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Fault-tolerant routing and wavelength assignment algorithm for multiple link failures in wavelength-routed all-optical WDM networks

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ABSTRACT

In this paper, we investigate the problem of enhancing multiple-fault restorability in the path protected wavelength-routed all-optical WDM networks. The system architecture considered is circuit-switched with dynamic arrival of session requests. We propose a mechanism, which is used to combat multiple link failures. A routing and wavelength assignment algorithm has been proposed with the name of fault-tolerant routing and wavelength assignment algorithm. The comparison of this algorithm has also been made with the best-fit and first-fit algorithms. This algorithm deals with the optical networks with multiple faults and is effective for the varying load applied to nodes. This algorithm works well for the load applied to the nodes varying from low to high.

1. Introduction

The explosive growth of the Internet over the last decade has created a significant increase in bandwidth requirement for long-haul optical networks. Currently, optical networks primarily incorporate wavelength division multiplexing (WDM) as a means of increasing the 10 Gbps bit rate that each wavelength is capable of carrying. WDM is an approach that can exploit the huge opto-electronic bandwidth mismatch requiring that each end-user's equipment operate only at electronic rate, but multiplexed on the same fiber. Optical networks employing WDM offers the promise of meeting the high bandwidth requirements of emerging communication applications, by dividing the huge transmission bandwidth of an optical fiber into multiple communication channels with bandwidth compatible with the electronics processing speed of the end-users. Under WDM, the optical transmission spectrum is carved up into a number of non-overlapping wavelength bands, with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak electronics speed [1]. Thus, by allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms. As optical networking technology continue to develop, WDM systems capable of supporting data rates of 40 Gbps are likely to become a commonplace. A wavelength-routed optical WDM network consists of an *optical switching fabric*, comprising "active-switches"

There has been great interest in WDM networks consisting of wavelength routing nodes interconnected by optical fibers. Such networks carry data between access stations in the optical domain without any intermediate optical to/from electronic conversion. To be able to send data from one access node to another, one needs to establish a connection in the optical layer similar to the one in a circuit-switched network. This can be realized by determining the path in the network between the two nodes and allocating a free wavelength on all of the links without any intermediate electronics processing, while using one WDM channel per link. The entire bandwidth on the lightpath is reserved for this connection until it is terminated, at which time the associated wavelength become available on all the links along the route. In the absence wavelength conversion, it is required that the lightpath occupy the same wavelength on all fiber links it uses. The requirement is referred to as the *wavelength-continuity constraint*. However, this may result in the inefficient utilization of WDM channels. Alternatively, the routing nodes may have limited or full conversion capability, whereby it is possible to convert an input wavelength to a subset of the available wavelengths in the network. Since, lightpath are the building block of the network architecture, there effective establishment is crucial. It is thus important to provide route to the lightpath requests and to assign wavelength on each of the links along the route among the possible choice so as to optimize a certain performance metric. This is known as the *routing and wavelength assignment* (RWA) problem. The wavelength assigned must be such that no two lightpaths that share a physical links use the same wavelength on that link. Moreover, in networks without wavelength converters, the

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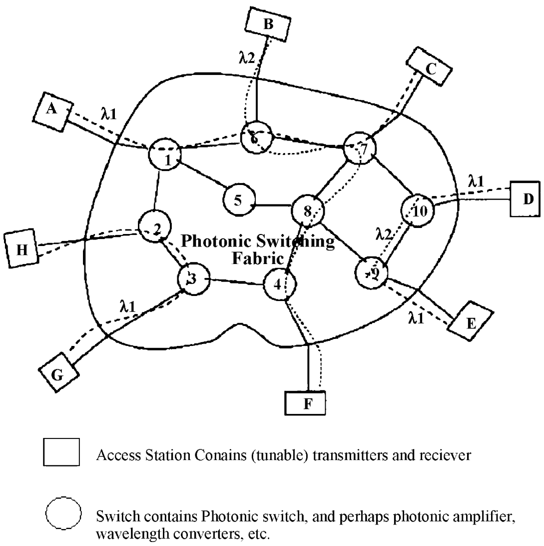

Fig. 1. Wavelength-routed optical network.

same wavelength must be used on all links of the lightpath. The RWA problem is critically important in increasing the efficiency of wavelength-routed optical networks. A wavelength-routed optical network is shown in Fig. 1. The network consists of an *optical switching fabric*, comprising "active-switches" connected by fiber links to form an arbitrary *physical topology*. Each end-user is connected to an active switch via a fiber link. The combination of an end-user and its corresponding switch is referred to as a network node. Actually, each switching node may support multiple end-users. Each node is equipped with a set of transmitters and receivers, both of which may be wavelength tunable. A transmitter at a node sends data into the network and a receiver receives data from the network.

The basic mechanism of communication in a wavelength-routed network is a *lightpath*. A lightpath is an optical communication channel between two nodes in the network, and it may span more than one fiber link. The intermediate nodes in the fiber path route the lightpath in the optical domain using their active-switches. The end-nodes of the lightpath access the lightpath with the lightpath operates. In Fig. 1, lightpaths are established between nodes *A* and *C* on wavelength channel λ_1, between *B* and *F* on the wavelength channel λ_2, and between *H* and *G* on wavelength channel λ_1. The lightpath between nodes *A* and *C* is routed via active-switches 1, 6 and 7. In the absence of any wavelength-conversion device, a lightpath is required to be on the same wavelength channel throughout its path in the network due to the requirement, which is referred to as the wavelength-continuity property of the lightpath. This requirement may not be necessary if we also have wavelength converters in the network. As shown in Fig. 1 the lightpath between nodes *D* and *E* traverses the fiber link from the node *D* to switch 10 on wavelength λ_1, get converted to wavelength λ_2 at switch 10, traverses the fiber link between switch 10 and switch 9 on wavelength λ_2, gets converted back to wavelength λ_1 at switch 9, and traverses the fiber link from switch 9 to node *E* on the wavelength λ_1.

A fundamental requirement in a wavelength-routed optical network is that two or more lightpaths traversing the same fiber link must be on different wavelength channels so that they do not interface with one another. For a wavelength-routed all-optical network [2], failure could interrupt a large number of communication sessions in progress, such as voice and data transmissions. So, we need to develop approximate protection scheme which minimizes the data loss when a link failure occurs. As a result, the design of wavelength-routed all-optical network must incorporate some mechanisms of protection against certain type of failures, for instance node failures; link failures channel failures, wavelength converter failures, and optical switch failures. Upper layers of protocols have their own procedures to recover from link failures. However, the recovery time for upper layers may be significantly larger (of the order of seconds), whereas the fault–recovery time in the optical layer should be of the order of milliseconds in order to minimize data losses. Furthermore, it is beneficial to consider fault–recovery mechanism in the optical layer for the following reasons: (a) the optical layer can efficiently multiplex protection resources among several higher-layer network applications and (b) survivability at the optical layer provides protection to the higher-layer protocols that may not have built-in fault–recovery. Therefore, it is imperative that these networks have fault tolerance capability. *Fault tolerance* refers to the ability of the network to reconfigure and reestablish affected traffic on a component failure. A network with the restoration capability is known as a *survivable network*. It requires redundant capacity or spare resources. There are many types of failures and faults which can block the path and these can be channel faults, link faults, optical switch faults and wavelength converter faults. Most of the earlier work has concentrated on single-link failure, where only one network link fails at a given instant of time. It has been recognized that dual-link failure should also be considered in designing failure recovery mechanism [3]. Some more dual-link failures have been discussed in [4,5]. First-fit and best-fit algorithms [5] have also been discussed in literature.

This paper deals with the fault-tolerant routing strategy for link failure for more than two link failures in wavelength-routed all-optical networks. Network studies have shown that frequent cable cuts results in link failure, which results in tremendous data loss due to the amount of traffic carried on those links. In order to achieve protection against failures, we must provide spare wavelengths also, optimum route should be provided. We can achieve redundancy by means of spare wavelengths with the advancements in WDM techniques.

2. Mathematical model

We denote the path and the network-wide parameters by upper-case letters and link parameters by lower case letters. Subscripts and superscripts refer to specific instances of links, node pairs and routes. We have assumed the network without wavelength conversion.

- N is the number of nodes in the WDM network; $N \in V$.
- l is the length of the route or the number of links in the route or path selected.
- r is the number of routes available where $r \in R$.
- P_B^r is the blocking probability of r routes.
- P_B is the overall blocking probability of the network.
- P_{BW}^r is the blocking probability caused by insufficient wavelength.
- P_{BC}^r is the blocking probability caused by lack of converter.
- L^r is the load of the route r.
- $N\lambda$ is the number of free wavelengths.

Given N node WDM network, all the nodes forms a set V, and all directed links are contained in as set E. Suppose fixed path routing policy is adopted the lightpath establishment, the predetermined directed routes are indicated with a set R. For each route $r \in R$, the blocking probability for the connections along route r can be divided into two mutual exclusive parts; P_{BW}^r and P_{BC}^r. The total blocking probability for a network with wavelength conversion is given by:

$$P_B^r = P_{BW}^r + P_{BC}^r, \quad r \in R \tag{1}$$