Available online at www.sciencedirect.com
SCIENCE DIRECT
Computer Communications 28 (2005) 987–999
computer communications
www.elsevier.com/locate/comcom

Restoration mechanisms for handling channel and link failures in optical WDM networks: tunable laser-based switch architectures and performance analysis

Harini Krishnamurthy[a,1], Krishna M. Sivalingam[b,2,*], Manav Mishra[c,3]

[a]*Amazon.com Inc., Seattle, WA 98144, USA*
[b]*Department of Computer Science and Electrical Engineering, University of Maryland, Baltimore County (UMBC), 1000 Hilltop Circle, Baltimore, MD 21250, USA*
[c]*Microsoft Corporation, Redmond, WA 98052, USA*

Received 24 July 2003; revised 12 November 2004; accepted 24 November 2004
Available online 16 December 2004

Abstract

In this paper, we study restoration mechanisms to handle channel and link failures in an optical wavelength division multiplexed (WDM) wavelength-routed wide-area backbone network based on a mesh topology. The solution uses a small number of *tunable lasers* to provide restoration capability. We consider two types of failures: *link failures* and individual *channel* (*or wavelength*) *failures* that occur when one or more transceivers fail at a node that is the source of lightpath(s) or due to a failure in an intermediate node's optical switch fabric. We use the restoration mechanism that attempts to find alternate paths and resources *after* failure occurs. In our proposed mechanism, restoration is first attempted using the tunable lasers to transmit on the failed wavelengths. If all the failed lightpaths cannot be restored using the tunable lasers, unused wavelengths on the same link are used, if optical wavelength conversion is available. For the remaining lightpaths requiring restoration, two different link-level restoration mechanisms called redirection algorithm (RDA) and disjoint path algorithm (DPA) are used.

Results based on discrete-event simulations to understand the performance of the proposed mechanisms, in terms of restoration efficiency and restoration times, are presented. The results show that for networks of varying size and node degree with 32 wavelengths on each link, using as few as eight tunable lasers per link provides good restoration efficiency under moderate traffic load. The performance of the proposed algorithms is compared to an earlier restoration mechanism based on broadcast, and it is seen that the proposed mechanism performs better, by offering both lower restoration times and higher restoration efficiency even with a small number of lasers. The impact of the number of tunable lasers on the performance is studied for failures occurring simultaneously on two links. It is seen that for a small number of such channel failures, as few as four tunable lasers per link are sufficient to recover from failures on a single link and on two links.

Keywords: Optical networks; Wavelength division multiplexed (WDM) networks; Failure recovery; Survivability; Restoration; Channel failures

1. Introduction

Significant advances in the field of optical communications and networking over the past few years have resulted in the widespread deployment of optical wide-area and metropolitan networks [1], based on optical Wavelength Division Multiplexing (WDM) technology. WDM technology enables the multiplexing of several independent streams of information, each on a different wavelength, on the same fiber [2]. This helps reduce the impact of the opto-electronic speed mismatch by providing multiple channels that operate closer to the electronic processing speed. Optical WDM

* Corresponding author. Tel: +1 410 455 3961; fax: +1 410 455 3969.
E-mail addresses: krishna@csee.umbc.edu (H. Krishnamurthy), krishna@csee.umbc.edu (K.M. Sivalingam), manavm@microsoft.com (M. Mishra).

[1] Most of this author's contributions were done while the author was a graduate student at Washington State University, Pullman and at University of Maryland, Baltimore County.

[2] Part of the research was supported by a grant from Cisco Systems, San Jose, CA, Intel Corporation and NSF grant No. ANI-0322959. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

[3] Most of this author's contributions were done while he was with Intel Corporation in Hillsboro, OR, USA.

0140-3664/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2004.11.004

networks have been considered for access, local area, metropolitan area, and wide area networks. In this paper, we consider a circuit-switched, mesh topology based wide-area wavelength routed network that consists of optical cross-connect routers connected by WDM links. Traffic session requests arrive based on a stochastic process and the system establishes a *lightpath* (an end-to-end all-optical circuit-switched connection) for each session.

Network monitoring statistics show that failures are not an uncommon occurrence in backbone networks [3–5]. Hence, fault-tolerance (or survivability) is an important consideration for such high capacity networks, since failures may result in significant degradation of network performance. The common types of failures that have been studied are node and link failures. The recovery mechanisms for such failures may be broadly classified as: (i) *protection or pro-active* schemes, where the recovery path with partially or fully allocated resources is determined at the time of session establishment; and (ii) *restoration or reactive* schemes, where the recovery path is determined after failure occurs. Another classification is to categorize the mechanisms as *link-level*, where the traffic is re-routed around the affected link leaving the rest of the path intact, and *path-level*, where the traffic is re-routed on a different path between the source and the destination.

In this paper, we consider *link* failures and *channel* failures. It is assumed that each link has a transmitter array at one end and a receiver array at the other. A channel failure occurs when one or more transmitters fails at the source of a lightpath or due to a failure in the switching fabric. Thus, recovery mechanisms are necessary for the lightpaths using the affected channels. A link failure can be considered as a special case of channel failures where all channels fail.

Our solutions are based on the restoration (i.e. reactive) method, where there is no prior resource allocation on a recovery path. The mechanism uses a small number of tunable lasers at every link. Tunable laser diodes have been widely accepted as essential components for future optical networks [6–11]. Tunable lasers are typically used in inventory control and in sparing, to reduce the overhead associated with maintaining fixed lasers as spares. This paper is the first, to the best of our knowledge, to consider the use of tunable lasers for restoration. The design goal is to use a small number of these devices, given their higher cost relative to fixed-tuned lasers.

The objective of the proposed tunable-laser based mechanism is to re-route affected traffic on the same link and use the link-level restoration mechanism only when absolutely necessary. To recover from channel failures, local restoration is first attempted by sending an affected session's traffic on its original wavelength using a tunable laser. If enough tunable lasers are not available to switch all the affected lightpaths, then unused wavelengths on the same link may be used if wavelength conversion is present at the routers. The remaining affected lightpaths, if any, are restored using a link-level restoration scheme. Two algorithms for link-level restoration are presented in the paper: the Neighbor Redirection Algorithm (RDA) where a node uses one of its neighbors as the designated redirector node for each of its links, and the Disjoint Paths Algorithm (DPA), where the affected lightpaths are re-routed on two link-disjoint paths.

We study the performance of the proposed mechanisms using discrete-event simulation for different network topologies and system configurations. The results indicate that as the spare capacity (i.e. the number of tunable lasers on a link) increases, the restoration efficiency increases. It is also observed that having four tunable lasers on a 32-wavelength link results in a fairly high restoration efficiency for moderate network loads for NSFNET, ARPANET, and other randomly generated topologies with up to 50 nodes. The performance of the algorithms is compared to a restoration mechanism described in [12] and it is observed that the proposed algorithms result in about 40% lower restoration times and higher restoration efficiencies even with a small number of tunable lasers. The impact of the number of tunable lasers on the restoration achieved for simultaneous failures on two links is also studied and compared to that when a single link is affected. It is observed that for a small number of channel failures, as few as four tunable lasers are sufficient to recover from failures on a single link and on two links.

The rest of this paper is organized as follows. Section 2 discusses related work on protection and restoration for optical WDM networks. Section 3 describes the network architecture used in the study and Section 4 presents the details of the proposed algorithms. Section 5 includes a study of the performance based on simulation. Section 6 summarizes the paper.

2. Related work

This section summarizes some of the previous work done in the area of recovery mechanisms for mesh-topology based optical networks. As described earlier, the mechanisms are classified as *protection* or *restoration* and also as link-level or path-level protection or restoration [3,13].

Models based on Integer Linear Programming (ILP) have been proposed to solve the problem of determining primary and backup paths when protection schemes are used, as in [4,14,15]. The formulation in [4] seeks to jointly optimize the set-up of primary paths and protection paths, while maximizing the revenue generated by the network. In [15], the problem is modeled as three different ILPs—the first to maximize restoration, the second to minimize the capacity, while setting up backup paths and the third, a joint optimization to minimize capacity. A scheme to control the connections in a network in which path protection is employed, is presented in [5].