On Traffic Allocations in Optical Packet Switches

Yi Li [*], Gaoxi Xiao[*], *Member*, *IEEE*,
and H. Ghafouri-Shiraz[**], *Senior Member*, *IEEE*

* Network Technology Research Centre
School of Electrical and Electronic Engineering
Nanyang Technological University
50 Nanyang Drive
Singapore 637553

** Department of Electrical, Electronic and Computer Engineering
The University of Birmingham
Edgbaston, Birmingham B15 2TT, UK

Abstract

In this paper, we study the impacts of traffic allocations on the performance of optical packet switches (OPS). In particular, two different cases are investigated where traffic loads are distributed over different (i) time slots (time dimension); and (ii) output ports (space dimension), respectively. These two cases are of significant importance as each has different applications and they form the basis of some more complicated schemes. Our main contributions are three fold. Firstly, for the most fundamental OPS configuration, we prove that its packet loss is a convex function of traffic load. For any other node configuration, we prove that its packet loss remains as a convex function of traffic load as long as a simple condition is satisfied. Secondly, for any OPS with its packet loss as a convex function of traffic load, we propose a simple algorithm for efficiently comparing some different traffic allocations and tell which one of them leads to the lowest packet loss. We also show that in either time or space dimension, the best packet-loss performance is achieved when traffic loads are uniformly distributed. Thirdly, for OPS with limited capability of adjusting a given traffic distribution, we propose a *Load Balancing* (LB) algorithm to minimize the packet loss. These contributions provide some useful guidelines and algorithms for achieving efficient traffic allocations in various OPS networks.

Index Terms — Contention resolution, optical buffer, optical packet switch, packet loss, traffic allocation, wavelength conversion.

I. INTRODUCTION

Optical fiber networks are handling a major part of today's high-speed data communications. While current optical networks are mostly transmitting data flows through circuit-switched optical connections, optical packet-switched (OPS) systems, which process the transmitted information at a much finer granularity of data packets, are expected to play an important role in the future systems [1]-[4]. The finer granularity, if handled efficiently without the expensive optical-electronic-optical (O/E/O) conversion, helps to achieve higher bandwidth utilization and better flexibility in traffic management [3], [5], [6].

A critical issue in OPS systems is the resolution of *packet contentions* where there are multiple packets destined for the same output port simultaneously. Based on today's technology, popular contention resolution methods mainly include optical buffering, generally by fiber delay lines (FDLs) [7]-[11], and wavelength conversion, which transfers the contending packets to other free wavelength channels (if any) in the destined output links [12]-[19]. Other solutions include deflecting the contending packets to another outgoing link (e.g., [20]), or exploring the space dimension in the multi-fiber links [21], [22], etc. All these solutions, unfortunately, are still subject to some hardware constraints, including bulky volume of FDLs, high cost of wavelength converters, and high complexity of large-sized optical switch in multi-fiber networks, etc.

Besides the hardware constraints, traffic distribution is another important factor that can significantly affect the performance of optical packet switches. For example, it is known that bursty traffic generally leads to higher packet loss [23], [24]. Therefore some schemes have been proposed to lower the traffic burstiness (e.g., [23], [25]). We consider the effects of traffic allocation in a more general framework, where traffic distribution can be adjusted in two different dimensions:

1. *Time dimension*, where changing the distribution of traffic load in different time slots is feasible yet the *ratio* of traffic loads destined for different output links (termed as *traffic pattern* hereafter) cannot be significantly modified. Existing results of smoothing the burstiness of data traffic at network boundary [23], [25] can be viewed as roughly belonging to this class: traffic is re-distributed in different time slots to achieve better fairness in time dimension, while the traffic pattern is largely decided by traffic load between different source-destination pairs and hence cannot be significantly changed.
2. *Space dimension,* where the traffic pattern can be adjusted yet the traffic distribution in time dimension is fixed. Examples include allocating outgoing packets on several different alternative routes as that in the deflection routing scheme [20]; or allocating traffic on different fibers in the same multi-fiber output link [21], [22], etc.

The above two classes of traffic allocations may happen simultaneously in real-world operations, though generally one of them would be of more significant effects than the other. In this paper, to achieve some straight yet insightful observations, however, we restrict our discussions to the most representative cases where traffic allocations happen in only *one* dimension. Our main contributions can be summarized as follows:

- For the most fundamental OPS configuration, we prove that its *packet loss* (defined as the statistical average number of lost packets in each time slot) is a convex function of traffic load. For any other node configuration, we prove that, as long as a simple *speeding-up condition* (defined later in Section II) is satisfied, its packet loss remains as a convex function of traffic load. For simplicity, hereafter we term such OPS configurations as having *convex packet loss*.

- For any OPS configuration with convex packet loss, we propose a simple algorithm that can efficiently make comparisons and tell which one of some different traffic allocations achieves the lowest packet loss. We also show that in both the time and space dimensions, uniform distribution where traffic load is evenly distributed among different time slots or output ports, leads to the best performance.
- For an optical switch with limited capability of adjusting a given traffic distribution, we propose a simple *Load Balancing* (LB) algorithm which minimizes the packet loss after the adjustments.

Together, these contributions provide some useful guidelines and algorithms for achieving efficient load allocation in various OPS networks.

The rest of this paper is organized as follows. In Section II, we prove that the most fundamental OPS configuration has convex packet loss, so it is with any other configuration satisfying the speeding-up condition. For any OPS with convex packet loss, we propose in Section III a simple algorithm for quickly telling which one of some given traffic allocations achieves the lowest packet loss. Also it is proved that the uniform traffic distribution leads to the best performance. In Section IV, we propose the LB algorithm and prove its optimality for any switch with convex packet loss. These conclusions are verified in Section V by simulation results. Section VI concludes this paper.

II. CONVEXITY OF PACKET LOSS IN DIFFERENT SWITCHES

We firstly study the packet-loss performance of the most fundamental OPS configuration, followed by discussions on the more general cases of other switches satisfying the speeding-up condition.

A. Convexity of Packet Loss in the Most Fundamental OPS Configuration

The most fundamental switch configuration we would study in this section is illustrated in Fig. 1. It is a typical model with extensive existing studies on its packet-loss and packet-delay performance (e.g., [8], [23], [27], [28]). In this model, there are N input and output links with M channels per link connected to the same switch matrix. The channels are assumed to be on the same wavelength, or equivalently, be equipped with redundant wavelength conversion capability. Apparently, in such a switch, there can be a maximum of $N \times M$ packets arriving in each time slot; and at most M packets be transmitted by each output link at one time. Note that the switch has no contention resolution resource other than the multiple (if $M > 1$) channels in each link. Throughout this paper, we assume that the arriving packets are synchronized and contained in the fixed-length time slots before entering the switching matrix [14], [18], [26].

In our analysis, the *average* traffic load, defined as the probability of having a packet arriving in each time slot from each input channel, is denoted as α. To define the traffic pattern, we denote ρ_i (i = 1,2,…,N) as the probability that a newly arrived packet is destined to the i-th output link. For the special case of uniform traffic pattern [8], [14], [27], [28], we have that $\rho_i = 1/N$, i = 1,2,…,N. Based on these definitions, the probability of having j packets destined for the output link i can be calculated as:

$$P_i(j) = \binom{NM}{j} \cdot (\rho_i \alpha)^j \cdot (1-\rho_i \alpha)^{N \cdot M - j}, \quad j = 0, 1, \ldots, NM. \tag{1}$$

When $j \le M$, all the *j* packets can be transmitted. When $j > M$, however, $j - M$ packets will be lost. Therefore, the average number of lost packets destined for output link *i* can be calculated as:

$$\begin{aligned} PL_i &= \sum_{j=M+1}^{N \cdot M} P_i(j) \cdot (j - M) \\ &= \left[\sum_{j=1}^{N \cdot M} P_i(j) \cdot j - \sum_{j=1}^{M} P_i(j) \cdot j \right] - M \cdot \left[\sum_{j=0}^{N \cdot M} P_i(j) - \sum_{j=0}^{M} P_i(j) \right] \\ &= NM \rho_i \alpha - \sum_{j=1}^{M} P_i(j) \cdot j - M + M \cdot \sum_{j=0}^{M} P_i(j) \\ &= NM \rho_i \alpha - M + \sum_{j=0}^{M} P_i(j) \cdot (M - j). \end{aligned} \tag{2}$$

The overall packet loss of the switch therefore can be calculated as

$$PL = \sum_{i=1}^{N} PL_i. \tag{3}$$

As later we shall see in Section V, the traffic model in Eqs. (1) - (3) is highly accurate.

Now we consider the adjustments of traffic distribution in two dimensions respectively. We see that the traffic distribution in time dimension can be reflected by the parameter α (A larger value of α denotes a higher traffic load, and vice versa.), while the traffic distribution in space dimension can be defined by the traffic pattern $\{\rho_i, \ i = 1, 2, \ldots, N\}$. Therefore, the two representative cases of traffic allocations can be re-phrased as follows:

1. ***Traffic allocations in time dimension***, where the traffic pattern $\{\rho_i,\ i=1,2,...,N\}$ is given and fixed. We are allowed to adjust α_t, $t=1,2,...,T$, without changing the overall traffic loads in *T* time slots $\sum_{t=1}^{T}\alpha_t$, to lower the packet loss in Eq. (3).
2. ***Traffic allocations in space dimension***, where α is given and fixed. We are allowed to adjust the traffic pattern $\{\rho_i,\ i=1,2,...,N\}$ to lower the packet loss in Eq. (3).

To prove that the most fundamental OPS configuration has convex packet loss in time dimension, we have

Theorem 1: With any given set of non-negative parameters $\{\rho_i,\ i=1,2,...,N\}$, the packet loss *PL* in Eq. (3) is a convex function of α.

Proof: See Appendix A. □

For traffic allocations in space dimension, similar to Theorem 1, we have:

Theorem 2: With any given value of α ($0 \le \alpha \le 1$), the packet loss *PL* in Eq. (3) is a convex function of ρ_i, $i=1,2,...,N$.

Proof: See Appendix A. □

Remark: Note that the underlying assumption in Eqs. (1)-(3) is that the traffic is independent and identically distributed (i.i.d) on the slot level. Such assumption has been adopted in analyses of OPS under aggregated traffic [29], low traffic [30], or traffic within short time intervals [31]. For other cases where this assumption does not apply, extensive studies have been done to derive proper analyses of their packet-loss performances (e.g.,

[31], [32]). However, none of these results, to the best of our knowledge, has been simple yet accurate enough for a solid proof of convexity as those in Theorems 1 and 2. To provide an alternative solution, we prove in the next subsection that, for *any* switch under *any* traffic load, as long as the speeding-up condition is satisfied, its packet loss remains as a convex function of traffic load. □

B. Convexity of Packet Loss in the Other OPS Configurations

The speeding-up condition can be defined as follows. Add additional traffic load to a switch, the packet loss will be increased. If the same amount of additional traffic load leads to a larger increase of packet loss under heavier traffic, we say that this switch satisfies the speeding-up condition. In other words, if for any $\beta_1 \le \beta_2$ and $\Delta\beta \ge 0$,

$$PL_i(\beta_1 + \Delta\beta) - PL_i(\beta_1) \le PL_i(\beta_2 + \Delta\beta) - PL_i(\beta_2), \tag{4}$$

we say that PL_i satisfies the speeding-up condition.

We may expect that the speeding-up condition is satisfied in most, if not all, well-engineered switches. Specifically, under low traffic load, when traffic is increased, the packet loss increases slowly, since most of the increased traffic can go through the switch smoothly. When traffic load becomes higher, however, an increasingly larger portion of the increased traffic will be blocked and lost. Finally, packet loss would increase at nearly the same speed as that of the traffic load, where virtually all the increased traffic is blocked.

To prove that any switch satisfying the speeding-up condition has convex packet loss, we have the lemma as follows:

Lemma 1: Assume $f(x)$ is a continuous function with first-order derivative. The *necessary and sufficient* condition that $f(x)$ is a convex function of x is that, for any $x_1 \leq x_2$ and $\Delta x \geq 0$, we have

$$f(x_1 + \Delta x) - f(x_1) \leq f(x_2 + \Delta x) - f(x_2). \tag{5}$$

Proof: See Appendix B. □

Comparing Eqs. (4) and (5), we have

Theorem 3: If PL_i, the packet-loss component of a switch either in time or space dimension, satisfies Eq. (4), it is a convex function of traffic load. If every component satisfies Eq. (4), then *PL* in Eq. (3) is a convex function of traffic load. □

III. CONVEXITY-BASED PACKET LOSS COMPARISONS

Given a fixed amount of total traffic load, there can be different allocations of it in time or space dimensions. Denote the packet loss corresponding to such allocations as $PL(\alpha_1, \alpha_2, \cdots \alpha_T)$ or $PL(\rho_1, \rho_2, \cdots \rho_N)$, where T and N denote the number of different components in time and space dimensions (e.g., time slots in time dimension or output ports in space dimension) respectively. In this section, we propose a simple algorithm to make comparisons between some different traffic allocations and quickly tell which one of them leads to the lowest packet loss. To start, we make the following definitions:

If for *any* permutation of $\{a_1, a_2, \cdots, a_K\}$, denoted as $\{\widehat{a_1}, \widehat{a_2}, \cdots, \widehat{a_K}\}$, , we have

$$PL\left(a_1,a_2,\cdots,a_K\right)=PL\left(\widehat{a_1},\widehat{a_2},\cdots,\widehat{a_K}\right), \tag{6}$$

we say that the packet loss function *PL* is *symmetric*.

We may reasonably expect that most OPS have exactly or nearly symmetric packet loss. For example, an OPS with the same capacity in each output link generally speaking has symmetric packet loss in space dimension. OPS with no buffer or small-sized buffer may have symmetric packet loss in time dimension as well, where exchanging the traffic load in different time slots leads to exactly or nearly the same packet loss.

For OPS with convex, symmetric packet loss, we define *traffic shifting* as the operation that moves a portion of a higher-value traffic component to a lower-value component without making the latter component exceed the former one. For example, we may apply a traffic shifting operation to transfer traffic allocation $\{0.3,\ 0.7\}$ into $\{0.4,\ 0.6\}$.

From Lemma 1, we can easily prove

Lemma 2: Assume $f(x)$ is a convex function with first-order derivative. For any $x_1 \le x_2$ and $0 \le \Delta x \le x_2 - x_1$, we have

$$f(x_1+\Delta x)-f(x_1)\le f(x_2)-f(x_2-\Delta x). \tag{7}$$

Proof: Replace in Eq. (5) the x_2 by $x_2-\Delta x$. □

Based on Lemma 2, we have the comparison method as follows:

Theorem 4: Assume the switch has symmetric, convex traffic loss. For two different allocations of the same amount of overall traffic load, if one of them can be transferred into the other one by a certain number of traffic shifting operations, the former one has higher packet loss. □

To quickly judge whether a traffic allocation can be transferred into another one by a certain number of traffic shifting operations, we propose the following theorem:

Theorem 5: Assume the switch has symmetric, convex traffic loss. For two different traffic allocations $\{a_1, a_2, \cdots, a_K\}$ and $\{b_1, b_2, \cdots, b_K\}$ where a_i's and b_i's $(i = 1,\ 2, \ldots, K)$ are each listed in an *non-decreasing* order of their values, $\{b_1, b_2, \cdots, b_K\}$ can be transferred into $\{a_1, a_2, \cdots, a_K\}$ by a certain number of traffic shifting operations if and only if

$$\sum_{i=1}^{k} a_i \geq \sum_{i=1}^{k} b_i, \quad k = 1, 2, \ldots, K-1. \tag{8}$$

Proof: See Appendix C. □

For example, by applying Theorem 5, we can prove that

$$PL(0.2,\ 0.3,\ 0.5) \leq PL(0.1,\ 0.35,\ 0.55).$$

Finally, for any convex and symmetric function *PL*, either from Theorem 5 or from the Jensen's Inequality [33], we have

$$PL\left(a_1, a_2, \cdots, a_K\right) \geq PL\left(\bar{a}, \bar{a}, \ldots, \bar{a}\right) \tag{9}$$

where $\bar{a} = \frac{1}{K}\sum_{i=1}^{K} a_i$. Therefore, we have the conclusion as follows:

Theorem 6: For any switch with convex and symmetric packet loss, uniform traffic allocation, which evenly distributes traffic load among different time slots or different output ports, achieves the best performance in time and space dimensions respectively. □

Remark: Note that the comparison method proposed in Theorems 4 and 5 has its limit: for two traffic allocations that cannot be transferred into each other by applying traffic shifting operations, e.g., $\{0.2, 0.3, 0.5\}$ and $\{0.24, 0.24, 0.52\}$, we cannot tell which one of them leads to lower packet loss by using the proposed method. This does not come as a surprise: the proposed method is based on a single condition that the packet loss is convex and symmetric. We cannot expect it to fix all the problems with such a minimum assumption. For those cases that cannot be judged by convexity condition, additional information has to be provided and more sophisticated algorithms have to be developed. □

IV. THE LOAD BALANCING (LB) ALGORITHM

In the last section, we proved that the uniform distribution leads to the best performance, in either time or space dimension. In practical switch implementations, however, various constraints may make the uniform distribution beyond reachable. For example, we may have limited buffer size for adjusting the traffic distribution in time dimension, or limited wavelength conversion for adjusting the traffic distribution in space dimension. In this section, we consider the problem of minimizing the packet loss in an OPS with *limited* capability of adjusting a given traffic distribution. We propose a simple *Load Balancing* (LB) algorithm and prove its optimality under the simple condition that the switch has convex and symmetric packet loss (which probably holds in most OPS, as we pointed out earlier).

The main idea of the LB algorithm is to repetitively apply the traffic shifting operations to move traffic loads from the most-loaded component(s) to the least-loaded component(s), until the traffic distribution is adjusted to be uniform, or the capability of adjusting traffic distribution has been exhausted. As an example, hereafter we discuss the traffic allocations in time dimension in detail.

Without loss of generality, we assume that the traffic distribution $\alpha_t,\ t=1,2,...,T,$ has $\alpha_1 \le \alpha_2 \le ... \le \alpha_T$. The given capability of adjusting the traffic distribution is denoted as $\beta_{\max}$. In other words, $\frac{1}{2}\sum_{t=1}^{T}|\alpha_t - \alpha_t'| \le \beta_{\max}$, where $\{\alpha_t'\}$ denotes the traffic distribution after the adjustments.

LB Algorithm in Time Dimension

1. Calculate the *distance* of the given traffic distribution from the uniform distribution

$$\overline{\beta} = \frac{1}{2}\sum_{t=1}^{T}\left|\alpha_t - \overline{\alpha}\right| \tag{10}$$

   where $\overline{\alpha} = \frac{1}{T}\sum_{t=1}^{T}\alpha_t$. If $\beta_{\max} \ge \overline{\beta}$, then the given traffic pattern can be adjusted to the uniform traffic distribution, stop; otherwise, let $\beta = \beta_{\max}$ and go to Step 2.

2. **Deduction operation:** Find all the traffic distribution components with the largest value $\alpha_m = ... = \alpha_T$. Note that m can be equal to T. Let

$$\Delta\beta = \min\left(\alpha_T - \alpha_{m-1},\ \frac{\beta}{T-m+1}\right) \quad (11)$$

$$\alpha_j = \alpha_j - \Delta\beta, \quad j = m, m+1, ..., T \quad (12)$$

$$\beta = \beta - \Delta\beta \times (T - m + 1) \quad (13)$$

Repeat the above procedure until $\beta = 0$.

3. **Addition operation:** Re-initialize $\beta = \beta_{\max}$. Find all the components with the smallest value $\alpha_1 = ... = \alpha_s$. Note that *s* can be equal to 1. Let

$$\Delta\beta = \min\left(\alpha_{s+1} - \alpha_1,\ \frac{\beta}{s}\right) \quad (14)$$

$$\alpha_j = \alpha_j + \Delta\beta, \quad j = 1, ..., s \quad (15)$$

$$\beta = \beta - \Delta\beta \times s \quad (16)$$

Repeat the calculations in Eqs. (14) - (16) until $\beta = 0$. □

The LB Algorithm in the space dimension would be nearly the same, except that it is ρ_i, $i = 1,2,...,N$, instead of α_t, $t = 1,2,...T$, that is adjusted. The very similar descriptions of the detailed algorithm therefore are omitted.

Next we prove that the LB algorithm's optimality in lowering packet loss with any given traffic distribution and $\beta_{\max}$. Once again we use traffic allocation in time domain as an example, while the optimality of the algorithm in space dimension can be proven similarly.

Denote the packet loss in a single time slot under traffic load α as $PL(\alpha)$. Since $PL(\alpha)$ is a convex function of α, from Lemma 1, we have that

$$PL(\alpha_1) - PL(\alpha_1 - \Delta\beta) \le PL(\alpha_2) - PL(\alpha_2 - \Delta\beta) \quad (17)$$

for any $\alpha_1 \le \alpha_2$ and $\Delta\beta \ge 0$. It indicates that in the Step 2 of the LB algorithm, reducing the most-loaded traffic component leads to the *quickest* decrease of packet loss. Meanwhile, still from Lemma 1, we have

$$PL_i(\alpha_1 + \Delta\beta) - PL_i(\alpha_1) \le PL_i(\alpha_2 + \Delta\beta) - PL_i(\alpha_2) \quad (18)$$

for any $\alpha_1 \le \alpha_2$ and $\Delta\beta \ge 0$. It indicates that in the Step 3 of the LB algorithm, adding traffic to the least-loaded traffic component leads to the *slowest* increase of packet loss. Combining the observations in Eqs. (17) and (18), the optimality of the LB algorithm is proved.

V. SIMULATION RESULTS AND DISCUSSIONS

A. Packet Loss in the Most Fundamental OPS Configuration

We start by studying the packet-loss performance in the most fundamental OPS configuration as illustrated in Fig. 1. To evaluate the effects of traffic allocations in time dimension, we assume that the overall traffic loads in *T* time slots, measured by $\sum_{t=1}^{T} \alpha_t$, is given and fixed. Specifically, we let $T = 4$ and $\alpha = \frac{1}{T}\sum_{t=1}^{T} \alpha_t = 0.5,$ and consider several different cases as follows:

$$
\begin{aligned}
&\text{(a)} \quad \{\alpha_1, \alpha_2, \alpha_{3,}\alpha_4\} = \{0.5, 0.5, 0.5, 0.5\} \\
&\text{(b)} \quad \{\alpha_1, \alpha_2, \alpha_{3,}\alpha_4\} = \{0.6, 0.6, 0.4, 0.4\} \\
&\text{(c)} \quad \{\alpha_1, \alpha_2, \alpha_{3,}\alpha_4\} = \{0.7, 0.7, 0.3, 0.3\} \\
&\text{(d)} \quad \{\alpha_1, \alpha_2, \alpha_{3,}\alpha_4\} = \{0.8, 0.8, 0.2, 0.2\} \\
&\text{(e)} \quad \{\alpha_1, \alpha_2, \alpha_{3,}\alpha_4\} = \{0.9, 0.9, 0.1, 0.1\}
\end{aligned}
\tag{19}
$$

By using Theorem 5, it can be easily proved that each traffic allocation can be achieved by applying traffic shifting operations to the latter ones. For simplicity, we differentiate them by introducing the *deviation* degree γ :

$$
\gamma = \frac{\sum_{t=1}^{T} |\alpha_t - \alpha|}{T}. \tag{20}
$$

The above five different cases then can be denoted as with different values of γ varying from 0 (case (a)) to 0.4 (case (e)).

As to the traffic patterns in space dimension, we consider several cases as follows:

(i) *Uniform traffic pattern*, where $\rho_i = 1/N$, $i = 1, 2, ..., N$;

(ii) *Geometric traffic pattern*, where $\rho_i / \rho_{i-1} = R,\ i = 2, 3, ..., N$. In other words, the average traffic loads destined to different output links distribute as a geometric sequence. We present two different cases where $R = 1.1$ and $R = 1.2$ respectively, and

(iii) *Hotspot traffic pattern*, where we assume that each of the three hotspot output links has traffic destined to it five times as high as that destined to each of the other output links, where the number of input/output links are configured as $N = 8$.

When $N = 8$, again it can be proved by using Theorem 5 that each traffic pattern can be achieved by applying traffic shifting operations to the latter ones. The proof is trivial yet quite lengthy. Thus it is omitted in this paper.

We let $N = 8$, $M = 4$, $\alpha = 0.5$, and $T = 4$ (Note that such parameter values will be adopted in all the following simulations unless otherwise specified.). Throughout this paper, the simulation results are plotted as the average of ten rounds of independent simulations with different random number generators and/or different seeds for random number generation. In each round of simulation, at least 10^6 packet arrivals have been simulated. To avoid random fluctuations, the packet loss calculations are only carried out after the packet-loss performance has reached a stable status.

Both the analytical and the simulation results are presented in Fig. 2. We see that for any value of γ, uniform traffic pattern leads to the best performance in space-dimension traffic allocations. Meanwhile, for any traffic pattern, $\gamma = 0$ leads to the best performance in time-dimension traffic allocations. Therefore, the optimality of the uniform traffic distribution in both dimensions is verified. The global optimal solution (i.e., the global minimum packet loss) is achieved when the traffic distribution in both time and space dimensions is uniform. More generally and more significantly, we see that either in time dimension or in space dimension, those traffic allocations that can be achieved by applying traffic shifting operations to the others enjoy lower packet loss, which matches the conclusions of Theorems 4 and 5 in Section III. It is also demonstrated that the proposed analytical models are highly accurate, generating analytical results almost perfectly matching the simulation results.

B. Packet Loss Evaluation of Some Other OPS Configurations

Optical packet switches are typical implemented with contention resolution components such as FDLs or SWCs or both, where a typical example is shown in Fig. 3. Since it is notoriously difficult to achieve accurate yet simple analytical models for such node configurations under general non-uniform traffic loads [9], [17], [27], [28], we investigate their packet-loss performance through numerical simulations.

Fig. 4 shows the results where the switch is equipped with shared FDLs but no SWC. We denote the number of FDLs as N_{FDL} and assume that they can be accessed by all the input ports. When there are more contending packets that can be handled by FDLs, the contending packets will be randomly selected to be buffered. We assume that all the incoming/outgoing channels are on the same wavelength (may be viewed as multi-fiber case). From Fig. 4, we see that though the existence of FDLs helps to lower packet loss, the comparison method proposed in Theorems 4 and 5 remains valid, and the uniform traffic distribution still leads to the best performance in both time and space dimensions. In other words, all the major conclusions hold.

Node configuration with SWCs but no FDL is evaluated in Fig. 5. We assume that there are totally W different wavelengths in each link, and a certain number (denoted as N_{SWC}) of SWCs are installed in the switch, which can be accessed by all the input ports. We consider two different cases where the M channels in each output link belong to a single-fiber (W = 4) or multiple fibers (W = 2), respectively. In both cases, we set N_{swc} = 2. The results in Fig. 2 meanwhile can be viewed as for the special case with unlimited wavelength-conversion capability. When $W = 4$, all contentions have to be resolved by

SWCs. When W = 2, the two channels on each wavelength help to resolve some contentions. Fig. 5 demonstrates that all the conclusions mentioned earlier remain valid.

Finally, we evaluate the node configuration with both the SWCs and the FDLs, where the simulation results are presented in Fig. 6. We assume that a packet contention will be resolved by wavelength conversion as long as such is applicable before an FDL is used. All the conclusions hold in single-fiber (W = 4) as well as multi-fiber (W = 2) cases. Due to space limitation, only the single-fiber case results have been presented. The multi-fiber case results appear to be curves of very similar shapes yet at lower values.

C. Load Balancing Algorithm in the Most Fundamental Node Configuration

Fig. 7 presents the simulation results where the LB algorithm is applied in the most fundamental node configuration as illustrated in Fig. 1, where the multiple channels (M = 4) in each link are either of the same wavelength or equipped with unlimited wavelength-conversion capability. The packet loss performance versus the adjustment capability $\beta_{\max}$ in time domain is shown in Fig. 7(a), where we assume that the traffic pattern is uniform. Two different cases, namely Case 1 where α_t = {0.2, 0.4, 0.6, 0.8} and Case 2 where α_t = {0.1, 0.3, 0.7, 0.9} respectively, have been considered. The packet losses are steadily lowered with increased values of $\beta_{\max}$, until finally the uniform time-domain distribution is achieved (where $\beta_{\max} = 0.4$ in Case 1 and $\beta_{\max} = 0.6$ in Case 2 respectively).

For traffic allocations in space dimension, it is presented in Fig. 7(b) the effectiveness of the LB algorithm. Again we consider two different cases: geometric-distributed case where $\rho_i / \rho_{i-1} = R = 1.3,\ i = 2,3,...,N$, and the hotspot case. For both cases, we let $\alpha = 0.5$.

Both the analytical and the simulation results show that, the lowest packet losses are achieved when $\beta_{\max} = \frac{1}{2}\sum_{i=1}^{N}\left|\rho_i - \frac{1}{N}\right|$, that is, $\beta_{\max} \approx 0.246$ for the geometric-distributed case, and $\beta_{\max} = 0.375$ for the hotspot case respectively, where the traffic patterns are adjusted to be uniform.

D. Load Balancing Algorithm in Some Other OPS Configurations

For OPS implemented with FDLs and/or SWCs as illustrated in Fig. 3, their packet-loss performance versus the adjustment capability $\beta_{\max}$, in both time and space dimensions, have been extensively simulated. Due to space limitation, we present in Fig. 8 through Fig. 10 only the results for load allocations in time dimension, while all the conclusions hold in space dimension as well. We still consider Case 1 where α_t = {0.2, 0.4, 0.6, 0.8}; and Case 2 where α_t = {0.1, 0.3, 0.7, 0.9} respectively, where traffic pattern is still assumed to be uniform.

Fig. 8 shows the performance of OPS with only FDLs, where $N_{FDL} = 2$ and $W = 1$. Compared with Fig. 7, with FDLs the packet losses in Fig. 8 are largely reduced. However, the effectiveness of the LB algorithm is not affected, which still manages to achieve the best performance at exactly the same value of $\beta_{\max}$ as that in Fig. 7(a). Very similar observations could be made in Fig. 9, where we have SWCs ($W = 4$ and $N_{SWC} = 2$) but no FDL, as well as in Fig. 10, where we have both SWCs ($W = 4$ and $N_{SWC} = 2$) and FDLs ($N_{FDL} = 2$).

V. CONCLUSIONS

In this paper, we evaluated the impacts of traffic allocations on the performance of OPS. Firstly, we revealed the convexity of the packet-loss functions in various OPS. Specifically, for the most fundamental OPS configuration, we proved that it has convex packet loss. For any other node configuration, we proved that its packet loss remains as a convex function of traffic load as long as the speeding-up condition is satisfied. Secondly, for any OPS with convex packet loss, we proposed a simple algorithm for efficiently comparing some different traffic allocations and tell which one of them leads to the lowest packet loss. We also showed that in either time or space dimension, the lowest packet loss is achieved under uniform traffic distribution. Thirdly, for OPS with limited capability of adjusting a given traffic distribution, we proposed a simple Load Balancing algorithm for minimizing the packet loss after the adjustment. These contributions are not restricted to any particular node configuration, therefore they provide some useful guidelines and algorithms for achieving efficient traffic allocations in various OPS networks.

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APPENDIX A: PROOF OF THE CONVEXITY OF TRAFFIC LOSS IN THE MOST FUNDAMENTAL OPS CONFIGURATION

Proof of Theorem 1: We prove the convexity of the packet loss function by showing that $\frac{d^2}{d\alpha^2}\left(PL\right) \geq 0$. More specifically, we prove that,

$$\frac{d^2}{d\alpha^2}\left(PL_i\right) \geq 0,\ i = 1, 2, \ldots N. \tag{A.1}$$

We have:

$$\begin{aligned}
\frac{d^2}{d\alpha^2}\left(PL_i\right) &= \frac{d^2}{d\alpha^2}\left[NM\rho_i\alpha - M + \sum_{j=0}^{M} P_i(j)\cdot(M-j)\right] \\
&= \frac{d^2}{d\alpha^2}\left[\sum_{j=0}^{M} P_i(j)\cdot(M-j)\right] \\
&= \sum_{j=0}^{M}\left[(M-j)\cdot\frac{d^2}{d\alpha^2}P_i(j)\right] \\
&= \sum_{j=0}^{M}(M-j)\cdot\frac{d^2}{d\alpha^2}\left[C_{NM}^{j}\cdot\left(\rho_i\alpha\right)^{j}\cdot\left(1-\rho_i\alpha\right)^{NM-j}\right] \\
&= \sum_{j=0}^{M}(M-j)\cdot\Big[C_{NM}^{j}\cdot j\cdot(j-1)\cdot\rho_i^{j}\alpha^{j-2}\left(1-\rho_i\alpha\right)^{NM-j} \\
&\quad -2C_{NM}^{j}\cdot j\cdot(N\cdot M-j)\cdot\rho_i^{j+1}\alpha^{j-1}\left(1-\rho_i\alpha\right)^{NM-j-1} \\
&\quad +C_{NM}^{j}\cdot(NM-j)\cdot(NM-j-1)\rho_i^{j+2}\alpha^{j}\left(1-\rho_i\alpha\right)^{NM-j-2}\Big]
\end{aligned} \tag{A.2}$$

By expanding the above equation with $j = 0, 1, \ldots, M$, we have that the coefficient of each item $\rho_i^{\,j+2}\alpha^{j}\left(1-\rho_i\alpha\right)^{NM-j-2}$, $j = 0, 1, \ldots, M$, can be calculated as:

$$
\begin{aligned}
&(M-j)\cdot C_{NM}^{j}\cdot(NM-j)\cdot(NM-j-1)-2\left[M-(j+1)\right]\\
&\cdot\left[C_{NM}^{j+1}\cdot(j+1)\cdot(NM-j-1)\right]+\left[M-(j+2)\right]\cdot\left[C_{NM}^{j+2}\cdot(j+2)\cdot(j+1)\right]\\
&=(M-j)\cdot\frac{NM\cdot(NM-1)...(NM-j+1)}{j!}\cdot(NM-j)\cdot(NM-j-1)\\
&\quad-2\cdot(M-j-1)\cdot\frac{NM\cdot(NM-1)...(NM-j)}{(j+1)!}\cdot(j+1)\cdot(NM-j-1)\\
&\quad+(M-j-2)\cdot\frac{NM\cdot(NM-1)...(NM-j-1)}{(j+2)!}\cdot(j+2)\cdot(j+1)\\
&=\left[NM\cdot(NM-1)\cdot(NM-2)...(NM-j-1)\right]\\
&\quad\times\left[\frac{M-j}{j!}-2\cdot\frac{(M-j-1)\cdot(j+1)}{(j+1)!}+\frac{(M-j-2)\cdot(j+1)\cdot(j+2)}{(j+2)!}\right]\\
&=0
\end{aligned}
\tag{A.3}
$$

Therefore, Eq. (A.2) can be simplified to be

$$
\frac{d^2}{d\alpha^2}\left(PL_i\right)=C_{N\cdot M}^{M-1}\cdot(N\cdot M-M+1)\cdot(N\cdot M-M)\rho_i^{M+1}\alpha^{M-1}\left(1-\rho_i\alpha\right)^{N\cdot M-M-1}. \tag{A.4}
$$

Since $N\geq 1$, $M\geq 1$, $0\leq\rho_i\leq 1$, $0\leq\alpha\leq 1$, and $(1-\rho_i\alpha)\geq 0$, we have $\frac{d^2}{d\alpha^2}\left(PL_i\right)\geq 0$. Therefore, PL_i is a convex function of α. Consequently, PL is a convex function of α. □

Proof of Theorem 2: As α and ρ_i are at symmetric positions in the function PL_i, $i=1,2,...N$, by applying the same technique as above, we can prove that PL is a convex function of ρ_i, $i=1,2,...N$. □

APPENDIX B: PROOF OF THE CONVEXITY CONDITION

Proof of Lemma 1: (i) *Necessity*. Since $f(x)$ is a continuous convex function with first-order derivative, we have that, for any $x_1\leq x_2$,

$$f'(x_1) \le f'(x_2). \tag{B.1}$$

For any $x_1 \le x_2$ and $\Delta x \ge 0$, there are possibly two different cases: **Case (a)** $x_1 + \Delta x \le x_2$; and **Case (b)** $x_1 + \Delta x > x_2$. Hereafter we discuss the two cases separately.

Case (a) where $x_1 + \Delta x \le x_2$: for such case, from the well-known mean value theorem, we have that there exists an there exists an x_1^*, $x_1 \le x_1^* \le x_1 + \Delta x \le x_2$, such that

$$f(x_1 + \Delta x) - f(x_1) = f'(x_1^*) \cdot \Delta x. \tag{B.2}$$

Meanwhile, there exists x_2^*, $x_2 \le x_2^* \le x_2 + \Delta x$, such that

$$f(x_2 + \Delta x) - f(x_2) = f'(x_2^*) \cdot \Delta x. \tag{B.3}$$

From Eq. (B.1), since $x_1^* \le x_2 \le x_2^*$, we have that

$$f'(x_1^*) \le f'(x_2^*). \tag{B.4}$$

Therefore, from Eqs. (B.2)-(B.4), we obtain that

$$f(x_1 + \Delta x) - f(x_1) \le f(x_2 + \Delta x) - f(x_2) \tag{B.5}$$

Case (b) where $x_1 + \Delta x > x_2$: Similar to that in Case (a), there exists a y_1, $x_1 \le y_1 \le x_2$, such that

$$f(x_2) - f(x_1) = f'(y_1) \cdot (x_2 - x_1). \tag{B.6}$$

Meanwhile, there exists a y_2, $x_2 < x_1 + \Delta x \le y_2 \le x_2 + \Delta x$, such that

$$f(x_2+\Delta x)-f(x_1+\Delta x)=f'(y_2)\cdot\left(x_2+\Delta x-x_1-\Delta x\right)=f'(y_2)\left(x_2-x_1\right). \qquad \text{(B.7)}$$

Since $y_1 \le x_2 < y_2$, similar to that in Eq. (B.4), we have

$$f'(y_1) \le f'(y_2), \qquad \text{(B.8)}$$

which in turn, similar to that in Eq. (B.5), leads to the conclusion that

$$f(x_2)-f(x_1) \le f(x_2+\Delta x)-f(x_1+\Delta x), \qquad \text{(B.9)}$$

or equivalently,

$$f(x_1+\Delta x)-f(x_1) \le f(x_2+\Delta x)-f(x_2). \qquad \text{(B.10)}$$

Therefore, the necessity is proven for both case (a) and case (b).

(ii) *Sufficiency.* For any $x_1 \le x_2$, let $y_1 = x_1,\ y_2 = \frac{x_1+x_2}{2}$, and $\Delta y = \frac{x_2-x_1}{2}$. From the given condition, since $y_1 \le y_2$, we have

$$f(y_1+\Delta y)-f(y_1) \le f(y_2+\Delta y)-f(y_2), \qquad \text{(B.11)}$$

or equivalently,

$$f\left(\frac{x_1+x_2}{2}\right)-f(x_1) \le f(x_2)-f\left(\frac{x_1+x_2}{2}\right). \qquad \text{(B.12)}$$

Therefore,

$$f(x_1) + f(x_2) \geq 2f\left(\frac{x_1 + x_2}{2}\right), \tag{B.13}$$

which proves that $f(x)$ is a convex function of x. Therefore, the sufficiency of the condition is also proven. □

APPENDIX C: PROOF FOR THE TRAFFIC ALLOCATION COMPARISON METHOD

Proof of Theorem 5: (i) ***Necessity.*** We prove by contradictory. If there exists an M, $1 \leq M \leq K-1$, such that

$$\sum_{i=1}^{M} a_i < \sum_{i=1}^{M} b_i, \tag{C.1}$$

By applying any number of traffic shifting operations to $\{b_1, b_2, \cdots, b_K\}$, it is trivial to prove that $\sum_{i=1}^{M} b_i$ will never been decreased. In other words, inequality (C.1) always holds after *any* number of traffic shifting operations. Therefore $\{b_1, b_2, \cdots, b_K\}$ can never be transferred into $\{a_1, a_2, \cdots, a_K\}$.

(ii) ***Sufficiency.*** From the given condition, we have that $\sum_{i=1}^{K-1} a_i \geq \sum_{i=1}^{K-1} b_i$ and $\sum_{i=1}^{K} a_i = \sum_{i=1}^{K} b_i$. Therefore $a_K \leq b_K$. Apply a traffic shifting operation to $\{b_1, b_2, \cdots, b_K\}$ by letting $\widetilde{b_K} = a_K$ and $\widetilde{b_{K-1}} = b_{K-1} + (b_K - a_K)$, where $\widetilde{b_K}$ and $\widetilde{b_{K-1}}$ denote the new values of b_K and b_{K-1} after the operation, respectively. In other words, we shift a portion of b_K to

b_{K-1} such that after the operation, $\widetilde{b_K} = a_K$. Since $\sum_{i=1}^{K-2} a_i \geq \sum_{i=1}^{K-2} b_i$ and $\widetilde{b_K} = a_K$, we have $a_{K-1} \leq \widetilde{b_{K-1}}$. Similar to the above, we can apply a traffic shifting operation to $\widetilde{b_{K-1}}$ to shift a part of it to b_{K-2} such that after the shift, the new value of $\widetilde{b_{K-1}}$ equals to a_{K-1}. The procedure can be repeated until finally after $K-1$ traffic shifting operations, $\{b_1, b_2, \cdots, b_K\}$ is transferred into $\{a_1, a_2, \cdots, a_K\}$. □

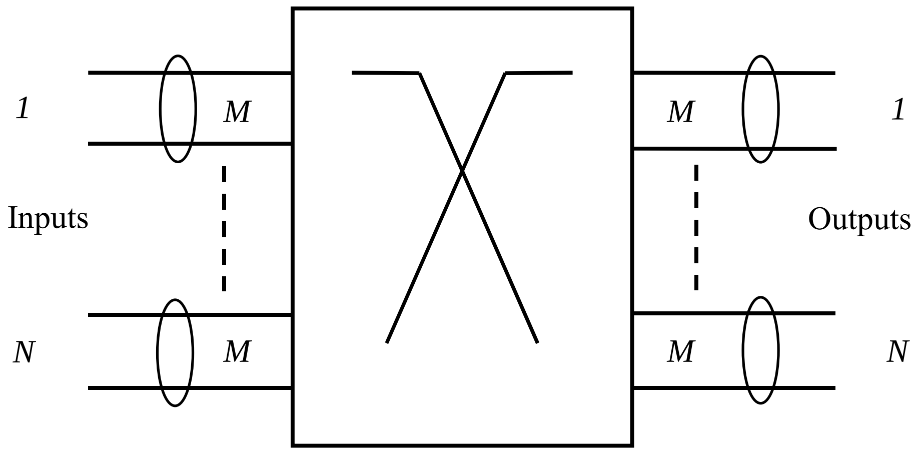


Fig. 1: The most fundamental OPS configuration.

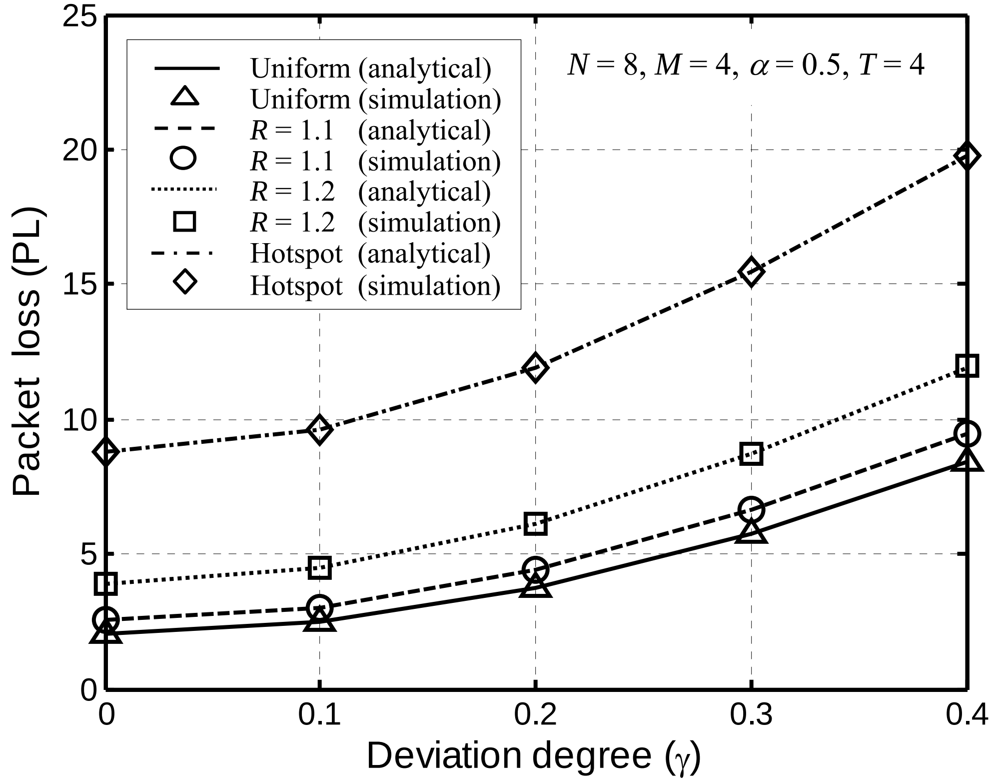


Fig. 2: Performance of the most fundamental OPS under various load distributions in time and space dimensions.

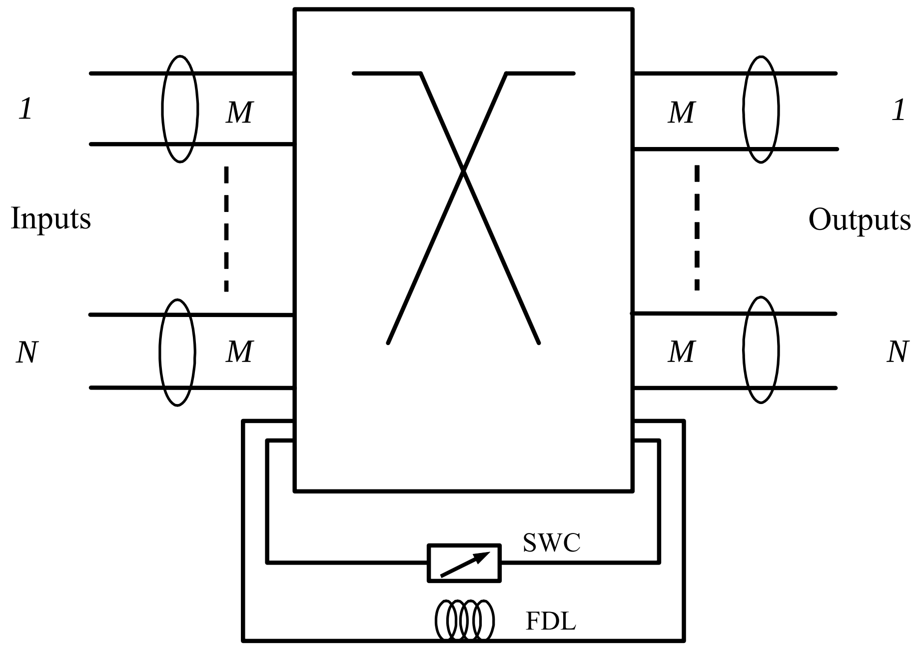


Fig. 3: Typical OPS configuration with SWCs and FDLs.

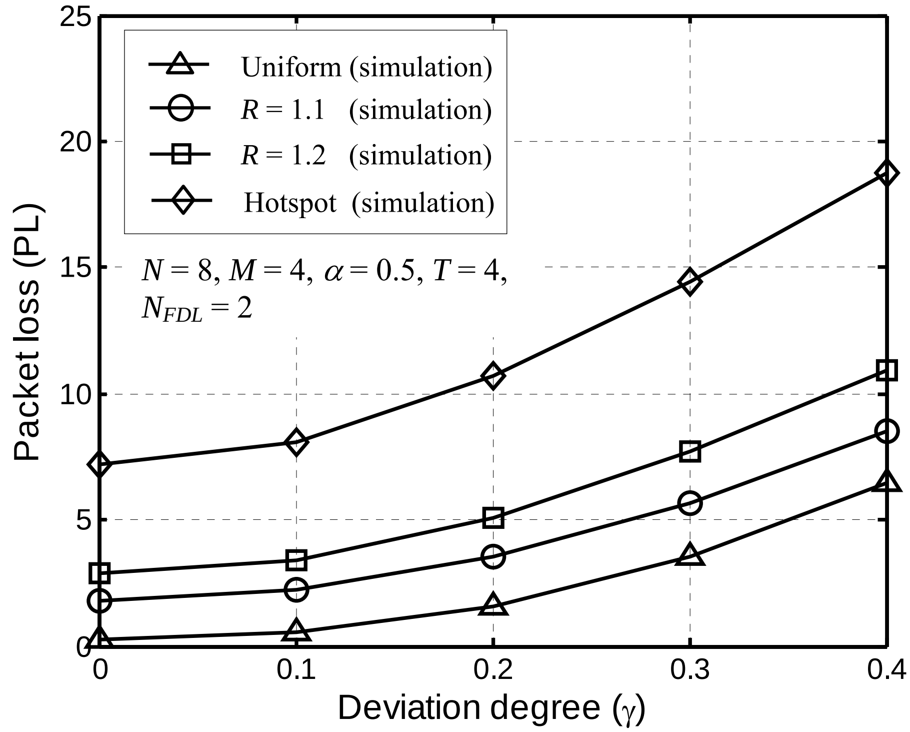
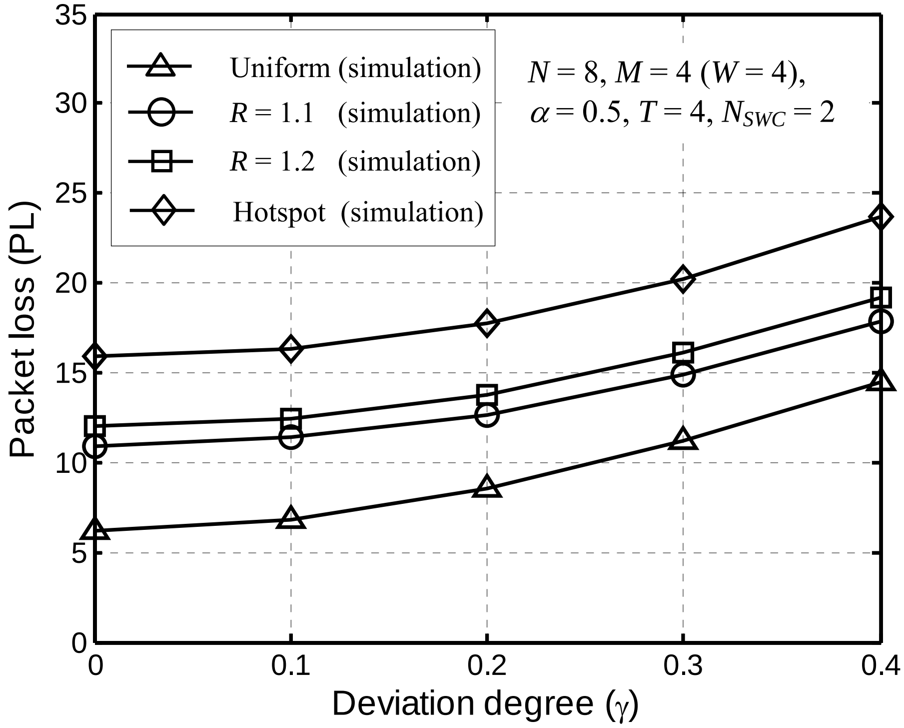
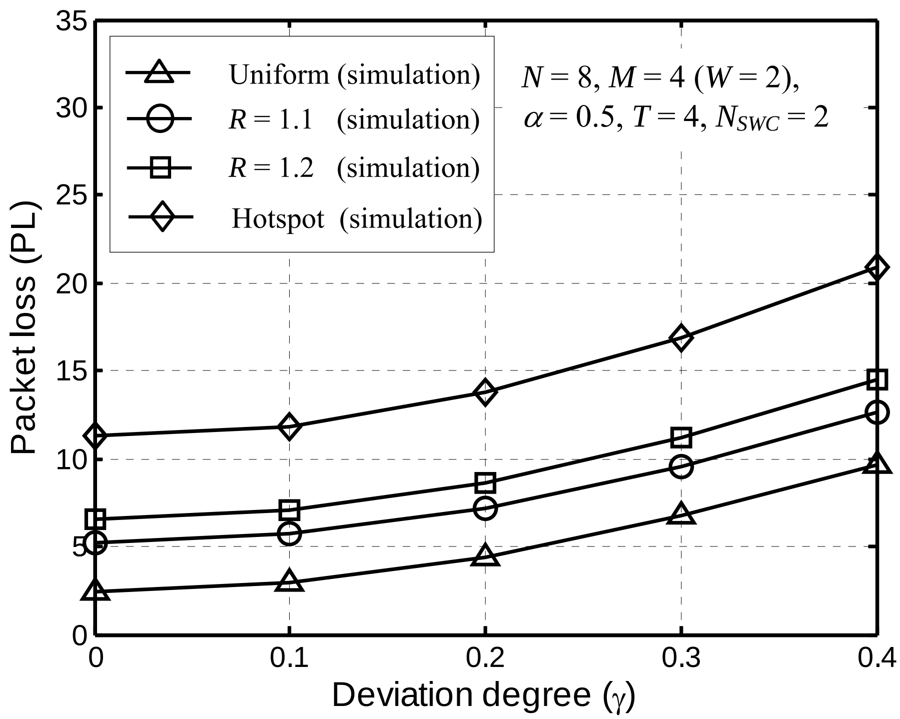


Fig. 4: Packet-loss performance in the OPS with FDLs but no SWC.



(a) $M = 4$, $W = 4$ (single-fiber case).



(b) $M = 4$, $W = 2$ (multi-fiber case).

Fig. 5: Packet-loss performance in the OPS with SWCs but no FDL.

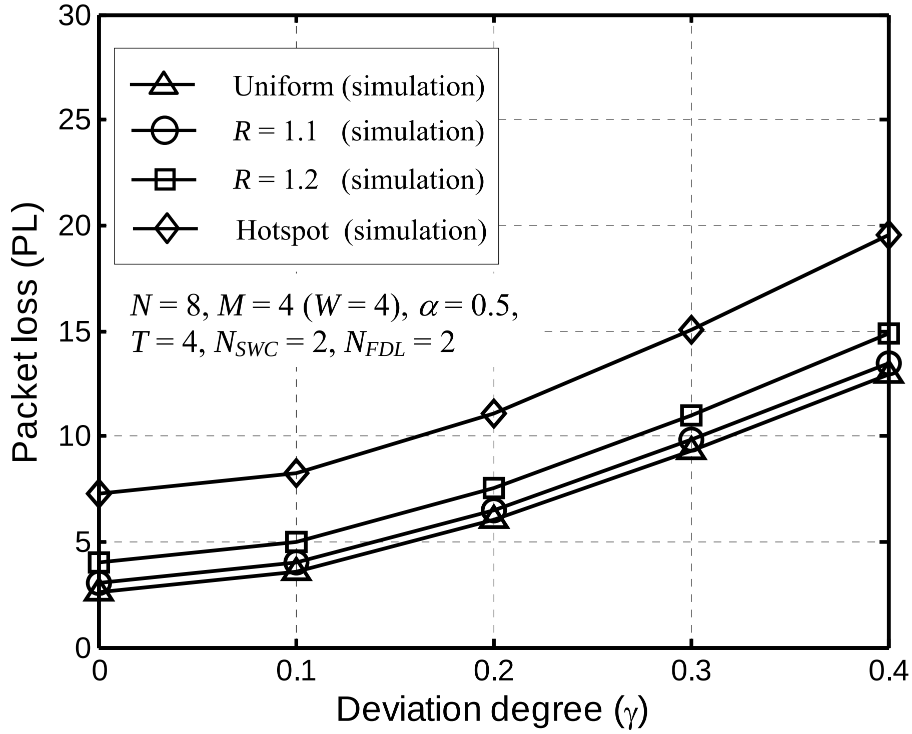
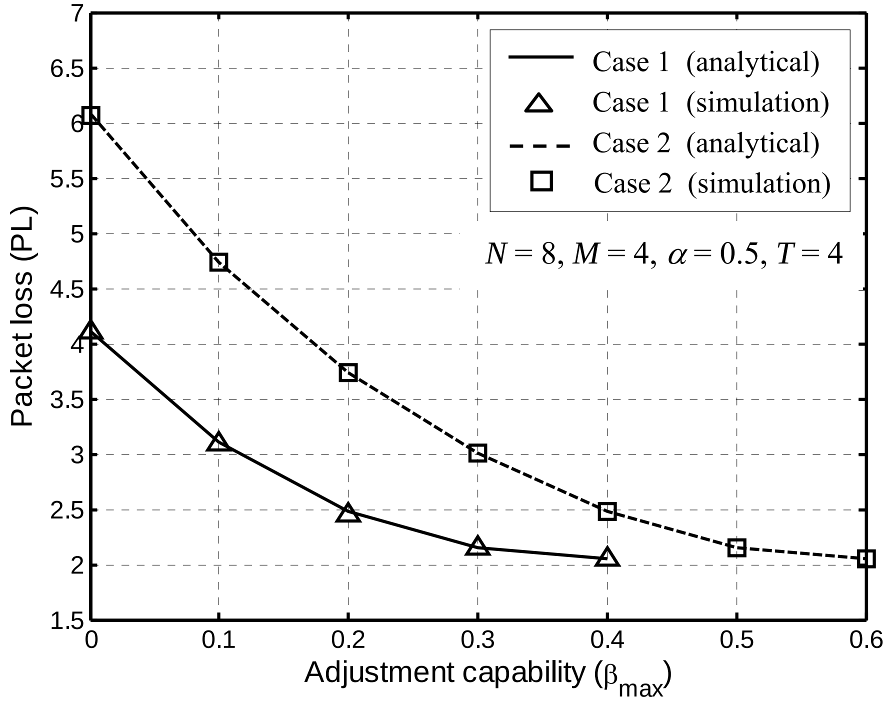
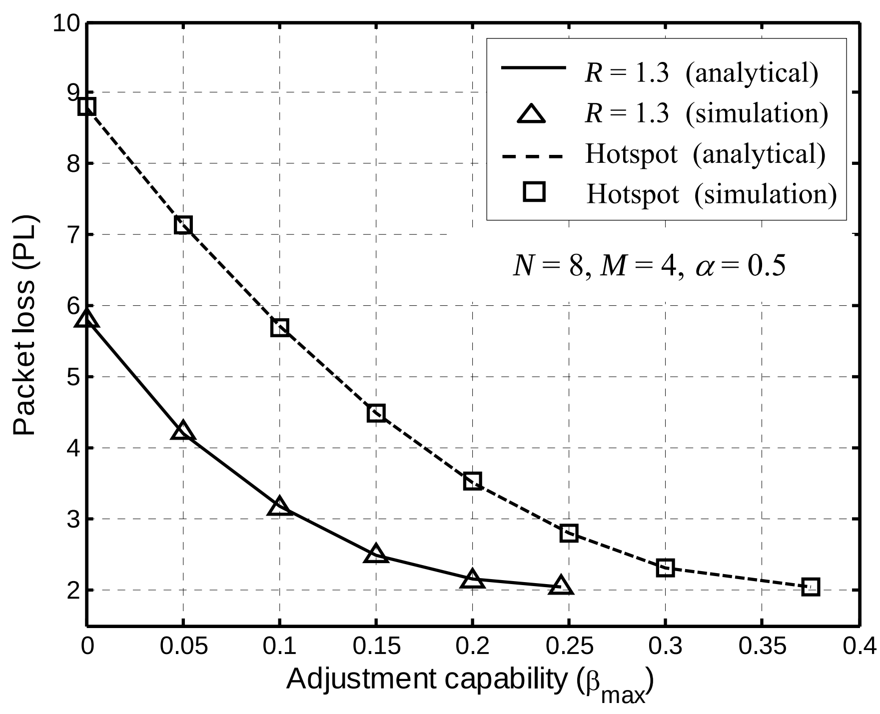


Fig. 6: Packet-loss performance in the OPS with both SWCs and FDLs.



(a) Adjustments in time dimension (uniform traffic pattern).



(b) Adjustments in space dimension.

Fig. 7: Performance of the LB algorithm in the most fundamental OPS configuration.

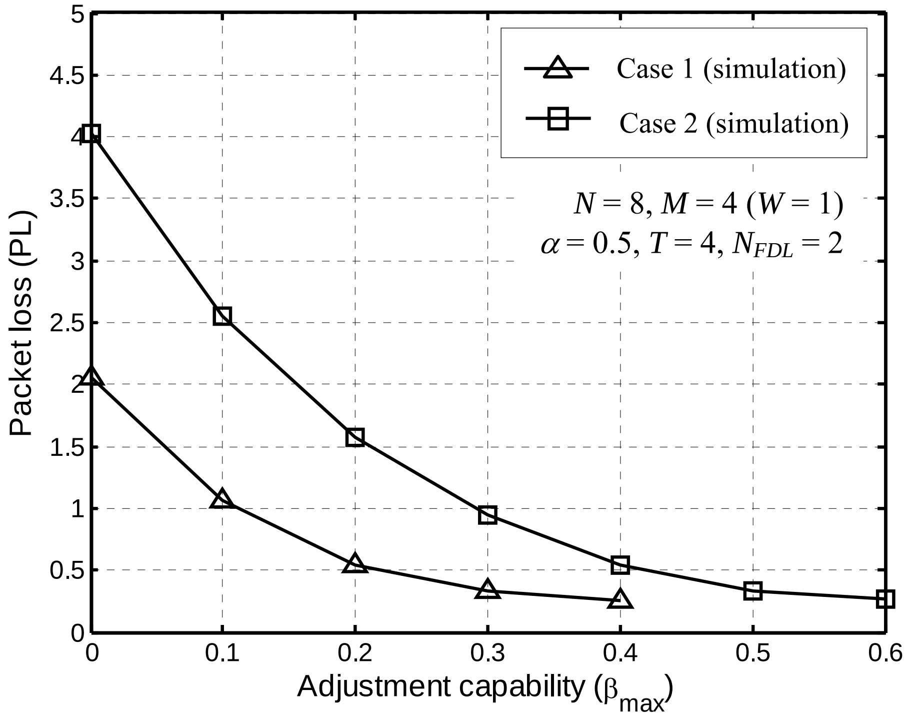


Fig. 8: Performance of the LB algorithm in OPS with only FDLs ($N_{FDL} = 2$). Traffic allocation adjustments are made in time dimension (uniform traffic pattern).

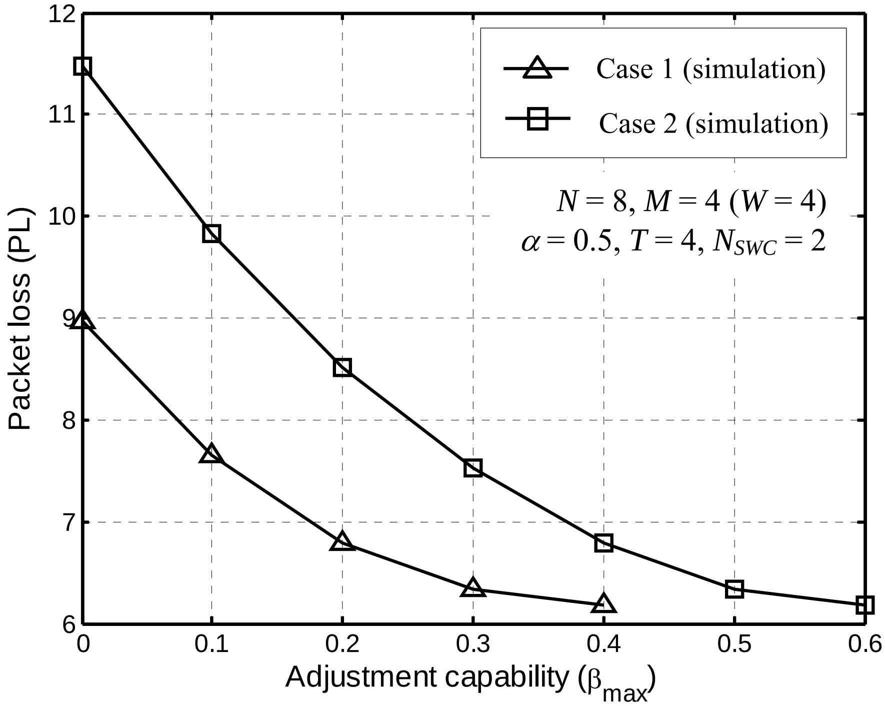


Fig. 9: Performance of the LB algorithm in OPS with only SWCs. ($N_{SWC} = 2$). Traffic allocation adjustments are made in time dimension (uniform traffic pattern).

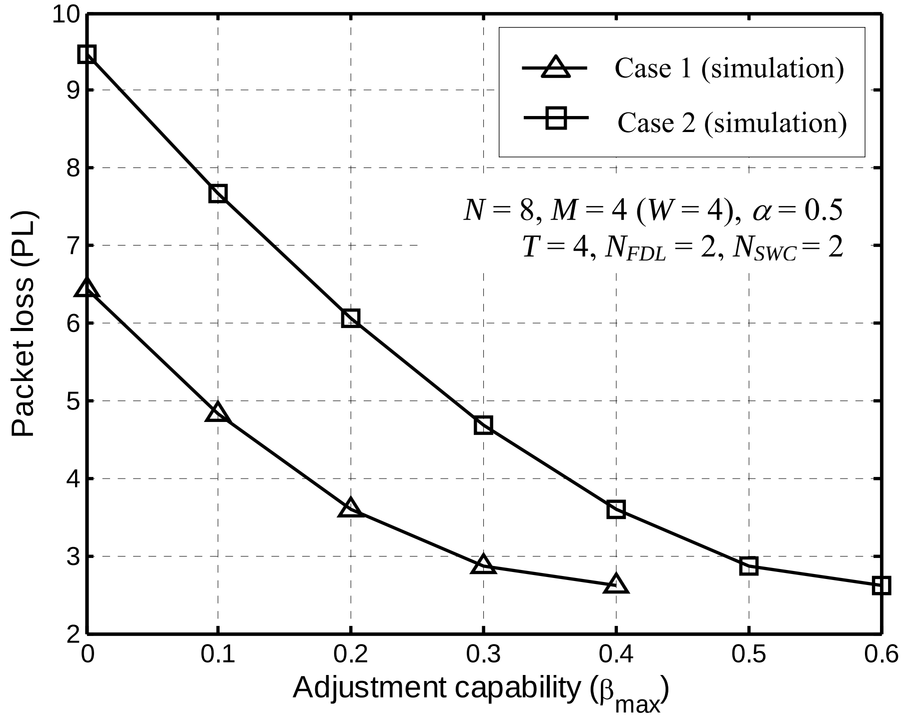


Fig. 10: Performance of the LB algorithm in OPS with both FDLs and SWCs (N_{FDL} = 2, N_{SWC} = 2). Traffic allocation adjustments are made in time dimension (uniform traffic pattern).