coordinated in case of failure, 2) provides a keep alive signal for the backup fabric so that overall restoration time can be minimized, and 3) allows other network functions such as connection verification in OXC systems.

3.2 Proposed OXC Architecture with 1:1 Switch Fabric Protection

![System Controller]

Fig. 3.1 Schematic of the proposed MEMS-based OXC architecture.

Figure 3.1 illustrate an OXC system with the proposed 1:1 protection scheme. We consider MEMS-based switching fabric in our proposed structure. The OXC system
has two identical MEMS SFs: one serves as the working SF while the other serves as the protection SF. On top of the SFs and the interface linecards is the system controller, which is responsible for lightpath provisioning and maintaining a record of system status. For each bi-directional port on the linecard, there are input and output $2\times2$ optical switches, a laser transceiver, and input and output power monitors realized by optical taps and photo detectors. The optical signal can be routed through either fabric according to the states of the input and output $2\times2$ switches. Under normal operation, the signal is routed through the working SF, while the output of the laser transceiver travels through the protection SF.

The laser transceiver on the interface linecard offers several distinct advantages. Firstly, it served as a light source providing a “keep alive” signal. As its light power pass through the protection SF, an active re-optimization on mirror alignment is enabled. This advantage is significant when we considering system with large port count using 3-D MEMS technology, where mirror alignment is one of the key factors affecting the restoration time. The keep-alive signal essentially guarantees the protection SF is always in a ready mode. When failure occurs on the working SF, reconfiguration on the protection side is not needed during restoration, resulting in a more responsive protection switching. The laser transceiver can establish a direct communication channel between input and output ports which is
absent otherwise in all-optical switching system because of the lack of access to the transmitted signal's overhead bytes in traditional OEO switching systems. This communication channel can be used to realize connection verification during initial circuit provisioning and signaling, as well as other possible networking functions which can only be found in the traditional electronic switching systems before. We should also point out that since the laser transceiver is used for inter-port communication, its data rate can be much lower than that of the signal. Typical low-cost OC-3 transceiver (155Mbps) is more than sufficient for such application.

3.2 Protection Scheme

The operation of protection switching in our proposed scheme is illustrated in Fig. 3.2. In Fig. 3.2(a) the connection failure occurs in the working fabric, results in a loss of signal (LOS) detected by the output power monitor. The output port then first toggles the output 2×2 switch and prepares to receive signal from the protection SF. It simultaneously signals to the input port using the laser transmitter via the protection fabric. This is illustrated in Fig. 3.2(b). Upon receiving the message, the input port changes the state of the input 2×2 switch and redirects the optical signal to the protection fabric so that the connection is restored, as shown in Fig. 3.2(c). Compared to the scheme proposed in [13] where 3-dB coupler is used instead of 2×2
switches, lightpath restoration here causes no interruption to functional connections on other ports, and higher level system controller is not involved during the entire restoration process. In addition, the direct communication link between ports results in fixed communication bandwidth between the ports and the system controller even when the port count is scaled to a large number.
Figure 3.2 Schematic of the proposed OXC system. (a) A connection failure occurred in the working fabric. (b) Signaling between input/output ports. (c) The signal path is re-routed to the protection fabric. The connection is restored.

3.2.1 Experimental Setup

In Fig. 3.3, a single-port switch setup is employed to experimentally demonstrate the feasibility of proposed protection scheme in the setup, prototype linecards are constructed for both the input and the output port with all the key components such as the 2×2 switch, optical transceiver and power monitor. Between the two linecards are two optical fiber patch cords to emulate lightpath through the SF. In addition, a 1×1 switch on/off switch is inserted in the upper optical patch cord to simulate connection failure. PC1/DAQ card is also used to control the optical signal source, the sampling scope and the 1×1 on/off optical switch. The protection algorithm described above is implemented in commercially available windows-based control software (LabVIEW) and is installed in both PCs.
PC2, which is connected to SW2 and the laser transceiver via a high speed digital I/O card, represents the linecard’s onboard digital signal processor which is essential to establish the direct communication between input and output ports. Since the connection is unidirectional in the experiment, the laser transceiver is put in a loopback configuration, representing the transmitter on the output side and the receiver on the input side. The optical transceiver is operated at 100Kbps, limited by the speed of I/O card and the processing power of PC2. A continuous digital bit stream is sent through the I/O card to the transceiver. The bit pattern can be changed to indicate the occurrence of connection failure.
3.2.3 Software Implementation and Control Algorithm

Both PC are installed with LabVIEW for the execution of protection switching algorithm. The algorithm is explained with the aid of Fig. 3.4.

![Flow chart of control algorithm for fabric protection switching scheme.](image)

The control algorithm is separated into two parts. Each of them forms a control loop and is running on a individual personal computer. The part running on PC1 is responsible for continuously monitoring the connection status via the tow power monitors. Another control loop running on PC2 will continuously generate digital bit patterns and send out repeatedly through the laser transceiver, while it will also receive back the digital patterns from its input ports. The program will then perform
an instantaneous pattern matching. If the received pattern matches the normal pattern which indicates the switch is function properly, the program will do nothing but wait for the next pattern. However, when the program detects a loss of signal (LOS) at the PC1, it will trigger the fabric protection mechanism. Firstly, the PC1 program will issue a trigger to toggle the 2×2 switch on the output side linecard. At the same time the program on PC1 will issue another triggering signal to its counter part running on PC2. PC2 will then changes the transmission pattern to indicate a connection failure on this port. Upon the receiving of this triggering pattern after the transceiver loop-back, the program will use a pattern match up mechanism to confirm this digital bit sequence. Finally, the program will issue command to toggle the 2×2 switch at the input side of the switch. As a result, the light traffic will be re-directed to the protection path of the OXC system. Thus the protection switching operation finishes here successfully.

3.2.4 Experiment Results

Figure 3.5 displays the sequence of connection restoration. A drop in signal power is fast measured at the output power monitor upon connection failure. Control pulse for the output 2×2 switch is then generated. The control pulse for input 2×2 switch is generated when the change of transmission pattern is detected. This is followed by
restoration of signal power. The slight difference in signal power before and after the protection switching is due to different insertion losses of the working and protection lightpaths.

![Signal from Output Tap Monitor](image)

**Figure 3.5** Experimental result of the proposed protection scheme.

The overall restoration time we achieved in this experiment is 16ms. Two major limitations introduced the delay during the experiment. The first delay is the switching time of the 2x2 switch, which is measured to be 8ms from the rising edge of output 2x2 switch control pulse to the restoration of signal power at the output power monitor. Such delay can be reduced by employing 2x2 switch with faster switching time (<1ms) [16]. The other delay is due to the execution time of the windows-based control program which highly depends on the processing power of
personal computer. This delay is shown in Fig. 3.5 as the duration between the two rising edge of the two control pulses. This extra overheard can be significantly reduced if the protection algorithm is implemented in hardware such as field programmable gate arrays (FPGA) or microprocessors, and restoration time of <5 ms should be achievable.
3.3 Connection Verification Scheme

An important functional requirement for any OXC system is the capability of verifying the intended lightpath provisions through the optical SF are executed correctly. This process is called connection verification. Previously, connection verification has been demonstration by using a pilot tone signal to modulate the MEMS mirror's tilt angle and hence of output optical power. Here, we utilize the addition of laser transceiver on OXC system linecard and hence the direct inter-port communication channel to achieve the connection verification.

Suppose we wish to provision and verify a connection from port $i$ to port $j$ of the SF in Fig. 3.1 (refer to previous OXC system diagram). The system controller will first issue a command to configure the SF according to the provision. At the same time, the $2 \times 2$ switches of input port $i$ and output port $j$ are in the states such that the output of the laser transceiver is routed through the working SF. Input port $i$ then uses its laser transceiver to send its port ID in repeated frame of digital patterns to output port $j$ via the working SF. In the latter experimental demonstration, the format of the transmitted frame is shown in Fig. 3.6.
<table>
<thead>
<tr>
<th>1 bit</th>
<th>8 bits</th>
<th>1 bit</th>
<th>22 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start bit</td>
<td>Port ID</td>
<td>Fabric Type</td>
<td>Payload</td>
</tr>
</tbody>
</table>

Figure 3.6 Data field in the transmitted frame used in the connection verification.

The “Start” bit is always 1 indicating the start of a frame. The “Fabric Type” bit indicates whether it is for the connection verification of the working fabric or the protection fabric by 1 or 0, respectively. The 8 bits port ID can represent up to 256 ports. The “payload” is used for general inter-port communication purpose. In idle mode, a pattern of “101010…” is used as the payload. As a result, the frame looks like “1 00011010 1 101010…10”.

When output port \( j \) receives the port ID and confirms it is matched with that of input port \( i \), it toggles the output 2×2 switch and informs the system controller that the connection is set up correctly. If the received port ID does not matched with the provisioned one, output port \( j \) alerts the system controller that the connection is incorrectly provisioned.

Knowing output port \( j \) confirm the connection via the system controller, input port \( i \) then flip the 2×2 switch. At this point, the signal is routed through the optical fabric. System controller then request optical signal power level measurement from the tap monitor. Insertion loss of the connection is checked against the acceptable
range. The system then either declares the insertion loss of the established lightpath is too high, or acknowledges the connection verification on the working SF.

After the laser transceiver signal passes from port $i$ to port $j$ via the protection SF, protection SF’s connection verification can be performed by sending the port ID from input port $i$ and verifying at output port $j$.

We should noted that connection verification here by using direct inter-port communication channel avoid the dithering of MEMS mirrors [15], which already requires sophisticated servo control mechanism to maintain the precision of its tilt angles.

### 3.3.1 Experimental Setup

The same experimental setup for the protection switching experiment describe in section 3.2 is employed to demonstrate the proposed connection verification algorithm. The $1\times1$ on/off switching used to simulate connection failure event is removed from the experiment. All controls and data logging is again carried out by the computer based data acquisition (DAQ) cards.
The algorithm is again implemented in LabVIEW. The entire connection verification scheme is divided into two control loops and executed on two separated PCs. The flow chat illustrating the coordination between the two PCs during the connection verification process is shown in Fig. 3.7.
3.3.2 Experiment Result

![Diagram showing voltage over time](image)

Figure 3.8 Experimental result of connection verification scheme

In Fig. 3.8, the steps of connection verification are displayed. The first control pulse in Fig. 3.8(a) indicated the starting of the connection verification process. After the output port receives and verifies the matching of the bit patterns it toggles its 2x2 switch as the second control pulse is raised in Fig. 3.8(b). In a very short time, the input port has acknowledged the output port's confirmation of the bit patterns. Thus, it flips its 2x2 switch as well (Fig. 3.8(c)). The forth control pulse in Fig. 3.8(d) is raised after the system controller compared the signal power level between input and output port and conform the insertion loss is within specification. At this point, the
connection is verified for the working fabric. The same bit pattern matching process will be finished again before the control pulse in Fig. 3.8(e) rises to indicate the connection is verified for the protection fabric.

The total time need for performing connection verification is 57ms, which is again limited by the execution time of the Window-based software. This is especially significant for the sending and receiving digital bit pattern part. This extra overhead can be significantly reduced if the algorithm is implemented in hardware such as field programmable gate arrays or microprocessors.
Chapter Four
Connection Availability in OXC Systems

4.1 Markov Modeling

In Chapter 3, we demonstrated a 1:1 protection switching schemes for OXC systems.

In this chapter, we introduce the Markov-modeling technique to evaluate the improvement in OXC system reliability by adopting the 1:1 protection scheme.

System reliability of OXC is typically expressed in terms of connection availability. When a lightpath is established from port $i$ to port $j$ in an OXC system, the connection availability of the lightpath is defined as [17]

$$\text{Connection Availability} = \frac{\text{Period when the connection is functional during the entire service lifespan}}{\text{Service lifespan}}$$

The difference between the denominator and the numerator is the connection down time to port failure. Given that 3-D MEMS SF is a new device and its reliability data is not readily available, investigation of the connection availability over a range of port failure provide a strong indication on the feasibility of using MEMS-based OXC systems to realize survivable optical networks.
4.2 Protected System

Figure 4.1 displays the equivalent reliability block diagram of the 1:1 protected OXC system shown in Fig. 3.1. In terms of reliability, the two SF are connected in parallel whereas the linecards and the SFs are connected in series. To sustain a connection, the corresponding ports on at least one SF and both associated linecards have to be functional.

![Reliability block diagram for the protected OXC system](image)

Since each port on SF has two possible states, the functional state and the failed state, the connection status of the OXC system has four possible states, listed in Table 4.1.

Each connection status is described by \((w, p)\) where \(w\) and \(p\) represents the states of the working and protection SF respectively, with “1” indicates functional and “0” indicates failed. Based on these four states, the Markov diagram of the connection status in protected OXC system is shown in Fig 4.2.
Table 4.1 Possible states of the proposed OXC system

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 1)</td>
<td>1</td>
<td>1</td>
<td>Both SFs are good. Connection is up.</td>
</tr>
<tr>
<td>(1, 0)</td>
<td>1</td>
<td>0</td>
<td>Only working SF is functional. Connection is up.</td>
</tr>
<tr>
<td>(0, 1)</td>
<td>0</td>
<td>1</td>
<td>Only protection SF is functional. Connection is up.</td>
</tr>
<tr>
<td>(0, 0)</td>
<td>0</td>
<td>0</td>
<td>Both SF are failed. Connection is down.</td>
</tr>
</tbody>
</table>

Figure 4.2 State transition diagram of the proposed 1:1 protected OXC system

Each transition between the connection states is labeled with the associated transition (failure) rate(s). These include the failure rates of SF's port $F_{SW}$, the laser transceiver
$F_{TR}$, the linecard $F_{LC}$. The repair rate is represented by $R$. Failure in SF's port triggers the transition from (1, 1) to (1, 0) or (0, 1), and the transition from (1, 0) or (0, 1) to (0, 0). We assume that port on working and protection fabric do not fail simultaneous and therefore no transition between (1, 1) and (0, 0) is labeled with $F_{SW}$. The SF's port failure rate $F_{SW}$ can be attributed to single port failure event or a cluster failure event triggered by DSP failure, as described in chapter two. In Table 4.2, because of the unavailability of MEMS mirror failure rate, we shall consider the SF's port rate to be a variable.

Table 4.2 Failure rates for various components in the system

<table>
<thead>
<tr>
<th>Components</th>
<th>Symbols</th>
<th>Failure Rates [18]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2 optical switch</td>
<td>$F_{2x2}$</td>
<td>52 FITS</td>
</tr>
<tr>
<td>Optical Tap/Photodetector</td>
<td>$F_{PM}$</td>
<td>100 FITS</td>
</tr>
<tr>
<td>Connector</td>
<td>$F_{C}$</td>
<td>10 FITS</td>
</tr>
<tr>
<td>Linecard Electronics</td>
<td>$F_{E}$</td>
<td>1000 FITS</td>
</tr>
<tr>
<td>Transceiver</td>
<td>$F_{TR}$</td>
<td>571 FITS</td>
</tr>
<tr>
<td>MEMS Switch Fabric (per port)</td>
<td>$F_{SW}$</td>
<td>Variable</td>
</tr>
</tbody>
</table>

The linecard failure $F_{LC}$ is the sum of first four components' failure rates listed in Table 4.2. Notice that the laser transceiver $F_{TR}$ is not part of $F_{LC}$. Failure in linecard leads directly to a connection outage (0, 0) from (1, 1), (1, 0), and (0, 1). Transceiver failure only disables the protection switching mechanism and therefore is associated
with the transition between (1, 1) and (1, 0). We also assume that the corrective maintenance strategy will bring the OXC back to its initial functioning state. As a result, all transition labeled with R end at the state (1, 1). The average repair rate $R$, which can also be regarded as mean down time (MDT), is set to be 4 hours [15].

4.2.1 Markov Process

The state variable of the connection at time $t$ is denoted by $X(t)$. The connection is assumed to have only four possible states denoted by (1, 1), (0, 1), (1, 0) and (0, 0). The event $\{X(t) = j\}$ means that the connection at time $t$ is in state $j$, $j = (1, 1), (0, 1), (1, 0), (0, 0)$. The probability of this event is denoted by

$$P_j(t) = P( X(t) = j ) \quad \text{for} \quad j = (1, 1), (0, 1), (1, 0), (0, 0)$$

(4.1)

The connection is assumed to start in state (1, 1), at time $t = 0$, which means the OXC system is fully functional. The transitions between the states may be described by a stochastic process $\{X(t); t \geq 0\}$.

Transitions that can be approximately described by a stochastic process with the Markov property: Given that a connection is in state $i$ at time $t$ [i.e., $X(t) = i$], the future states $X(t + \nu)$ do not depend on the previous states $X(u)$, where $u < t$. In other words, when its present state is known, the probability of any particular future behavior of the process is not altered by additional knowledge about its past behavior.
Markov property is defined by

\[ P(X(t + v) = j \mid X(t) = i; X(u) = x(u); 0 < u < t) \]

\[ = P(X(t + v) = j \mid X(t) = i) \quad \text{for all possible } x(u); 0 < u < t \quad (4.2) \]

Such kind of stochastic process satisfying the Markov property is regarded as a Markov process. The conditional probabilities

\[ P(X(t + v) = j \mid X(t) = i) \quad (4.3) \]

are the transition probabilities of the Markov process.

We assume all the failure rates of components in our system and the repair rate is exponentially distributed. From the memory-less property of the exponential distribution, if the Markov process has transition probability \( P(X(t + v) = j \mid X(t) = i) \) does not depend on the time \( t \) but only on the time interval \( v \) for the transition, the transition probabilities are said to be stationary (or at the steady state).

\[ P(X(t + v) = j \mid X(t) = i) = P_{ij}(v) \quad (4.4) \]
4.2.2 Steady State Probability Calculations

In other words, after the connection has been running for some long enough duration, it has lost its dependency of its initial state $X(0)$. At such steady state, we could observe from the state transition diagram in Fig. 4.2 that the transition matrix of our system is

$$ A = \begin{bmatrix}
-3R & F_{SW} + F_{TR} & F_{SW} & F_{LC} \\
R & -F_{SW} - F_{TR} & 0 & F_{SW} + F_{LC} \\
R & 0 & -F_{SW} & F_{SW} + F_{LC} \\
R & 0 & 0 & -2F_{SW} - 3F_{LC}
\end{bmatrix} \quad (4.5) $$

such that

$$ X(t + \nu) = A X(t) \quad (4.6) $$

At the steady state, $P_j(t)$ tends to a constant value when $t \to \infty$ [19],

$$ \lim_{t \to \infty} \frac{dP_j(t)}{dt} = 0 \quad j = 00,01,10,11. \quad (4.7) $$

Then the steady state equations for the proposed OXC system is

$$ \begin{bmatrix}
-3R & F_{SW} + F_{TR} & F_{SW} & F_{LC} \\
R & -F_{SW} - F_{TR} & 0 & F_{SW} + F_{LC} \\
R & 0 & -F_{SW} & F_{SW} + F_{LC} \\
R & 0 & 0 & -2F_{SW} - 3F_{LC}
\end{bmatrix} \begin{bmatrix}
P_{11}(t) \\
P_{10}(t) \\
P_{01}(t) \\
P_{00}(t)
\end{bmatrix} = \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix} \quad (4.8) $$

Thus matrix operation in $(4.8)$ leads to
\[(F_{LC} + 2 F_{SW} + F_{TR}) \cdot P_{II}(t) = R \cdot (P_{I0}(t) + P_{01}(t) + P_{00}(t)) \quad (4.9)\]
\[(F_{LC} + R + F_{SW}) \cdot P_{I0}(t) = (F_{SW} + F_{TR}) \cdot P_{II}(t) \quad (4.10)\]
\[(F_{LC} + R + F_{SW}) \cdot P_{01}(t) = F_{SW} \cdot P_{II}(t) \quad (4.11)\]
\[R \cdot P_{00}(t) = F_{LC} \cdot P_{II}(t) + (F_{SW} + F_{LC}) \cdot (P_{I0}(t) + P_{01}(t)) \quad (4.12)\]

Since the system could only be in one of the four states at a certain time, so we know that the sum of the state probability is always equal to one. That is,

\[P_{II}(t) + P_{I0}(t) + P_{01}(t) + P_{00}(t) = 1 \quad (4.13)\]

By solving the equations (4.9) to (4.13), we can obtain the steady state probability of the system

\[P_{II}(t) = \frac{R}{(F_{LC} + R + 2 \cdot F_{SW} + F_{TR})} \quad (4.14)\]
\[P_{I0}(t) = \frac{R \cdot (F_{SW} + F_{TR})}{(F_{LC} + R + 2 \cdot F_{SW} + F_{TR}) \cdot (R + F_{SW} + F_{LC})} \quad (4.15)\]
\[P_{01}(t) = \frac{R \cdot F_{SW}}{(F_{LC} + R + 2 \cdot F_{SW} + F_{TR}) \cdot (R + F_{SW} + F_{LC})} \quad (4.16)\]
\[P_{00}(t) = \frac{F_{LC}^2 + F_{LC} \cdot (R + 3F_{SW} + F_{TR}) + F_{SW}(2F_{SW} + F_{TR})}{(F_{LC} + R + 2 \cdot F_{SW} + F_{TR}) \cdot (R + F_{SW} + F_{LC})} \quad (4.17)\]

Since the connection is only functional when at least one of the two SFs is carrying the traffic, the probability of connection outage equals to the probability of \(P_{00}\) state. 

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The connection availability equals the sum of probabilities of the three other states.

4.3 Unprotected System

For OXC system without a 1:1 protection, its reliability block diagram is shown in Fig. 4.3. Such serial arrangement implies failure of any one component among all directly leads to a connection outage.

![Reliability block diagram of the unprotected OXC system](image)

Figure 4.3 Reliability block diagram of the unprotected OXC system

Figure 4.4 displays the state diagram of the connection in unprotected OXC system. Here, 1 and 0 represent the connection is functional and failed respectively. Transition from state 1 to state 0 can be triggered by 1) failure in either input or output interface linecard or both, $2F_{LC}$, 2) failure of the port with which the connection is associated. The port failure can be either a single port event or a cluster event described in chapter two. It should be noted that laser transceiver, $2\times2$ switch have been removed from linecard in unprotected OXC systems, the linecard's failure rate $F_{LC'}$ is different from the one used in the protected OXC systems $F_{LC}$. Transition from state 0 to state 1 means that the connection is repaired and the
transition $R$ is the reciprocal of mean-time-to-repair (MTTR). In this thesis, we assume MTTR to be 4 hours.

![State transition diagram of the unprotected system](image)

Figure 4.4 State transition diagram of the unprotected system

The connection availability of such unprotected system equals the probability that the system stays in the "1" state, which is calculated in equation (4.18).

$$P_I = \frac{R}{(2F_{LC} + F_{sw} + R)} \quad (4.18)$$

### 4.3 Results and Comparisons

Figure 4.5 shows the calculated connection availability in the proposed protection system and that of an unprotected system. Although the unprotected system has a lower complexity, its connection availability with the per-port failure rate in the range from 0 to 5000 FIT. On the contrary, system with proposed protection scheme shows significant improvement in connection availability, satisfying the typical five 9s (>0.99999) requirement for telecommunication system. This also correspond to a mean down time per year is 3.24 minutes per year even if the switching fabric has a
failure rate as high as $10^5$ FIT per port.

![Graph showing connection availability for protected and unprotected OXC systems](image)

Figure 4.5 Calculated availability: protected vs. unprotected OXC systems

4.4 Summary

In conclusion, the proposed 1:1 MEMS-based OXC system with the protection scheme demonstrate significant improvement in connection availability. Even at large port failure rate, the OXC system still maintain the five 9's availability standards. Such result indicate that survivable optical network can be achievable by using 3-D MEMS-based optical SF bearing a large range of uncertainty in MEMS mirrors failure rate.
Chapter Five
Conclusion and Future work

5.1 Conclusion

Optical Cross Connects (OXC) with all optical SFs has been intensively studied during the past decades because of its potential use as provisioning and restoration vehicles in next generation mesh-based core optical network. Currently, efforts have been focused on the design and fabrication of the MEMS-based SF. To realize survivable optical networks by deploying MEMS-based OXC system, reliability of OXC system have to be carefully investigated.

In this thesis, studies on reliability issues in OXC systems are carried out. Firstly, we studied two available switch fabrics (SF) configuration of building large scale 3-D MEMS-based OXC switch fabric. They are the modular and the monolithic switch fabrics. The reliabilities of these two arrangements are compared and analyzed. We have shown that the modular SF outperforms the monolithic switch in both operational cost and service quality because of the different replacement mechanisms. We also investigate the significant impact on the SF’s reliability of adding overbuild ports to the SFs.

Then connection availability of OXC system is studied. We have used the
stochastic modeling technique to evaluate how the connection availability varies for different per-port SF failure rate and we studied the impact of adding 1:1 redundancy as protection to the SF in the OXC system. The result shows a protection on SF leads to a drastic improvement in the system's connection availability, even at high per-port SF failure rate the protected system could still guarantee high connection availability standard. This implies that survivable optical network can be achievable by using 3-D MEMS-based optical SF even the MEMS mirror's failure rate remains uncertain.

We also proposed and experimentally a novel 1:1 protection scheme for large-port-count MEMS-based OXC system. With the introduction of low-cost laser transceiver on the linecards, a direct communication channel between input and output ports is established. Through this communication channel, rapid restoration against connection failure and network function such as connection verification are realized. A connection verification experiment has also been carried out to show one example of possible added network functions by introduction direct inter-port communication. The proposed schemes are in a single-port based design so that the system complexity will not be affected as port count increases. All these features of the proposed scheme make the structure an attractive candidate for building a very large port-count OXC in next generation optical networks.
5.2 Future work

There are still a number of elements that remain to be investigated. More careful studies can be conducted with detailed parameters.

For the comparisons between monolithic SF and modular SFs, we have done a series of calculations based on approximated reliability numbers and series of assumptions on the failure rate of different components. Particularly, as there is still no solid reliability data for the MEMS mirrors currently, we could not estimate the actual range of the system reliabilities. Such reliability data of the MEMS may appear in a few years of time and then a more concrete analysis could be conducted with detailed reliability parameters. Another important assumption in our study is that for the microprocessors and other electronics used in the OXC system, only hardware reliabilities is considered. However, one of the major failure possibilities of these electronic components is contributed by software failures. Such software failure rates of the electronics are expected to be much higher than their hardware failure rates. Therefore, in order to have a more accurate estimation, software reliabilities have to be included. Furthermore, the building cost of both systems is only an indication number. A more careful study should be carried out so that further evaluation can be made on the advantages for either system. The reliability numbers for each component can be carefully collected and the building costs should be
evaluated with more accurate estimation. These may require industrial experience and expertise, but it is important to have such comparison. As the communication bandwidth grows rapidly, more company will want to purchase and install such a large scale MEMS-based OXC in the coming few years. Therefore, making a decision between the two architectures is inevitable.

The proposed protection scheme is experimentally demonstrated with a switching time of 16ms. This result can only serve the purpose of a proof-of-principle experiment. It is not fast good enough for a common standard of 10ms of protection switching time. Efforts can be made to improve this protection switching experiment. One possible area to be improved is to shorten the execution time of the software control algorithms. A better approach is to implement the experiment program in a real-time system such a PXI system instead of using a windows based personal computer. The windows-based development software LabVIEW can be then replaced by some lower level development languages such as CVI or C/C++.

Finally, with the explicitly established direct communication channel using the low cost transceiver added on input and output linecards, efficient inter-port communication is offered. Such communication channel is ideal for realizing signaling functions between the input and output ports. Therefore, more value added
network functions can be investigated and demonstrated with our proposed OXC architecture.
References


[18] “Proprietary vendor communications”.


Appendix A

Reliability Modeling for Systems

Reliability modeling is a way to examine a multiple component system calculating its overall reliability, the probability that the system will work. Many systems can be modeled using series structures, parallel structures or combinations of both.

A series system is composed of series of elements, the failure of any of which will result in a system failure. A parallel system is composed of a group of elements, the failure of all of which is necessary for a system failure. It should be noted that the term series and parallel here is defined in the reliability sense. It is quite possible for two components to be electrically parallel but reliability-wise in series.[17]

Series Systems

![Diagram of Fiber, Lens, and MEMS Mirror in series]

Figure A.1 Reliability block diagram for a series system.

As shown in Fig. A.1, the example of a single port model forms a series system is composed of three elements, the failure of any element in this single port system will
cause a port failure. The single port reliability is

\[ R_p = R_{\text{fiber}} \times R_{\text{lens}} \times R_{\text{MEMS}} \]

The total failure rate of the port \( \lambda_p \) is

\[ \lambda_p = \lambda_{\text{fiber}} + \lambda_{\text{lens}} + \lambda_{\text{MEMS}} \]

**Parallel Systems**

A parallel system is composed of \( n \) elements that perform identical functions, the success of any of which will lead to system success. In other words, all the components must fail in order to have a system failure.

![Reliability block diagram for a parallel system](image)

**Figure A.2 Reliability block diagram for a parallel system**

Consider the example in Fig. A.2, the block diagram represents a parallel system composed of two identical SFs, each with reliability \( R_{SW} \). Each element must then have a probability \( 1 - R_{SW} \) of equipment failing. The system reliability \( R \) for these two SFs is the probability that more than one SF is remains functional.
\[ R = 1 - (1 - R_{SW})^2 \]

And the corresponding failure rate for this parallel system is

\[ \lambda = \frac{\lambda_{SW} \cdot \lambda_{SW}}{\lambda_{SW} + \lambda_{SW}} \]
Appendix B

Renewal Process

An OXC system using SF is put into operation and is functioning at time $t = 0$. When the SF fails, it is replaced by a new SF of the same type, and restored to an "as good as new" condition. When this SF fails, it is again replaced, and so on. Assuming the replacement time is negligible. Then we have a sequence of lifetimes $T_1, T_2, T_3 \ldots \ldots$, which are independent and identically distributed random variables with distribution function

$$F_T(t) = P(T_i \leq t) \quad \text{for} \quad t > 0, i = 1,2, \ldots \ldots \quad (B.1)$$

This kind of process is called an ordinary renewal process [22]. The events of replacements are called renewals, while the time intervals between consecutive events are called renewal periods.

Notice that the joint probability of $X$ has C.D.F., $F(x)$, and $Y$ with C.D.F., $G(x)$, is

$$P(X + Y \leq t) = E[P(X + Y \leq t \mid X)]$$

$$= E[G(t - X)]$$

$$= \int_0^t F(x)G(t - x)dx$$

$$= F(x) * G(x) \quad (B.2)$$
As a result of equation (2), probability of having \( n \) replacement within time period \( t \):

\[
P(S_n \leq t) = P(T_1 + T_2 + \cdots + T_n \leq t) = F_T^{(n)}(t)
\]  

(B.3)

where \( S_n \) is the time until the \( n \)th renewal.

The Probability of having exactly \( k \) replacement within time period \( t \):

\[
P( N(t) = k) = P( S_{k-1} \leq t, S_k > t) \nonumber \\
= P(S_{k-1} \leq t) \cap P( S_k \leq t) 
\]  

(B.4)

In addition, we know that

\[
P(S_k \leq t) \subseteq P(S_{k-1} \leq t) 
\]  

(B.5)

From equation (4), (5)

\[
P( N(t) = k) = P( S_{k-1} \leq t) - P(S_k \leq t) 
\]  

(B.6)

Finally, by combining the results of above equations, the average number of renewal is

\[
E[N(t)] = \sum_{r=0}^{\infty} r \cdot P(N(t) = r) = \sum_{r=0}^{\infty} r \cdot (F^{(r)}(t) - F^{(r+1)}(t)) \\
= \sum_{r=1}^{\infty} r \cdot F^{(r)}(t) - \sum_{r=0}^{\infty} r \cdot F^{(r+1)}(t) = \sum_{r=1}^{\infty} r \cdot F^{(r)}(t) - \sum_{r=1}^{\infty} (r-1) \cdot F^{(r)}(t) \\
= \sum_{r=1}^{\infty} r \cdot F^{(r)}(t) - \sum_{r=1}^{\infty} r \cdot F^{(r)}(t) + \sum_{r=1}^{\infty} F^{(r)}(t) \\
= \sum_{r=1}^{\infty} F^{(r)}(t)
\]
The renewal function, $W(t)$, is given by

$$W(t) = E[N(t)] = \sum_{r=1}^{\infty} F^{(r)}(t)$$

(B.7)
Appendix C

LabVIEW Programs

LabVIEW is a graphical development environment for signal acquisition, measurement analysis, and data presentation developed by National Instrument.

(a) LabVIEW program for Switch Fabric protection scheme, Digital I/O side
(b) LabVIEW program for Switch Fabric protection scheme, Analog Input Side