FAULT TOLERANT CROSSCONNECT AND WAVELENGTH ROUTING IN ALL-OPTICAL NETWORKS

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ABSTRACT

This paper proposes a fault tolerant design of optical crossconnect (FTOXC) which can tolerate link, channel, and internal optical switch failures at the cost of spare optical switches/channels, extra input/output (I/O) ports for an optical switch, and associated wavelength converters. Failure restoration is based on a unified restoration scheme and a fault tolerant wavelength routing algorithm (FTWRA). The FTOXC and FTWRA can be applied to any all-optical network and can recover many types of failures. The tradeoff is between the number of spares and the blocking probability.

I. INTRODUCTION

For a wavelength routed all-optical network (WRAON) [1], network failures could interrupt a large number of communication sessions in progress, such as voice and data transmissions. As a result, the design of a WRAON must incorporate some mechanisms of protection against certain types of failures, for instance node failures, link failures, channel failures, wavelength converter failures, and optical switch failures. It is also desirable that these failures be handled within the optical network, rather than in higher layers.

In order to achieve protection against failures, spares must be provided for the corrupted traffic while being restored. With the advent of WDM techniques, it is possible to provide redundancy by means of spare wavelengths. Several simple failure restoration techniques for WDM mesh networks have been proposed in [2-5,9]. In [9], they concluded that the use of spare wavelengths is better in terms of the total number of fibers.

Therefore, in this paper we will propose a fault-tolerant optical crossconnect (OXC) architecture and the corresponding wavelength routing algorithm subject to the current technology constraints. The fault-tolerant OXC (FTOXC), which can be utilized as a normal OXC with converters rather than only in the fault-tolerant environment, was built from the combination of OXCs with and without conversion as shown in [1]. In addition, a fault-tolerant wavelength routing algorithm (FTWRA) is also proposed which is a quasi-distributed dynamic routing scheme similar to [6]. The controller in each OXC communicates with other controllers by an in-band wavelength within the network for collecting information from the network and for finding the best routes.

The rest of this paper is organized as follows. Section II introduces the basic architecture of the FTOXC in a WRAON. Section III identifies different fault scenarios and proposes the corresponding failure restoration schemes. Section IV proposes the FTWRA algorithm. Section V concludes this paper.

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II. ARCHITECTURE

Fig. 1 shows a WDM all-optical network employing wavelength routing, which consists of OXCs interconnected by optical links. Each link is assumed to be bidirectional and actually consists of a pair of unidirectional links.

If there are Λ wavelengths on each link, an OXC can be viewed as consisting of Λ independent switches, one for each wavelength as shown in Fig. 2. Each optical switch has Δ inputs and Δ outputs where Δ is the number of input/output links.

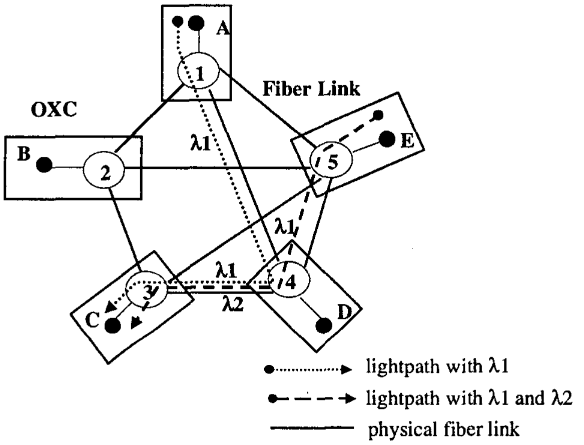

Fig. 1: A WDM network with OXCs interconnected by fiber links.

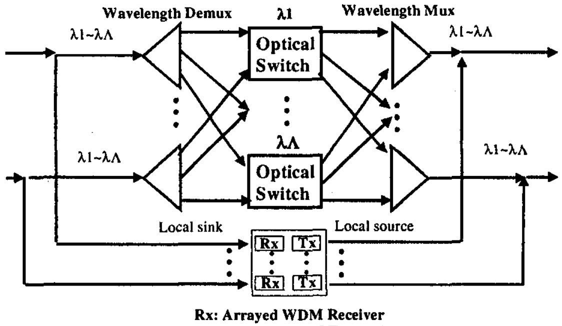

Fig. 2: Structure of an OXC without wavelength converters.

If we are allowed to use wavelength converters, a signal at a particular wavelength on an input link can be converted to any other wavelength on any of the output links as long as two connections do not use the same wavelength on a single link. This can be achieved in principle by using wavelength converters in conjunction with a large switch inside an OXC as shown in Fig. 3. This configuration adds significant complexity to the OXC but should yield somewhat better wavelength reuse, thereby improving the network performance. The OXC now has a single wavelength-independent switch with $\Lambda \cdot \Delta$ inputs and $\Lambda \cdot \Delta$ outputs as compared to Λ wavelength-dependent switches each with Δ inputs and Δ outputs for an OXC without converters. In addition, $\Lambda \cdot \Delta$ wavelength converters are required.

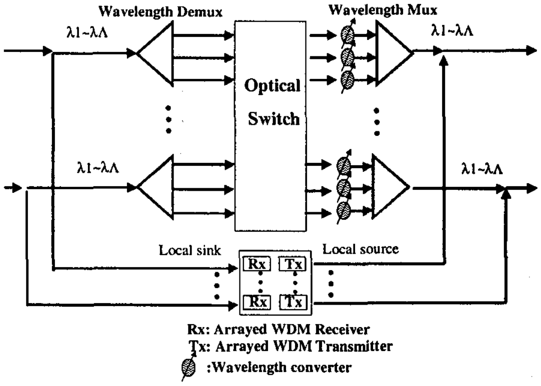

Fig. 3: Structure of an OXC with wavelength converters.

An arrayed multi-wavelength transmitter and an arrayed multi-wavelength receiver are required for either OXC structure in the above. Although sharing array transceivers with other links could reduce the amount of hardware required [1], such structure imposes an additional constraint on the wavelength assignment problem in that two connections originating from a given node must be assigned different wavelengths. Apparently this reduces the probability of reuse of wavelengths.

We propose an FTOXC in Fig. 4, which has a better network performance and can survive a single fault. The main modifications are on the optical switches and the wavelength converters. The FTOXC utilizes the wavelength-dependent optical switches in an OXC without converters. And each optical switch is extended with additional ports and corresponding wavelength converters to connect to other optical switches. The resulting FTOXC has Λ optical switches with $(\Lambda+\Delta-1)$ inputs and

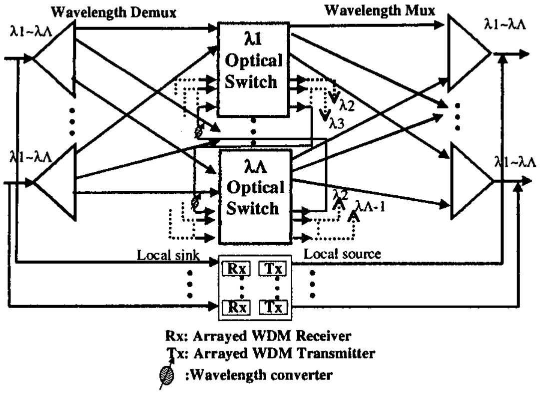

Fig. 4: Structure of an FTOXC.

(Λ+Δ-1) outputs as compared to Δ inputs and Δ outputs in Fig. 2, and Λ(Λ-1) converters as compared to Λ·Δ converters in Fig. 3. Completely optical methods for implementing the FTOXC can be easily achieved.

III. FAILURE SCENARIOS AND FAILURE RESTORATION

Assume that the fault detection mechanism in [8] is adopted in the proposed FTOXC. We present how FTOXCs configure to deal with the fault scenarios mentioned above.

A. Channel faults

The restoration scheme is shown in Fig. 5.

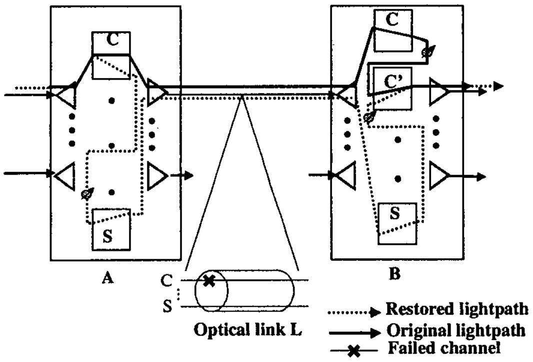

Fig. 5: Restoration from a single channel fault using a spare channel.

Let the channels *C* and *C'* be normal working channels and the channel *S* a spare channel. Upon detection of channel *C* failure in the link *L*, the controller in FTOXC node *A* configures the optical switch *C* to transfer the lightpath to the optical switch *S* and configures optical switch *S* to transfer the lightpath to the original link *L*. At the other end, FTOXC *B* configures the optical switch *S* to transfer the lightpath to the optical switch *C'* and configures the optical switch *C'* to transfer the lightpath from the optical switch *S* to the original channel.

B. Link fault

Take for example the lightpath in Fig. 6. The original normal lightpath is from the source node to *X*, then to *Z* , then to *W*, and finally to the destination node. Assume there is a link fault between nodes *X* and *Z*. After detecting the failure, this lightpath must be able to reroute around the failed link. In our restoration mechanism, the controller in node *X* configures the optical switch *C* to reroute the failed lightpath to the spare optical switch/channel *S* and keep the spare channel *S* to the destination node. How the nodes *Y*, *W*, and the nodes along the way to the destination know when to configure their spare optical switches is achieved by the coordination with node *X*. At the other end, the controller in node *Z* simply disconnects the failed lightpath.

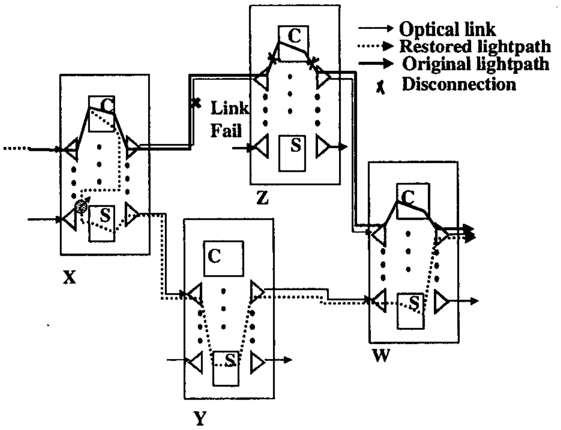

Fig. 6: Restoration from a link fault using a spare channel.

C. Optical switch fault

In Fig. 7, if the optical switch *C* within node *A* fails, node *A* informs the predecessor node *X* to redirect the lightpath to a spare channel and informs the successor node *B* to receive the lightpath from the spare channel and continue the original lightpath route.

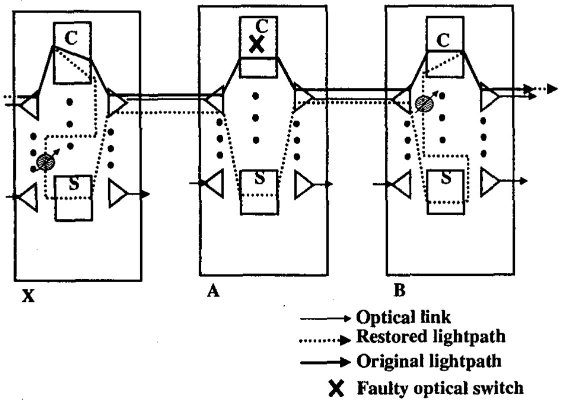

Fig. 7: Restoration from an optical switch fault.

D. Wavelength converter fault

This converter *D* fault is a dual of the channel *D* fault between link *A* to *B*.

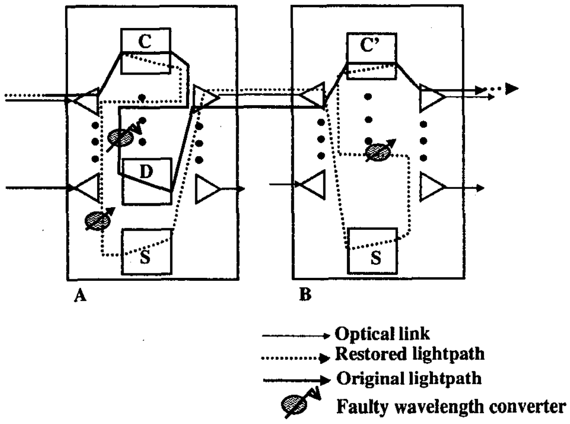

Fig. 8: Restoration from a wavelength converter fault.

E. FTOXC node fault

Due to the high cost, a spare node for fault tolerance is not recommended. Instead, we employ the idea in [7] that a node fault only affect the controller and the established lightpath can continue transferring data. When the neighboring nodes complete coordination, the whole network is updated with the deletion of the faulty node and its associated links.

IV. FAULT TOLERANT WAVELENGTH ROUTING ALGORITHM

We first present the FTWRA for normal routing in the following orders: graph transformation, routing, connect/disconnect, and overall flow chart.

A. Graph Transformation: Construct a weighted directed graph *G(V, E)* from the given network *G(N, L)* and the set of wavelengths Λ, where *V* is the set of vertices and *E* is the set of directed edges each with weight $c: E \rightarrow \mathbf{R}$.

The weight of a channel edge depends on its status. An idle channel has a weight $c(l, \lambda) = f$, and an occupied channel edge or a spare channel edge has a weight $c(l, \lambda) = \infty$. Similarly, the weight of a converter (normal) edge is determined by the same rule. An idle converter (normal) edge should have weight $c(l_m, \lambda_i, l_n, \lambda_j) = g\ (f)$ if λ_j or λ_i is not a spare channel, and a converter edge has weight $c(l_m, \lambda_i, l_n, \lambda_j) = \infty$ if a connection converts its wavelength λ_i on l_m to λ_j on l_n, or if λ_j or λ_i is the designated spare channel. The values of *f* and *g* can make the routing decision toward wavelength continuous path or wavelength convertible path.

B. Routing: Given the weighted graph *G(V, E)* and a call request with super source-to-destination vertex pair *w*, routing is to find the min-cost path corresponding to the route and the channels in the original network. Let P_w be the set of all paths connecting *w*. $\delta_{pe} = 1$ if edge *e* is on the path *p*, and $\delta_{pe} = 0$ otherwise. Assume that the integer vector *X* is the routing decision in which $x_p = 1$ means that the new call is routed on path *p* and $x_p = 0$ otherwise. Suppose that the objective is to minimize the cost $\sum_{p\in P_w}\sum_{e\in E} c(e)\delta_{pe}x_p$. Then the problem is defined as follows:

$$z_{pl} = \min\left\{ \sum_{p\in P_w}\sum_{e\in E} c(e)\delta_{pe}x_p \right\} \quad \text{s.t.} \quad \sum_{p\in P_w} x_p = 1$$

$x_p \in \{0, 1\}, \forall p \in P_w$.

Using any shortest-path algorithm, e.g., Dijkstra's algorithm, the above problem can be solved.

C. Connect and Disconnect: The network status needs to be updated whenever a call is connected or disconnected. The algorithm is as follows:

a. Connect: if a new call is routed through the channel/normal edge e, $c(e) \leftarrow \infty$. If a new call is routed through the converter edge e at node i, $c(e) \leftarrow \infty$.

b. Disconnect: If a call is disconnected from the channel/normal edge e, $c(e) \leftarrow f$. If a call is disconnected from the converter edge e at node i, $c(e) \leftarrow g$.

The overall algorithm is shown in Fig. 9.

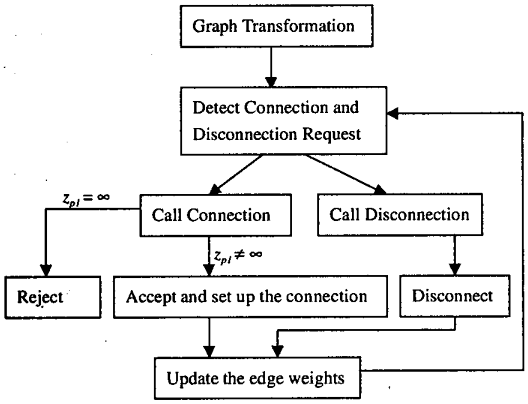

Fig. 9: The FTWRA algorithm.

When the restoration mechanism is being executed and needs the node to reestablish the route, the edges in the auxiliary graph require some modifications to find the spare route. The modifications are that the weights of unoccupied edges for the spare channels are reduced from infinite to zero and those of the occupied ones remain infinite. After such modifications, the restoration route will consist of spare channels only.

V. CONCLUSIONS

We have proposed in this paper a fault tolerant optical crossconnect node architecture to support wavelength routed all-optical networks. In addition to the introduction of a fault model and the corresponding restoration mechanism, a fault tolerant wavelength routing algorithm with dynamic spares was also proposed. This paper concentrates on the introduction and discussion of the proposed mechanism. The detail analysis and evaluation are left as future works. That is, the blocking probability under the proposed architecture needs further research to compare with those under other approaches.

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