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ScienceDirect
Computer Networks 51 (2007) 995–1012
Computer Networks
www.elsevier.com/locate/comnet

Performance evaluation of multi-fiber optical packet switches

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Received 18 July 2005; received in revised form 16 June 2006; accepted 3 July 2006
Available online 26 July 2006

Responsible Editor: M. Ajmone Marsan

Abstract

Multi-fiber WDM networks are becoming the major telecommunication platforms for transmitting exponentially increasing data traffic. While today's networks are mainly providing circuit-switched connections, optical packet-switching technologies have been investigated for years, aiming at achieving more efficient utilizations of network resources. In this paper, we have evaluated, for the first time, the packet-loss performance of multi-fiber optical packet switches (MOPS). Our main contributions are threefold. Firstly, we have proposed simple and accurate analytical models for analyzing packet-loss performance of (i) the most fundamental MOPS configuration, (ii) MOPS equipped with fiber delay lines (FDLs) and (iii) shared wavelength converters (SWCs). Secondly, we have shown that the MOPS network *cannot* achieve the same performance as the one with full wavelength conversion (FWC), which is quite different from the well-known conclusion in circuit-switched networks. However, MOPS does significantly outperform the classic single-fiber switches. By introducing a small number of FDLs or SWCs, it outperforms the highly expensive FWC solution as well. Finally, we have taken the hardware constraints into consideration by evaluating the performance of MOPS configurations having multiple limited-sized switching boards, which leads to some insights helpful for developing cost-effective MOPS configurations in the future.

Keywords: Optical packet switch; Multi-fiber networks; Contention resolution; Fiber delay line; Wavelength converter; Packet loss rate

1. Introduction

In recent years, booming Internet traffic has promoted wide implementations of wavelength-division multiplexing (WDM) networks. Currently the mainstream technology is to provide end-to-end circuit-switched connections. However, optical packet switching (OPS) is viewed as a long-term solution for achieving flexible and efficient utilizations of network capacities [1]. Extensive researches have been reported on various OPS configurations and implementations [2–10]. Also, some useful literature surveys associated with existing efforts are well documented in Refs. [2–5].

In OPS networks, a critical issue is to resolve the *packet contentions* when multiple packets are

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1389-1286/$ - see front matter
doi:10.1016/j.comnet.2006.07.001

destined for the same output port [2]. In the existing solutions, wavelength converters, typically shared among some or all of the input/output ports (known as *shared wavelength converters* or SWCs), are utilized to transfer the contending packets into other free wavelengths in the output link if such are available [11–14]. Fiber delay lines (FDLs) are adopted to provide optical buffering [15–19], and deflection routing is applied to explore the capacity in those links other than the originally destined ones [20]. These solutions can be jointly utilized to achieve better performance. Based on existing technologies, however, high-speed tunable wavelength converters are still immature and highly expensive; large volumes of FDLs can make the switch complicated and costly; and deflection routing may lead to complex traffic control and serious power-budget penalties.

Recently, *multi-fiber* networks, where each link contains multiple WDM fibers [1,21–28] are attracting increasing research interests. This is because in network deployments, generally a large number of fibers contained in a cable are laid underground [29]. More significantly, it has been shown that, circuit-switched multi-fiber networks with a moderate number of wavelengths in each fiber achieve better cost-effectiveness than single-fiber networks with high-density wavelengths [21,22]. It is also shown that a multi-fiber WDM network with no wavelength conversion performs almost the same as a single-fiber network with unlimited wavelength conversion capacity (known as *full wavelength conversion* or FWC) [1,23]. All these results, however, are for circuit-switched networks, with the assumption that end-to-end lightpaths are set up based on global link-state information. This assumption does not hold in packet-switched networks, where every node has to make quick, *local* decisions upon the arrivals of data packets.

In this paper, we have evaluated the performance of MOPS. Simple yet accurate analytical models are proposed for the most fundamental MOPS configuration as well as the MOPS with FDLs and/or SWCs. Analytical and extensive simulation results show that, under both uniform and non-uniform traffic loads,

- similarly to that in circuit-switched networks, multi-fiber networks with a moderate number of wavelength channels in each fiber significantly outperform single-fiber networks with high-density wavelengths, and
- differently from that in circuit-switched networks, multi-fiber OPS networks *cannot* achieve nearly the same performance as single-fiber networks with FWC. However, equipped with a few FDLs and/or SWCs, MOPS can easily outperform the single-fiber switch with FWC. Therefore, better cost-effectiveness could be achieved.

Finally, to take into account the hardware constraint that large-sized optical switching boards are complex and expensive [4,5,10], we have studied a simple node configuration containing multiple limited-sized switching boards. By demonstrating the relationship between packet loss rate (PLR) and the size of switching boards as well as the numbers of fibers and FDLs connected to each board respectively, we have obtained some insightful observations which are useful for the future developments of cost-effective MOPS networks.

This paper is organized as follows. In Section 2, we propose two different MOPS node configurations, with unlimited- and limited-sized switching boards respectively. Since the main focus of our study is performance evaluation rather than developing efficient MOPS configurations, we study the switches in their simplest forms where only the contention resolution function is reflected. Simple yet accurate analytical models are proposed in Section 3, for calculating packet loss rate in MOPS. Extensive simulations are conducted in Section 4 to evaluate the performance of MOPS configurations under both uniform and non-uniform traffic loads. Section 5 concludes the paper.

2. Node configurations

A generic MOPS node configuration is shown in Fig. 1, where all the incoming and outgoing wavelength channels are connected to a single switching board. To resolve packet contentions, a certain number of shared FDLs and/or SWCs can be installed. In this paper, we assume that each SWC has full conversion range. In other words, it can convert an optical packet from any incoming wavelength to any outgoing wavelength. Both SWCs and FDLs are shared among all the input/output ports and are accessible by all the contending packets. It is well-known that such resource-sharing configurations lower system cost while maintaining high efficiency of contention resolutions [14,16,30].

When there are many fibers in each link, the single switching board in Fig. 1 can be extremely large.