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Performance evaluation of multi-fiber optical packet switches

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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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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.

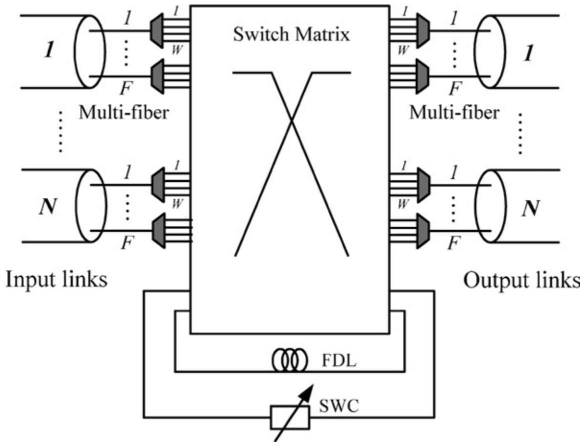

Fig. 1. Generic node architecture of single-board MOPS.

Specifically, we assume there are N input/output links with F fibers per link and W wavelength channels per fiber, therefore the switching board size would be as large as $N \cdot F \cdot W + N_{\mathrm{FDL}} + N_{\mathrm{SWC}}$, where N_{FDL} and N_{SWC} denote the numbers of FDLs and SWCs, respectively. Based on today's technology, manufacturing large-sized, high-speed OPS boards is still difficult and expensive [3,4]. Therefore, we have proposed a simple multi-board configuration as shown in Fig. 2, where every node contains multiple limited-sized switching boards, each of which operating on a single wavelength. For simplicity, we have assumed that each switching board is connected to the same number of T channels of each input/output link ($T \leqslant F$). Note that there could be multiple boards operating on the same wavelength (if $T < F$). Since different wavelengths would not be connected to the same board, SWCs are no longer useful while FDLs can still be installed. The multi-board configuration helps lower the complexity and the cost of the switch. However, the switch is no longer strictly non-blocking. We will study how PLR is affected by switching-board size and, for a given switching-board size, how PLR is affected by the number of incoming/outgoing fibers and FDLs connected to each board respectively.

3. Analytical models of packet loss in mops

For the MOPS configuration as shown in Fig. 1, we assume there are N input/output links with F fibers per link, where each fiber carries W wavelengths denoted as $\lambda_1, \lambda_2, \ldots, \lambda_W$, respectively. Since there are multiple λ_i's, $i = 1, 2, \ldots, W$, in each link, there is a "space dimension" for contention resolutions. Specifically, F packets destined for the same

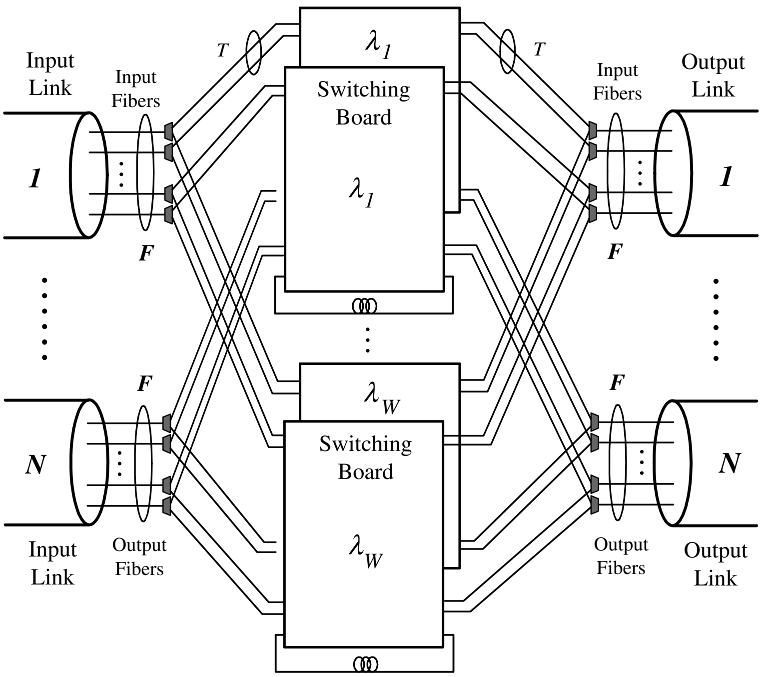

Fig. 2. Node architecture of multi-board MOPS.

output link on the same wavelength can be accepted without wavelength conversion or FDL. We start by considering MOPS without FDL or SWC (referred to as *pure MOPS* hereafter) where contention resolutions solely rely on exploiting the space dimension and then study MOPS with FDLs, SWCs and both of them, respectively.

3.1. Analysis of the pure MOPS model

We first consider the single-board, pure MOPS configuration by removing all the FDLs and SWCs from Fig. 1. Since contention resolutions on different wavelengths are independent operations in absence of wavelength conversion, we start by analyzing PLR on a single wavelength w ($1 \leqslant w \leqslant W$). In this paper, we assume that MOPS is operating in a time-slotted style where incoming packets are synchronized before entering the switching board(s).

Denote the probability that in each time slot there is a packet arriving at each input port as α_w; and this packet is destined for the ith output link with a probability $\rho_{w,i}$ (apparently, we have $\sum_{i=1}^{N} \rho_{w,i} = 1$). The probability that there are k packets destined for the same output port in the ith link on wavelength w can be calculated as

$$P_{w,i}(k) = \binom{NF}{k} \cdot (\rho_{w,i}\alpha_w)^k \cdot (1 - \rho_{w,i}\alpha_w)^{NF-k}. \quad (1)$$

For the special case where $F = 1$ and under uniform traffic loads, by letting $\rho_{w,i} = 1/N$, $i = 1, 2, \ldots, N$, in Eq. (1), we have the following well-known result [9,31]:

$$P_{w,i}(k) = \binom{N}{k} \cdot \left(\frac{\alpha_w}{N}\right)^k \cdot \left(1 - \frac{\alpha_w}{N}\right)^{N-k}. \quad (2)$$

The packet loss rate of the pure MOPS, given by Eq. (1), can be calculated as

$$\text{PLR} = \frac{\sum_{i=1}^{N}\sum_{w=1}^{W}\sum_{k=F+1}^{NF} P_{w,i}(k) \cdot (k - F)}{N \cdot F \cdot W \cdot \alpha}. \quad (3)$$

For the multi-board pure MOPS model where FDLs are removed from Fig. 2, the calculations of PLR are quite similar. Specifically, since there are T channels from each input/output link connected to the same board on the same wavelength, the modifications required include:

- F in Eqs. (1) and (3) should be replaced by T in order to calculate the PLR on each switching board;
- Eq. (3) should be properly revised to calculate the overall PLR, not on all the different wavelengths, but on all the different switching boards.

Detailed discussions are straightforward and therefore omitted.

3.2. Analysis of MOPS with shared FDLs

PLR analysis of OPS with shared contention resolution devices (FDLs and SWCs) under general non-uniform traffic loads is notoriously difficult [9,14,16]. The main reason is that in such switches, different output ports have different probabilities of having contentions and different probabilities that such contentions can be finally resolved by FDLs or SWCs respectively. The relations between these probabilities and the traffic loads destined for different output links, however, are highly complicated even under the simplest assumption we could reasonably make (e.g., that contending packets will randomly compete for the available resolution resources). To avoid the complicated analyses that can by themselves compose into lengthy separate reports, as that in virtually all the existing literature, we restrict ourselves to analyze MOPS with shared FDLs and/or SWCs under *uniform* traffic loads. Switch performance under general non-uniform traffics will be evaluated through extensive simulations.

For pure MOPS where $F > 1$, with the assumption that every output channel is identical and independent, the probability $P_w^F(x)$ of having totally x packets destined for the same output link on wavelength w (note that now each link has F channels on the same wavelength) can be obtained as

$$P_w^F(x) = \overset{F}{\underset{i=1}{\otimes}} P_w(k)|k = x, \quad (4)$$

where $P_w(k)$ is defined in Eq. (2), and the symbol $\overset{F}{\underset{i=1}{\otimes}}$ represents the convolution calculations necessary to be executed F times.

For MOPS with shared FDLs, we make the assumption that contending packets on different wavelengths have the same probability of being buffered. Under such case, PLR on different wavelengths would be the same, which equals to the overall PLR of the switch. Therefore in this subsection wavelength subscript is dropped in the analytical models.

For sake of simplicity, we have assumed that all FDLs are of the same length that can hold optical packets for one time slot. The analytical model is developed as follows. Denote $U(x)$ as the probability of having x contending packets that *cannot* be handled by F fibers in the same output link. We have

$$U(x) = \begin{cases} \sum_{k=1}^{F} P^F(k), & x = 0, \\ P^F(x+F), & x = 1, 2, \cdots, N \cdot F - F. \end{cases} \tag{5}$$

In this equation, $U(0)$ calculates the probability that no packet is lost when there are fewer than F packets destined for the same output link on the same wavelength; and $U(x)$, $x = 1, 2, \ldots, N \cdot F - F$, calculates the probability that x packets have to be either buffered or dropped. To calculate the probability of having x contending packets in all the output links that have to be either buffered or dropped, we have

$$C(x) = \bigotimes_{i=1}^{NW} U(k)|k = x. \tag{6}$$

Assume we have N_{FDL} FDLs. When the number of contending packets $x \leqslant N_{\mathrm{FDL}}$, all the packets can be buffered; otherwise, $x - N_{\mathrm{FDL}}$ packets will be lost. Therefore, similar to Eq. (3), the PLR of MOPS with shared FDLs can be calculated as

$$\mathrm{PLR} = \frac{\sum_{j=N_{\mathrm{FDL}}+1}^{NFW-FW} C(j) \cdot (j - N_{\mathrm{FDL}})}{N \cdot F \cdot W \cdot \alpha}. \tag{7}$$

Closer observations show that Eq. (7) has *not* considered the packets buffered in FDLs in the last time slot. These packets have to be handled altogether with newly arrived packets, which increases the traffic loads going through the switch. To take this part of "additional loads" into account, the average arrival rate of data packets destined for each output port can be approximately adjusted as

$$\alpha' = \alpha + \frac{\sum_{i=1}^{NFW-FW} C(i) \cdot \min(i, N_{\mathrm{FDL}})}{N \cdot F \cdot W}, \tag{8}$$

where α represents the probability of having a *newly arrived* packet destined for each output port. In other words, the effects of the buffered traffic are approximated as increasing the average arrival rate of the traffic in each time slot. The above analytical model requests iterative adjustments of α'. However, based on our experience we found that calculating the value of α' once leads to highly accurate analytical results.

Remark 1. In the above analysis, the negative correlation between the numbers of packets destined for different output ports (Specifically, the effect that more packets destined for some output ports means fewer packets destined for the others) has been neglected, which may affect the accuracy of the analysis. However, in this study, because of the following two reasons we have ignored it: (i) it significantly simplifies the analytical models and their extensions (e.g., the extension for analyzing MOPS with both FDLs and SWCs that later will be reported in Section 3.4); (ii) effects of neglecting the statistical dependence are not generally significant, especially in large-sized switches or under low traffic loads [31]. As we will see later on in Section 4, the simplified analytical model appears to be quite accurate under most cases. Comprehensive studies on the analytical models taking into account the effect of correlation can be found in Refs. [31,32].

Remark 2. In the above analysis, we assumed that each FDL is of the same length that can buffer a packet for one time slot. The analytical model can be extended to analyzing MOPS with variable-depth buffers where different FDLs have different lengths. Specifically, we only need to revise Eq. (8) to reflect the fact that some packets buffered in the current time slot will not contribute to increasing α' in the next time slot, but several time slots later instead. The detailed discussions, however, will be rather lengthy, since we need to define the distribution of FDL lengths as well as the scheme for choosing an FDL when there are multiple FDLs (of different lengths) available. Hence, such discussions are not included in this paper.

Note that for MOPS with shared FDLs, classic Markovian queuing model [31] can also achieve high analytical accuracy, as we will demonstrate in details in Appendix A. In this section, we have presented analytical models which utilize convolution method in an iterative approach. Later similar method will be adopted to analyze MOPS with SWCs as well as MOPS with both FDLs and SWCs. It remains as open problems to develop simple yet accurate Markovian models for MOPS with SWCs or with both FDLs and SWCs, which are of our future research interest.

3.3. Analysis of MOPS with SWCs

For MOPS with SWCs, we still conduct analysis under uniform traffic loads. Existing analytical models for SWC configuration have satisfactory accuracy yet tend to be quite complicated (e.g. [14]). We propose in this section a simpler, yet still accurate model. The main idea is as follows. In MOPS with SWCs, packet loss can be viewed as composed of two separate parts: those caused by exhausted output-link capacity; and those caused by insufficient number of SWCs. Specifically, when there are k packets destined for the same output link and $k \leqslant FW$, all packet losses (if any) could be viewed as caused by insufficient number of SWCs. If $k > FW$, $k - FW$ packets are dropped because of exhausted output-link capacity, while the other packet losses (if any) can still be viewed as caused by insufficient SWCs. Therefore, PLR of MOPS with SWCs can be calculated as a combination of these two parts.

We first calculate the PLR caused by exhausted output-link capacity, which equals to the probability of having more than FW packets destined for the same output link. Since the probability of having x packets destined for the same output link (Note that here each output link contains FW wavelength channels and calculation is based on Eq. (4)) equals to

$$P_L(x) = \overset{FW}{\underset{i=1}{\otimes}} P(k)|k = x. \tag{9}$$

Packet loss rate caused by exhausted output-link capacity can be calculated as

$$\mathrm{PLR}_1 = \frac{\sum_{j=FW+1}^{NFW} P_L(j) \cdot (j - F \cdot W)}{F \cdot W \cdot \alpha}. \tag{10}$$

To obtain the PLR caused by insufficient number of SWCs, packet loss caused by exhausted output-link capacity should be pre-excluded. Therefore, the average arrival rate of data packets to each output port can be adjusted to

$$\alpha_1 = \alpha \cdot (1 - \mathrm{PLR}_1). \tag{11}$$

Since each SWC, like an FDL, can resolve one packet contention in each time slot, the total lost packets due to insufficient number of SWCs therefore can be calculated in nearly the same way as that for calculating lost packets due to insufficient FDLs. Specifically, Eqs. (2), (4), (5) and (6) can be adopted directly based on α_1, while Eq. (7) needs to be slightly modified as follows:

$$\mathrm{PLR}_2 = \frac{\sum_{j=N_{\mathrm{SWC}}+1}^{NFW-FW} C(j) \cdot (j - N_{\mathrm{SWC}})}{N \cdot F \cdot W \cdot \alpha}, \tag{12}$$

where N_{SWC} denotes the total number of SWCs. Since those packet losses due to limited link capacity, reflected by PLR_1 in Eq. (10), have been pre-excluded from the calculations of PLR_2 in Eq. (12), the two parts of packet losses have no overlap with each other. Therefore, the gross PLR can be obtained by adding up the two parts.

$$\mathrm{PLR} = \mathrm{PLR}_1 + \mathrm{PLR}_2. \tag{13}$$

Remark. An important assumption that we have made in analyzing MOPS with FDLs is the uncorrelated traffic pattern, where traffic arrivals in different time slots are independent from each other. For bufferless switches such as MOPS with SWCs but no FDLs, such an assumption is not necessary since packet losses in such switches are solely decided by traffic arrivals in the current time slot.

3.4. Analysis of MOPS with both FDLs and SWCs

When FDLs and SWCs are both implemented in MOPS as shown in Fig. 1, packet contentions can be resolved in three different dimensions including (i) space dimension by multi-fiber links, (ii) wavelength dimension by SWCs, and (iii) time dimension by FDLs. To develop simple analytical models, we have separated the effects of these three dimensions as much as possible. Specifically, as shown in Fig. 3 we have developed an "equivalent" model which can closely resemble the packet-loss performance of the general MOPS, but with the effects of space and wavelength dimensions being separated into two different stages. Next we describe the operations in the two-stage model in details. It should be noted that the "equivalent" model is proposed in here solely to resemble the packet-loss performance of MOPS. The fact that this model is expensive and difficult to implement in practice does not affect fulfilling its objective.

In the first stage, we have assumed there are full wavelength conversions before *and* after the switching board. Since the full wavelength conversion before the switching board can resolve all the wavelength conflicts, packet losses in this stage, if any, are all caused by the exhausted outgoing link and FDL capacities. The full wavelength conversion after the first switching board is responsible for converting all the going-through packets back to their *original* wavelengths, such that wavelength constrain can be taken into account after the packet losses caused by insufficient capacities, which anyway cannot be resolved by SWCs as aforementioned, have been excluded. In the second stage,

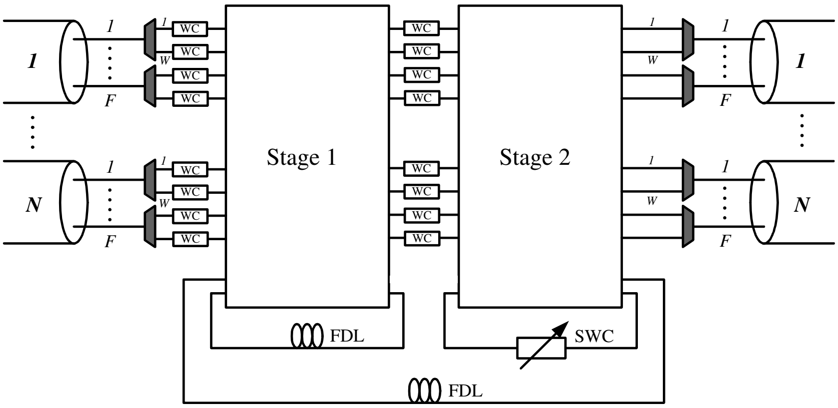

Fig. 3. The “equivalent” two-stage switch configuration of which the packet-loss performance closely resembles that in MOPS with both FDLs and SWCs.

SWCs will be applied to resolve packet contentions caused by wavelength conflicts.

The missing part in this description is how to use FDLs in the two stages respectively. We let FDLs help resolve packet contentions in the first stage as far as possible before handling packet contentions in the second stage. Specifically, if the number of FDLs is larger than the number of packet contentions in the first stage, we let the number of FDLs installed in the first stage be *equal* to the number of contentions in this stage; otherwise, we let all the FDLs be installed in the first stage. The leftover FDLs, if any, are installed in the second stage. Finally, we assume that the packets buffered in *both* the stages are circulated back to join the newly arriving packets in the next time slot.

The reasonability of introducing the two-stage model lies in the fact that the packet contentions caused by insufficient link capacities cannot be resolved by SWCs. FDLs can resolve those packet contentions caused by insufficient capacities as well as those caused by wavelength conflicts. Regardless of which type of contention an FDL resolves, the effect is basically the same: a packet is buffered until the next time slot. Therefore we assign resolving the first type of contentions a higher priority. As later we will see, this helps simplify the analysis.

Let us calculate the PLR in the first stage. By substituting $P_L(x)$, i.e., Eq. (9), into Eq. (5), we obtain the number of contentions caused by insufficient capacities as

$$U_1(x) = \begin{cases} \sum_{k=1}^{FW} P_L(k), & x = 0, \\ P_L(x + F \cdot W), & x = 1, 2, \cdots, NFW - FW. \end{cases} \tag{14}$$

Combining the N output links, the probability of having a total of x contending packets can be expressed as

$$C_1(x) = \bigotimes_{i=1}^{N} U_1(k) | k = x. \tag{15}$$

Similarly to that in Eq. (7), the PLR in the first stage can be calculated as

$$\mathrm{PLR_f} = \frac{\sum_{j=N_{\mathrm{FDL}}+1}^{NFW-FW} C_1(j) \cdot (j - N_{\mathrm{FDL}})}{N \cdot F \cdot W \cdot \alpha}. \tag{16}$$

To take into account the additional traffic coming from the buffered packets, similar to that in Eq. (8), the arrival rate of data packets needs to be adjusted as

$$\alpha_{\mathrm{f}} = \alpha + \frac{\sum_{j=1}^{NFW-FW} C_1(j) \cdot \min(j, N_{\mathrm{FDL}})}{N \cdot F \cdot W}. \tag{17}$$

We then proceed to analyze the second stage. We have assumed that the contending packets will firstly exploit wavelength conversion and then look for available FDLs. Therefore, if the number of contending packets in the second stage is larger than N_{SWC}, some packets need to be buffered if such is feasible. To take this part of buffered traffic into consideration, Eq. (17) needs to be further modified to

$$\alpha'' = \alpha_{\mathrm{f}} + \frac{\sum_{j=0}^{N_{\mathrm{FDL}}} C_1(j) \cdot \left[\sum_{i=N_{\mathrm{SWC}}+1}^{NFW-FW} C(i) \cdot \min(i - N_{\mathrm{SWC}}, N_{\mathrm{FDL}} - j)\right]}{N \cdot F \cdot W}. \tag{18}$$

In this equation, j ($0 \leqslant j \leqslant N_{\mathrm{FDL}}$) denotes the number of FDLs occupied in the first stage (therefore $N_{\mathrm{FDL}} - j$ FDLs are available in the second stage); and i ($0 \leqslant i \leqslant NFW - FW$) denotes the number of the contending packets in the second stage. When

$i > N_{SWC}$, $i - N_{SWC}$ packets would look for FDLs. The number of packets that can be actually buffered is therefore $\min(i - N_{SWC}, N_{FDL} - j)$. Furthermore, $C(j)$ in this equation is calculated by replacing α in the calculations of $C_1(j)$ by $\alpha_f(1 - PLR_f)$ (to better approximate the traffic arriving the second stage).

In the second and all of the following iterations, the modified arrival rate α'' will be adopted in Eq. (15) to get more accurate $C_1(j)$, and consequently more accurate PLR_f in (16). Meanwhile, the average arrival rate of the traffic reaching the second stage would be calculated as

$$\alpha_2 = \alpha'' \cdot (1 - PLR_f). \tag{19}$$

In the second and all of the following iterations, α_2, instead of $\alpha_f(1 - PLR_f)$, will be used to calculate $C(i)$ more accurately.

Finally, the packet loss rate in the second stage can be calculated as

$$PLR_s = \sum_{j=0}^{N_{FDL}} C_1(j) \cdot F_1(N_{SWC}, N_{FDL} - j) + \sum_{j=N_{FDL}+1}^{NFW-FW} C_1(j) \cdot F_2(N_{SWC}), \tag{20}$$

where $F_1(N_{SWC}, N_{FDL} - j)$ and $F_2(N_{SWC})$ denote the PLRs with $(N_{FDL} - j)$ FDLs and no FDLs respectively. In both cases, there are N_{SWC} shared wavelength converters. We have

$$F_1(N_{SWC}, N_{FDL} - j) = \frac{\sum_{i=N_{SWC}+N_{FDL}-j+1}^{NFW-FW} C(i) \cdot [i - N_{SWC} - (N_{FDL} - j)]}{N \cdot F \cdot W \cdot \alpha} \tag{21}$$

and

$$F_2(N_{SWC}) = \frac{\sum_{i=N_{SWC}+1}^{NFW-FW} C(i) \cdot (i - N_{SWC})}{N \cdot F \cdot W \cdot \alpha}. \tag{22}$$

Since PLR_f and PLR_s occur in two different stages with no overlapping, we have

$$PLR = PLR_f + PLR_s. \tag{23}$$

Remark. The values of α'' and α_2 need to be iteratively updated. In all calculations that we have performed results were converged by no more than three iterations. As shown in Section 4, the accuracy of our analytical models is reasonable.

Finally, we summarize our main contributions in analytical model developments as follows: For the pure MOPS, we extended the existing analysis for the classic single-fiber switches to MOPS, under both uniform and non-uniform traffic loads. For MOPS with FDLs, SWCs or both of them under uniform traffic loads, by carefully applying the convolution method, we have developed some new analytical models. These new models are rather simple yet, as later we will see, still highly accurate. Analyzing resource-sharing MOPS configurations under non-uniform traffic, however, remains as a big challenge.

4. Numerical results and discussion

In this section, we evaluate the packet-loss performance of single- and multi-board MOPS, under both uniform and non-uniform traffic loads, through extensive simulations. Meanwhile, accuracy of the proposed analytical models is also tested.

4.1. Single-board MOPS

Performance of the single-board pure MOPS under uniform traffic loads is demonstrated in Fig. 4. We let $N = 4$ and $F \times W$ be fixed at 32, where F varies from 1 to 16 and W from 32 to 2 accordingly. The worst performance happens in single-fiber switch ($F = 1$) where the space dimension for contention resolutions is not available. With an increasing number of fibers per link and a decreasing number of wavelength channels per fiber while keeping the product of them as a constant, the performance improves significantly. However, *unlike* that in circuit-switched networks, even when $F = 16$ and $W = 2$, pure MOPS still cannot perform nearly the same as OPS with FWC. This is because, in OPS networks we cannot make end-to-end wavelength assignment decisions based on global link-state information. As a result, the space dimension provided by multi-fiber links cannot be fully exploited: we may have exhausted capacities and consequently have packet losses on some wavelengths, while on other wavelengths idle capacities are still available. The high accuracy of the analytical model for pure MOPS (Eq. (3)) is also verified in Fig. 4, where analytical and numerical results perfectly match each other.

As aforementioned, in pure MOPS, PLRs on different wavelengths are independent of each other, with the overall PLR a simple linear combination of them. Therefore in the evaluations under non-uniform traffic loads, we simulate only on a single wavelength. Due to space limitations, we only

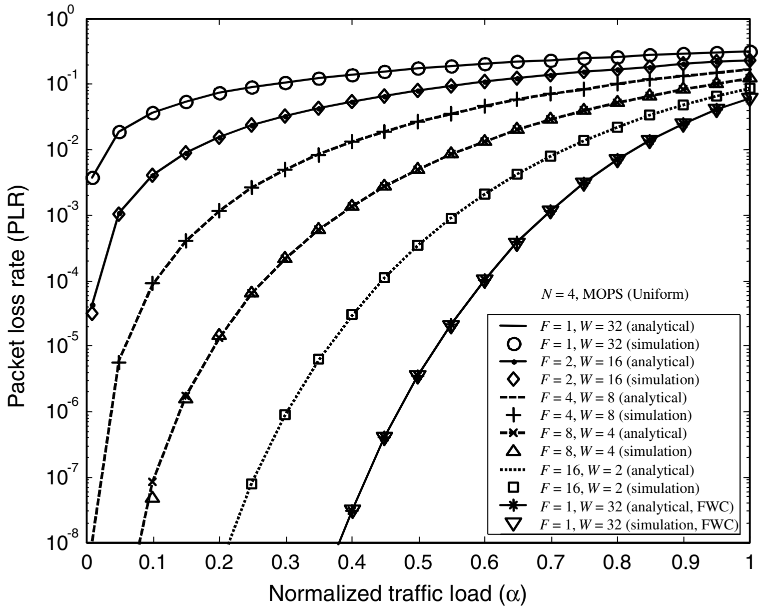

Fig. 4. PLRs of single-board pure MOPS under uniform traffic loads.

present in Fig. 5 the results for the case where traffic load destined for different output links is distributed as a geometrical sequence such that $\rho_i/\rho_{i-1} = R = 1.2$, $i = 2, 3, \ldots, N$. In this and all the other cases that we have tested, the conclusion is that MOPS achieve much better performance than single-fiber pure OPS, but not as good as OPS with FWC.

Single-board MOPS with FDLs under uniform traffic loads is evaluated in Fig. 6, where the switch configuration is set as $N = 4$, $F = 4$ and $W = 8$. We see that with an increasing number of FDLs (N_{FDL}), PLR drops quickly. When $N_{\mathrm{FDL}} = 12$, MOPS steadily outperforms the switch with FWC throughout the region of $\alpha < 0.6$, i.e., as long as the normalized

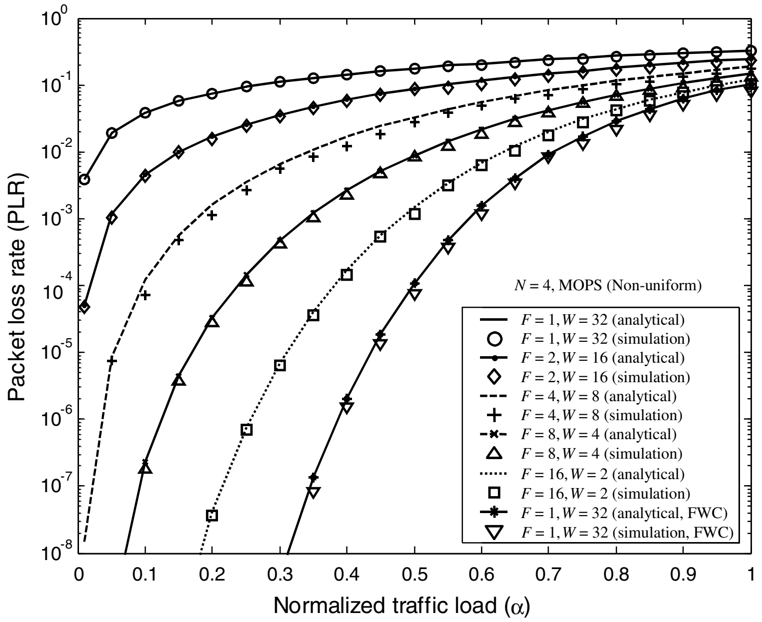

Fig. 5. PLRs of single-board pure MOPS under non-uniform, geometrically-distributed traffic loads where $R = 1.2$.

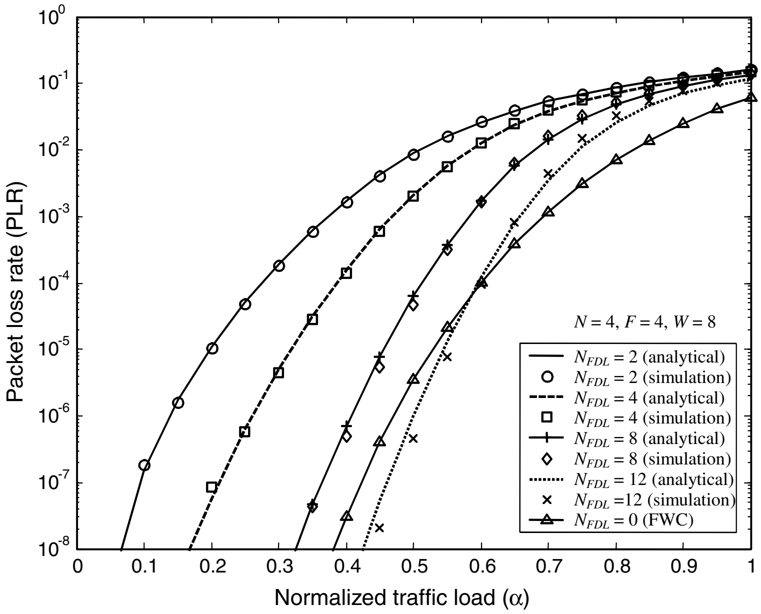

Fig. 6. PLRs of single-board MOPS wth FDLs under uniform traffic loads.

traffic load per channel is lower than 0.6. Meanwhile, the high accuracy of the analytical model in Eq. (7) is also verified. Simulation results under geometrically-distributed non-uniform traffic loads where $R = 1.2$ are presented in Fig. 7. We see that MOPS with 12 FDLs achieves lower PLR than OPS with FWC throughout the region where the normalized average traffic load per channel $\alpha < 0.5$.

Simulation and analytical results of MOPS with SWCs under uniform traffic loads are presented in Fig. 8, where we still let $N = 4$, $F = 4$ and $W = 8$. We see that when the number of SWCs is increased

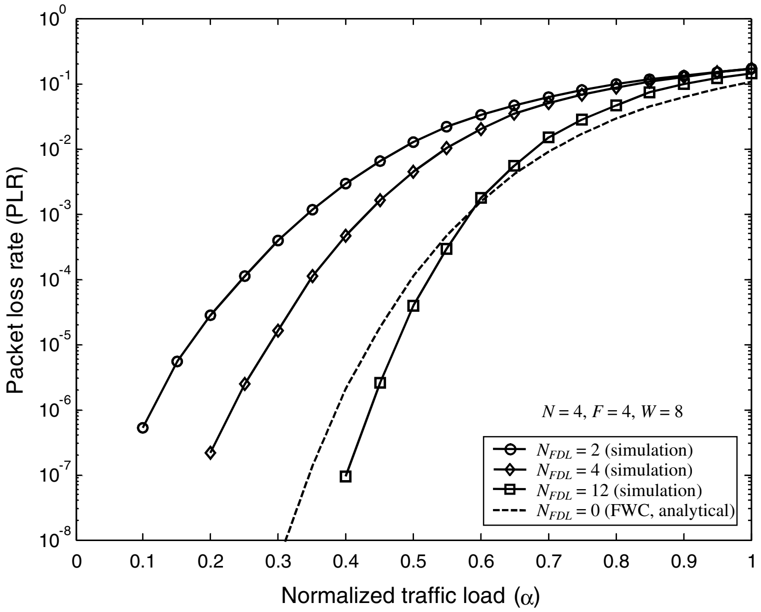

Fig. 7. PLRs of single-board MOPS with FDLs under non-uniform traffic loads where $R = 1.2$.

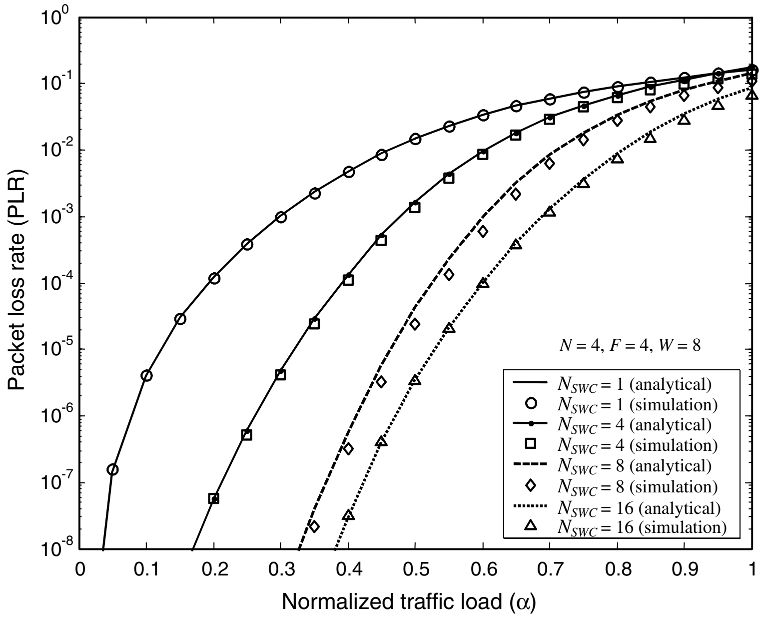

Fig. 8. PLRs of MOPS with SWCs under uniform traffic loads.

from one to four, PLR is lowered significantly. The improvements, however, become less significant when the number of SWCs is increased from 8 to 16. Such an observation is verified in Fig. 9, where we plot PLRs of MOPS with different number of SWCs. We see that the *improvements* in PLR performance become less significant with an increasing number of SWCs, until finally MOPS performs the same as OPS with FWC. More significantly, we see that having more fibers per link with fewer wavelength channels per fiber lowers the number of SWCs required to achieve the same performance as the FWC scheme. For example, where $F = 1$ and $W = 32$, 28 SWCs are needed to achieve the same

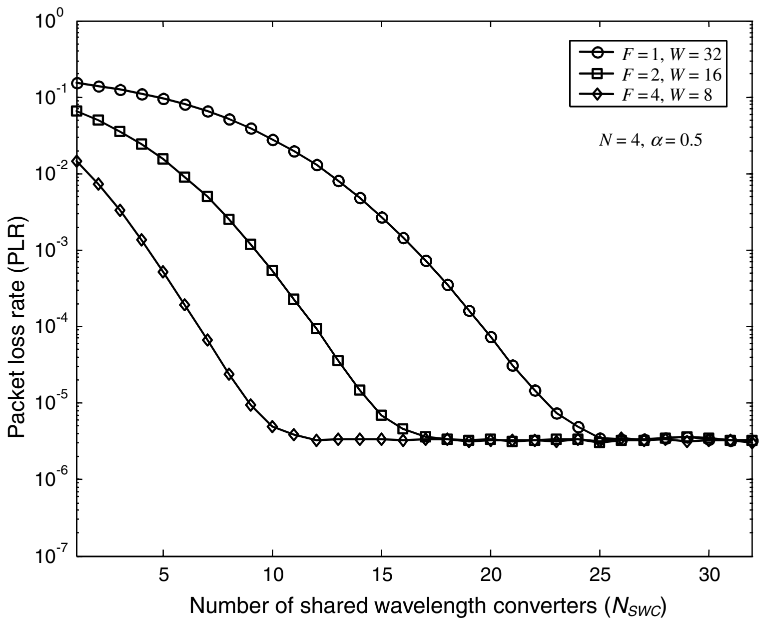

Fig. 9. PLRs of MOPS with different number of SWCs.

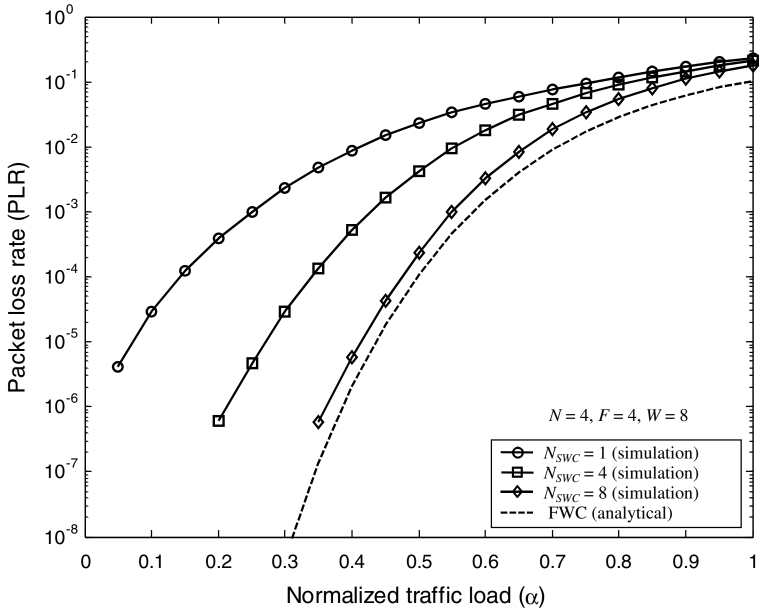

Fig. 10. PLRs of MOPS with SWCs under non-uniform, geometrically-distributed traffic loads where $R = 1.2$.

performance as OPS with FWC. This number can be reduced to 12 in a multi-fiber network where $F = 4$ and $W = 8$. Under non-uniform traffic loads, as we see in Fig. 10, the conclusion holds that having more fibers per link helps improve packet-loss performance and save SWCs. Finally, we point out that the satisfactory accuracy of the analytical model in Eqs. (9)–(13) is verified in Fig. 8.

For the most general MOPS model with both FDLs and SWCs, we have shown in Fig. 11 both the simulation and the analytical results under uniform traffic loads. The node configuration remains as $N = 4$, $F = 4$ and $W = 8$, while the numbers of FDLs and SWCs increase from 2 to 8 respectively. We can clearly see that our proposed analytical model is reasonably accurate, however, minor

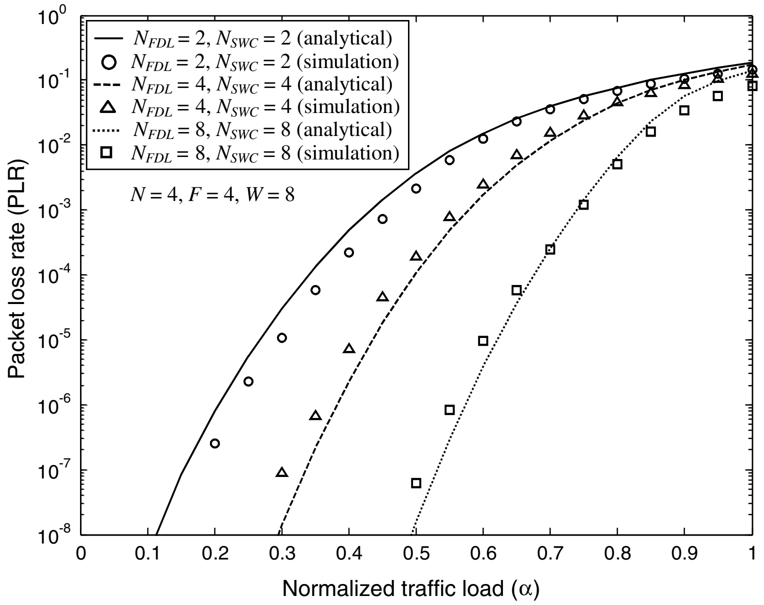

Fig. 11. PLRs of MOPS with both FDLs and SWCs under uniform traffic loads.

inaccuracy still exists due to several factors: (1) as in the remarks that we have discussed in Section 3, the analytical model does not considered the negative correlations between different channels; (2) the equivalent two-stage model is built purposely for the analysis simplicity but not the exact real switching node; (3) the traffic adjustment from the buffered packets is an approximation approach. Basically, the analysis results are still satisfactory to the performance evaluation and can be used for the complicated MOPS models.

4.2. Multi-board MOPS

The node configuration of multi-board MOPS is proposed in Fig. 2. The main objectives of our sim-

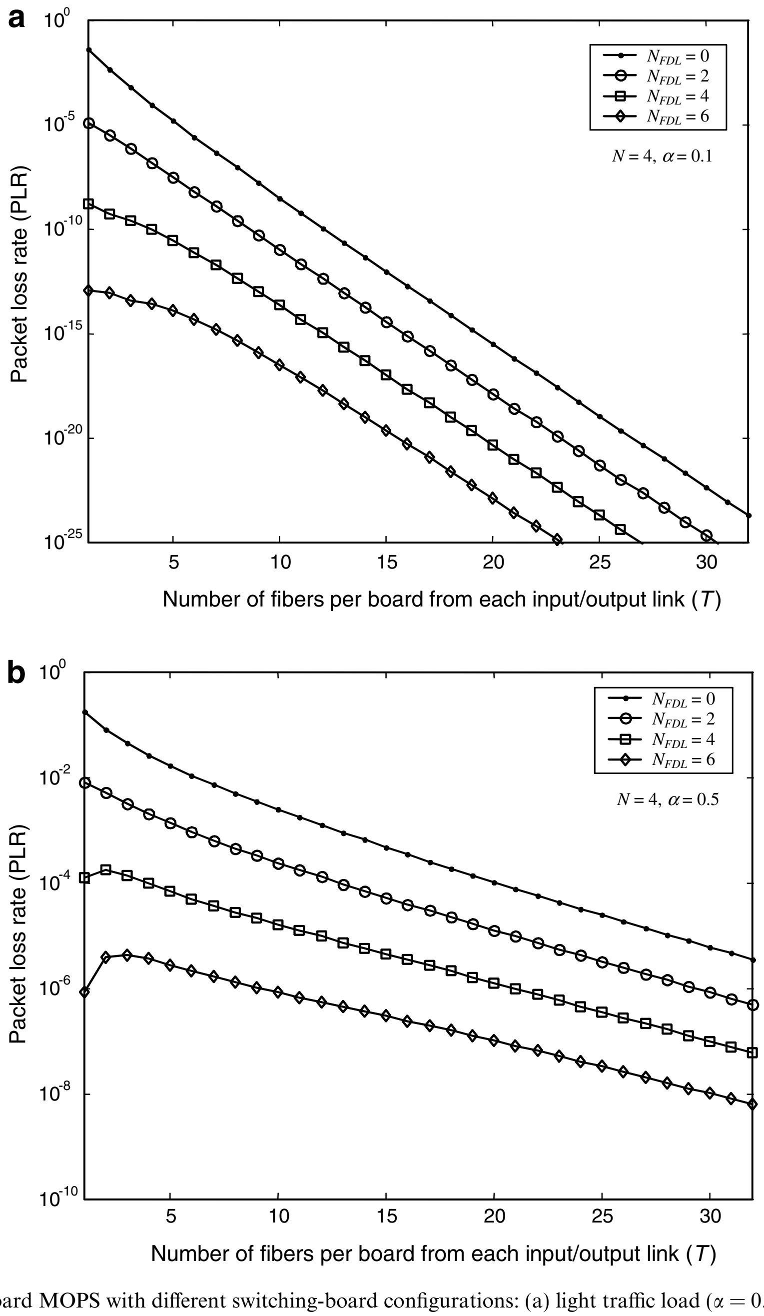

Fig. 12. PLRs of multi-board MOPS with different switching-board configurations: (a) light traffic load ($\alpha = 0.1$) and (b) moderate traffic load ($\alpha = 0.5$).

ulations include evaluating the impacts of switching-board size on PLR and for a given board size, the effects of having different numbers of fibers and FDLs connected to the switching board respectively. We assume that each board is connected to T channels of each input/output link on the same wavelength. Since the overall packet loss is simply a linear combination of those on different switching boards, we conduct simulations on only a single switching board.

We first evaluate PLRs with different switching-board sizes. As we know, a larger switching board connects more fibers and/or FDLs yet leads to higher cost. Due to space limitations, we present here only the analytical results (the accuracy of which has been verified in Section 4.1) under

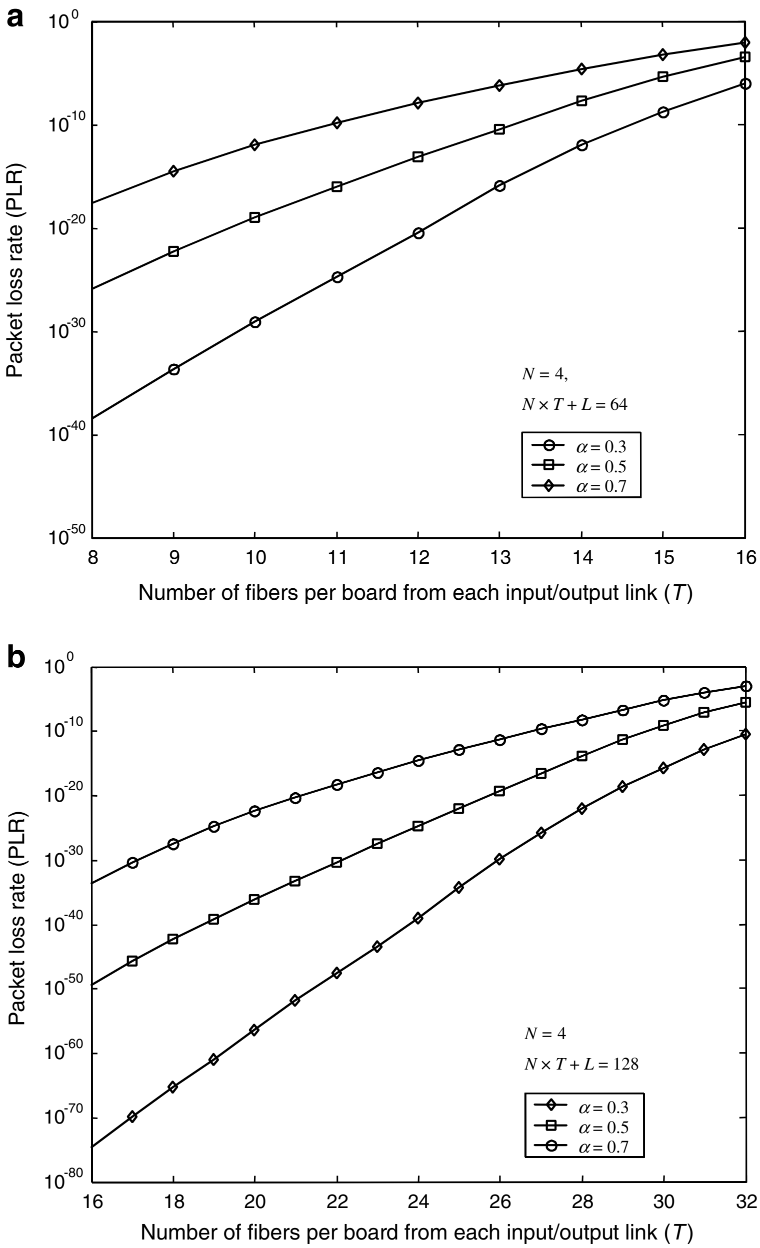

Fig. 13. PLRs of multi-board MOPS with fixed switching-board sizes: (a) 64 and (b) 128.

uniform traffic loads. The conclusions presented here hold in all the non-uniform cases we have tested. Fig. 12 presents the results under light ($\alpha = 0.1$) and moderate traffic loads ($\alpha = 0.5$), respectively. We see that under light traffic loads (i.e., Fig. 12(a)), larger values of T steadily lead to lower PLRs, while improvements achieved by larger values of N_{FDL} are even more significant. Under heavier traffic loads, however, the improvements, either by larger values of T or larger values of N_{FDL}, become drastically less significant. In fact, as we can see in Fig. 12(b), when T is increased from 1 to 2 in a switching board with $N_{\mathrm{FDL}} = 6$, PLR performance becomes even slightly worse. This is because that under light traffic loads, there are generally fewer than T packets destined for the same output link in a switching board with T fibers per link, especially when T is of a large value. Therefore, a larger value of T lowers PLR. For the occasional cases where there are more than T packets destined for the same output link, a limited number of FDLs can generally resolve the contentions. Under heavier traffic loads, on the other hand, with T fibers per link there is a good chance that there are more than T packets destined for the same link. Therefore, the improvements made by larger T or larger N_{FDL} become less significantly. In some cases where we increase the value of T without installing more FDLs, there may be actually more contending packets competing for the limited FDL resources, which leads to a higher PLR.

In Fig. 12, we have assumed that the switching-board size can be increased when necessary. In real-world implementations, however, we may have very limited freedom in choosing the switching-board size where there are only several options, e.g., 8×8, 16×16, etc. For a given switching-board size, an important issue is to decide how many fibers and FDLs should be connected to each board, i.e., the values of T and N_{FDL}, respectively. The switching board size S is given by $S = N \cdot T + N_{\mathrm{FDL}}$. As we have seen in Fig. 12, higher values of T and N_{FDL} generally lead to lower PLR. When both values cannot be set high simultaneously due to a given switching-board size, we expect that having more FDLs and fewer fibers per board would lead to lower PLR. This is because, more FDLs provide more contention-resolution capacities while fewer fibers carry lower traffic loads to each board. However, connecting fewer fibers to each board increases the number of switching boards needed to support a given multi-fiber network and hence, the control burdens may be increased as well. To better understand how to keep a balance between cost and performance, we plot in Fig. 13 the performance of two fixed-sized switching boards where S is set as 64 and 128, respectively. Numerical results confirm that larger N_{FDL} with smaller T lead to lower PLR. Moreover, the performance gains achieved by having larger N_{FDL} are more significant under lower traffic loads, regardless of the switching-board size. On the other hand, even under heavy traffic load like $\alpha = 0.7$, 12–16 FDLs connected to each board are sufficient to achieve a PLR lower than 10^{-12}. Therefore, for most applications, the number of FDLs per board does not need to be very large, while for some special applications, extremely low PLR (lower than 10^{-20}) could be achieved when necessary.

5. Conclusions

In this paper, we evaluated the performance of several typical MOPS configurations, with or without shared contention-resolution resources respectively. Simple yet highly accurate analytical models were proposed and extensive simulations were conducted as well. Analytical and simulation results showed that, by exploiting the space dimension of multi-fiber links, MOPS significantly outperforms the classic single-fiber OPS. With a limited number of FDLs and SWCs, MOPS even outperforms OPS with FWC. For MOPS containing multiple limited-sized switching boards, we have shown how their performance can be affected by the switching-board size, as well as the number of fibers and FDLs connected to each switching board respectively. These evaluations help achieve some insights helpful for the future developments of cost-effective MOPS networks.

Appendix A. Markovian model for mops with FDLS

We extend the Markovian model proposed in Ref. [31] to calculate PLR of MOPS with FDLs. Such extensions are feasible and straightforward since MOPS adopts some similar switching/buffering procedures as those in the classic electronic packet switches. Specifically, the Markovian model can be presented as follows.

Similar to the output queuing model in [31], we define the random variable A as the number of packet arrivals destined for the same output port in a given time slot:

$$a_k = \Pr[A = k] = \binom{N}{k} \cdot (p/N)^k \cdot (1 - p/N)^{N-k}. \quad \text{(A.1)}$$

Letting Q_m denote the number of packets in the destined queue at the end of mth time slot, and A_m the number of packet arrivals during the mth time slot, we have

$$Q_m = \min\{\max(0, Q_{m-1} + A_m - 1), b\}. \quad \text{(A.2)}$$

Here b denotes the buffer size. For finite N and b, Q_m can be modeled as a finite-state, discrete-time Markov chain with its state transition probabilities $P_{ij} = \Pr[Q_m = j | Q_{m-1} = i]$ given by

$$P_{ij} = \begin{cases} a_0 + a_1 & i = 0,\ j = 0, \\ a_0 & 1 \leqslant i \leqslant b,\ j = i - 1, \\ a_{j-i+1} & 1 \leqslant j \leqslant b - 1,\ 0 \leqslant i \leqslant j, \\ \sum_{m=j-i+1}^{N} a_m & j = b, 0 \leqslant i \leqslant j, \\ 0 & \text{otherwise} \end{cases} \quad \text{(A.3)}$$

The steady-state queue size can then be obtained directly from the Markov chain balance equations as

$$q_1 = \Pr[Q = 1] = \frac{(1 - a_0 - a_i)}{a_0} \cdot q_0, \quad \text{(A.4)}$$

$$q_n = \Pr[Q = n] = \frac{(1 - a_1)}{a_0} \cdot q_{n-1} - \sum_{k=2}^{n} \frac{a_k}{a_0} \cdot q_{n-k}, \quad 2 \leqslant n \leqslant b, \quad \text{(A.5)}$$

where

$$q_0 = \Pr[Q = 0] = \frac{1}{1 + \sum_{n=1}^{b} q_n / q_0}. \quad \text{(A.6)}$$

Letting ρ_0 denote the normalized switch throughput, we have

$$\rho_0 = 1 - q_0 \cdot a_0. \quad \text{(A.7)}$$

Therefore, the PLR of the output-queuing MOPS switch can be obtained as

$$\text{PLR} = 1 - \frac{\rho_0}{p}. \quad \text{(A.8)}$$

In MOPS with completely shared FDL buffers, let Q_m^i denote the number of buffered packets destined for output i at the end of the mth time slot. $\sum_{i=1}^{N} Q_m^i$ therefore denotes the total number of packets in the shared buffers at the end of the mth time slot. If the buffer size is infinite, we have

$$Q_m^i = \max\{0, Q_{m-1}^i + A_m^i - 1\}, \quad \text{(A.9)}$$

where A_m^i is the number of packets arriving during the mth time slot and destined for output i. When the buffer size is limited, strictly speaking, buffer

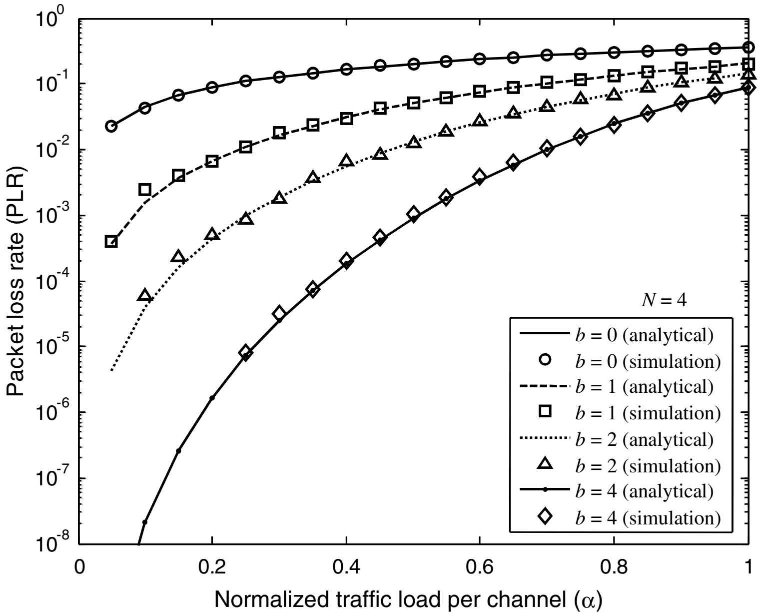

Fig. A.1. PLRs of output-queuing MOPS with FDL buffers by the Markovian model.

overflow invalidates Eq. (A.9). However, an approximate approach is adopted in [31] to calculate the PLR of the switch as

$$\mathrm{PLR} = \Pr\left[\sum_{i=1}^{N} Q^i \geqslant Nb\right]. \qquad (A.10)$$

As properly pointed out in [31], in the region of interest (e.g., the region with a PLR of less than 10^{-6}), the approximation does not lead to any significant inaccuracy.

We conducted a simple simulation test on the above output-queuing Markovian model. The results are presented in Fig. A.1. We see that the analytical results match the simulation results quite well.

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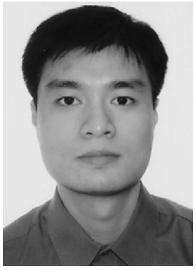

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