Performance of Hybrid Pump-Wavelength Configurations for Optical Packet Switch with Parametric Wavelength Converters

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***Abstract*—This paper proposes an optical packet switch (OPS) with parametric wavelength converters (PWCs) that combines the advantages of the static pump wavelength assignment (SPA) switch and the dynamic pump wavelength selection (DPS) switch to realize the optimum trade off between packet loss rate and processing time. The SPA switch has faster processing time than the DPS switch but lower performance in terms of packet loss rate. Their combination allows a network installer to adjust the network switch to suit user requirements. Simulations in a limited environment confirm that the performance of the SPA-DPS combination lies between those of its constituents. Replacing one dynamic PWC with a static PWC can greatly decrease the processing time with only a slight drop in packet loss rate. The results described herein provide useful information for designing switch systems that can satisfy various user requirements.**

***Index Terms*—Optical packet switching, Optical wavelength conversion, Wavelength division multiplexing**

I. Introduction

OPTICAL packet switching networks are emerging as a serious future candidate for next generation optical telecommunication networks to support high-throughput services such as voice over IP (VoIP) and high quality video streaming on demand. In an optical packet network with optical packet switches (OPSs) interconnected with optical fibers carrying wavelength division multiplexed (WDM) signals, packets are transmitted from source to destination without any optical-electrical-optical (O/E/O) conversion.

Each optical fiber entering an OPS carries several wavelengths for packet transmission. It is demultiplexed into individual wavelengths, each of which is connected to the appropriate output port of the switch fabric. Each output port is assigned a different wavelength. Output contention occurs when two or more packets with the same wavelength try to enter the same output port in the same time slot. Only one of the contending packets is forwarded to the output fiber; the others are dropped. The switch refers to its scheduling algorithm to decide the interconnection between the inputs and outputs of each wavelength.

Wavelength conversion [1] is widely used to avoid contention. A signal with one wavelength is converted to another wavelength. The wavelength of the contending packet that is not selected at the output is converted into another available wavelength and sent to the same output fiber.

A parametric wavelength converter (PWC) [2] is one approach to wavelength conversion because multiple wavelengths, multi-channels, can be converted simultaneously. To define both the original wavelength, λ_w, requiring conversion, and the new wavelength, $\lambda_{w'}$, continuous pump wavelength, λ_p, is set as $\lambda_p = (\lambda_w + \lambda_{w'})/2$. Therefore, the selection of λ_p defines the conversion pairs of λ_w and $\lambda_{w'}$. Multiple wavelength conversion based on the parametric process is becoming feasible. A number of simultaneous multiple wavelength conversion experiments with over 30 channels have been reported using fiber [3] and $LiNbO_3$ waveguides [4]. The studies in [5], [6] show that guard bands can be provided with suitable channel spacing. With this in mind, the remainder of this paper assumes that guard bands are provided in the adopted channel spacing.

Several studies on OPSs that use PWCs were described in [2], [7], [8]. All of them use a PWC to convert each requested wavelength at one time, where the pump wavelength of each PWC is preassigned in a static manner. These switches are generically referred to as the static pump wavelength assignment (SPA) switch. Note that if none of the PWCs support the requested wavelength conversion, some requests may be blocked, even though the desired output fiber has sufficient available wavelengths.

The dynamic pump wavelength selection (DPS) switch is an OPS using PWCs, where the set of pump wavelengths is dynamically changed in every time slot [9]; it overcomes the conversion pair limits of the SPA switch. In the DPS switch, the pump wavelengths are selected, PWC by PWC, so as to maximize the number of conversion pairs supported. Results in [9] show that the DPS switch has lower packet loss rate than the

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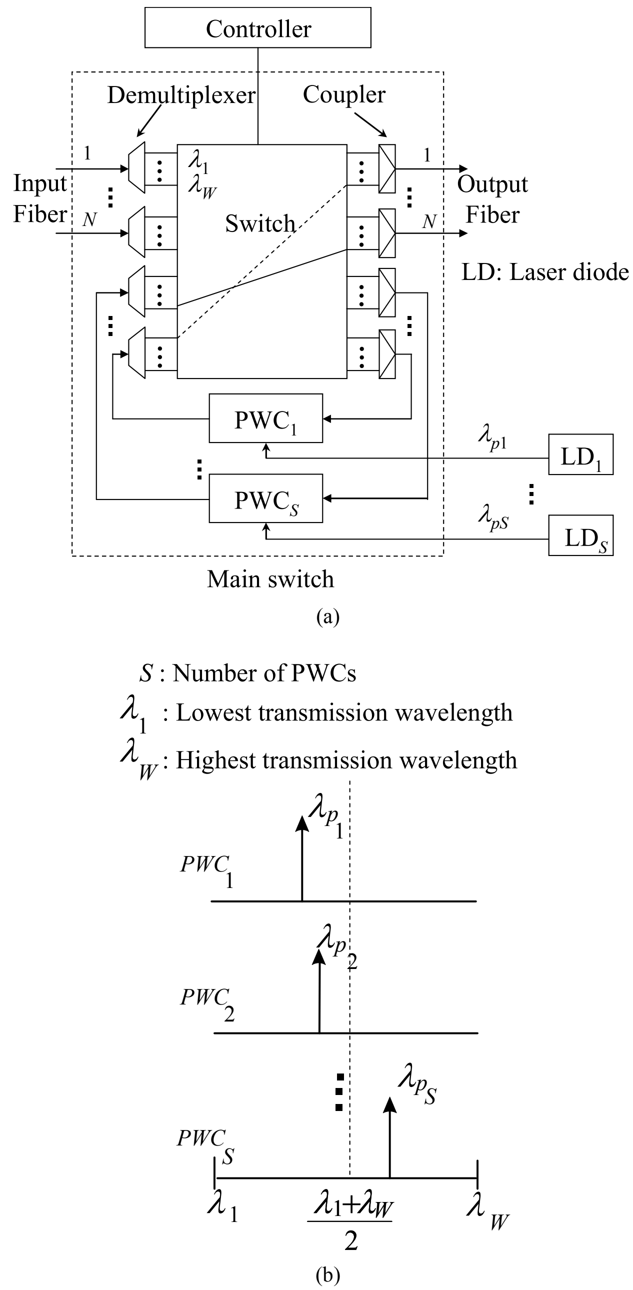

Fig. 1. SPA switch architecture.

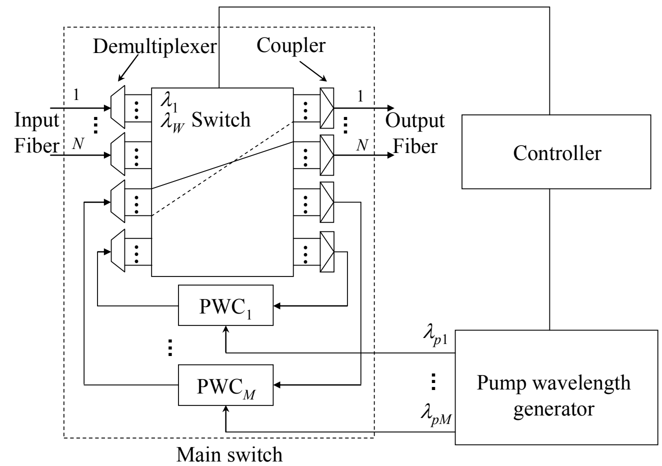

Fig. 2. DPS switch architecture.

SPA switch. However, its scheduling algorithm takes longer to process than that of the SPA switch, since the DPS switch attempts maximum matching, while the SPA switch targets maximal matching.

This paper proposes a hybrid pump wavelength configuration switch that combines the advantages of the SPA and DPS switches and so can trade the packet loss rate off against the processing time.

II. Conventional Static Pump Wavelength Assignment Switch

The SPA switch [7], whose pump wavelengths are fixed, consists of two parts, the controller and the main switch, as shown in Fig. 1(a). They communicate with each other electrically. The controller matches input to output ports for each request by analyzing the set of pre-assigned conversion pairs needed at the PWCs. The main switch connects input and output ports with/without PWCs, as determined by the controller. It is an optical packet switch with N input and output fibers and S PWCs, each with its own pump wavelength generated by laser diodes (LDs) for wavelength conversion. Each fiber carries W different wavelengths. Demultiplexers are set at PWC outputs. Each demultiplexed wavelength has a one-to-one correspondence with an input port of the switch fabric. The individual wavelengths, coming through individual input ports of the switch fabric, are grouped by an optical coupler before being forwarded to the output fiber.

For the general case, the set of pump wavelengths is defined as $\Lambda_p = \{\lambda_{p1}, \lambda_{p2}, \ldots, \lambda_{ps}, \ldots, \lambda_{pS}\}$, where λ_p is the pump wavelength and p_s is the transmission wavelength index for the s PWC. The lowest packet loss rate is achieved when each PWC has a different pump wavelength lying near to the center of transmission wavelengths [7]. Therefore, λ_p in this paper is set based on [7], as shown in Fig. 1(b).

III. Conventional Dynamic Pump Wavelength Selection Switch

The DPS switch [9], whose set of pump wavelengths can be altered on a time slot basis, consists of three parts: the controller, pump wavelength generator, and main switch, as shown in Fig.2. The controller performs both matching of input and output ports and selection of pump wavelengths in an integrated manner on a time slot basis. It controls both switching configuration and pump wavelength selection. It uses electrical signals to communicate with the pump wavelength generator and the main switch. The pump wavelength generator sets pump wavelengths that are determined by the controller in every time slot. The main switch is an OPS with D PWCs. Each PWC has pump wavelengths generated by the pump wavelength generator.

The performances of the SPA and DPS switches in terms of packet loss rate were investigated in [9]. The results showed that

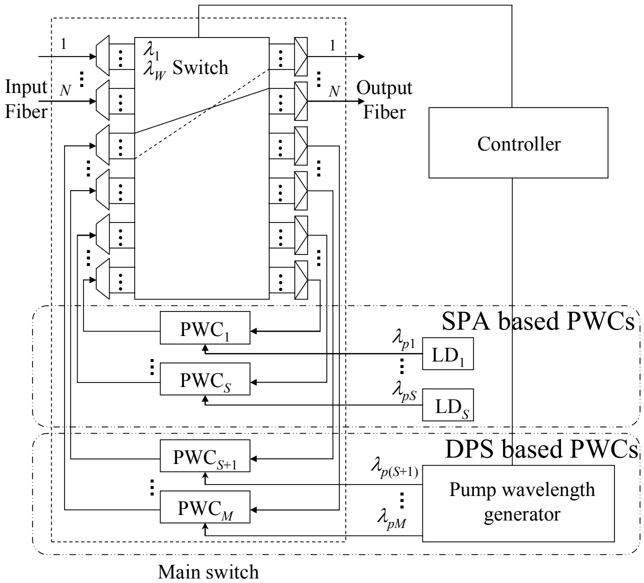

Fig. 3. HPC switch architecture.

the DPS switch has lower packet loss rate than the SPA switch under both uniform and biased (non-uniform) traffic. However, the complexity of DPS, $O(NW)^D$, is higher than that of the SPA switch, $O(NW)^2$. Therefore, its scheduling algorithm takes long to process.

IV. Proposed Hybrid Pump-Wavelength Configuration Switch

Our proposal, the hybrid pump-wavelength configuration (HPC) switch, can trade packet loss rate off against the processing time of the scheduling algorithm. Its packet loss rate and processing time is expected to be intermediate between SPA and DPS results [10].

The HPC switch combines the advantages of the SPA switch and the DPS switch, i.e. short processing time and low packet loss rate, respectively. The HPC switch consists of three parts: main switch, the controller, and pump wavelength generator, as shown in Fig. 3

The main switch consists of N input and output fibers. Each fiber carries W wavelengths, λ_1 to λ_W. The switch uses M PWCs to convert contending wavelengths at output ports. PWCs are divided into two groups, SPA-based PWCs and DPS-based PWCs. The first group, SPA-based PWCs, consists of S PWCs, PWC_1 to PWC_S. Each SPA-based PWC has its own pump wavelength generated by laser diodes (LDs). The DPS-based PWCs consist of M - S PWCs: PWC_{S+1} to PWC_M. DPS-based pump wavelengths can be altered on a time slot basis.

The controller performs both matching of input and output ports and the selection of pump wavelengths in an integrated manner on a time slot basis. The matching process consists of three phases, Phase I, Phase II, and Phase III. In Phase I, matching between inputs and outputs is performed without wavelength conversion. The unmatched requests from phase I are considered for matching in phase II. In Phase II, matching between inputs and outputs is performed using the matching algorithm in [7] and the SPA-based PWCs. The unmatched requests from phase II are considered for matching in phase III. In Phase III, matching between inputs and outputs is performed using the matching algorithm in [9] and the DPS-based PWCs. The reason for using SPA-based PWCs before DPS-based PWCs is that the pump wavelengths of DPS-based PWCs can be changed to better serve unmatched requests.

The pump wavelength generator generates pump wavelengths that are determined by the controller for the DPS-based PWCs in every time slot. Implementation approaches for the pump wavelength generator include tunable laser diodes (TDLs), and a multiwavelength light source and a switch [9].

We consider a pump wavelength generator that uses TDLs because its hardware is similar to that of the SPA switch, i.e. less complex than the one that uses a multiwavelength light source and a switch. Moreover, TLDs are commonly used in industry. To evaluate cost, we define C_{SW} as main switch cost, C_{PWC} as PWC cost, C_{LD} as the cost of the LD used in the SPA switch, C_{TLD} as the cost of the TLD used in the DPS switch, M as the required number of PWCs, S as the required number of SPA-based PWCs. HPC switch cost is $C_{SW} + \{M \times C_{PWC}\} + \{S \times C_{LD}\} + \{(M - S) \times C_{TLD}\}$. While SPA switch cost is $C_{SW} + \{M \times C_{PWC}\} + \{M \times C_{LD}\}$, and that of the DPS switch is $C_{SW} + \{M \times C_{PWC}\} + \{M \times C_{TLD}\}$. The HPC switch is $(M - S)C_{TLD} - (M - S)C_{LD}$ times more expensive than the SPA switch, but $(S \times C_{TLD}) - (S \times C_{LD})$ times cheaper than the DPS switch.

The matching time of the HPC switch depends on the number of DPS-based PWCs, so the time complexity of the DPS switch is $O(NW)^{(M - S)}$. It does not depend on the number of SPA-based PWCs. If the matching time exceeds one time slot, the pipelined scheduling approach presented in [11] can be adopted to extend the allowable matching time. Therefore, there is no effect on throughput. In this approach, scheduling is performed in a pipeline manner, where K subschedulers are used. Each subscheduler is allowed to take more than one time slot for matching.

V. Performance Evaluation

The performance of the HPC switch is compared to that of SPA and DPS switches. Two metrics are used to evaluate HPC switch performance. The first is packet loss rate, which is the ratio of the total number of packets that are not transmitted to the intended output ports to the total number of packets that arrive at input ports. The second measure is processing time, which is the time taken by the matching algorithm to run from the beginning of Phase I until the completion of Phase III. To compare the processing time of the switches, we normalize times against that of the DPS switch; the same parameters and computer are used. We use the processing time ratio, instead of the actual processing time, since the latter is proportional to the processor speed of the controller.

An OPS with $N = 16$ and $W = 32$ with PWCs is considered. We generated 10^9 incoming packets. It is assumed that packets have a fixed size and the time dedicated to switch packets from

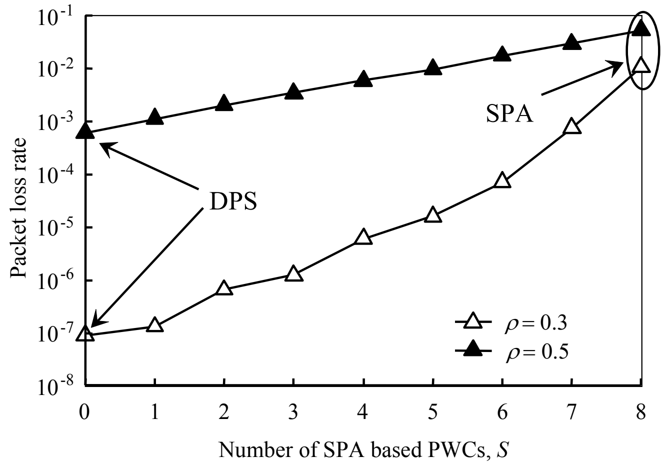

Fig. 4. Packet loss rate of HPC switch at different S values, (N = 16, W = 32, M = 8).

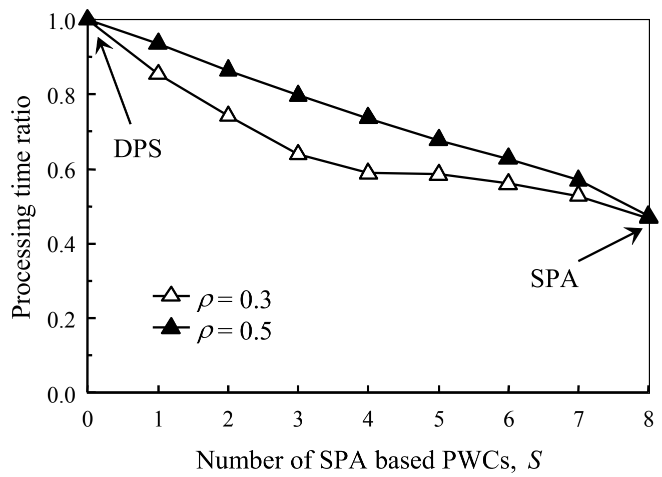

Fig. 5. Processing time ratio of HPC switch at different S values, (N = 16, W = 32, M = 8).

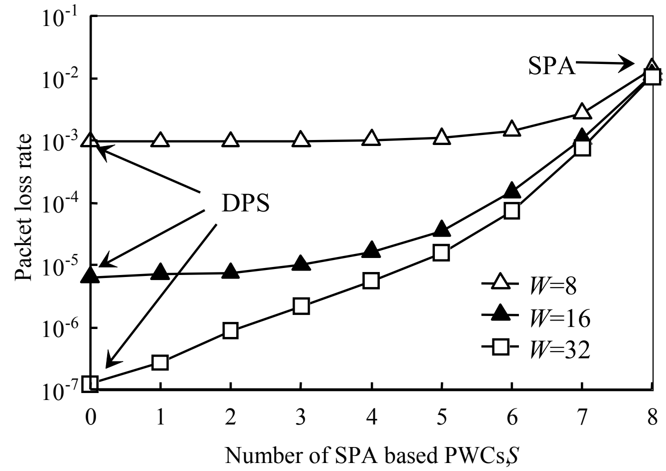

Fig. 6. Packet loss rate of HPC switch at different S values, (N = 16, M = 8, ρ = 0.3).

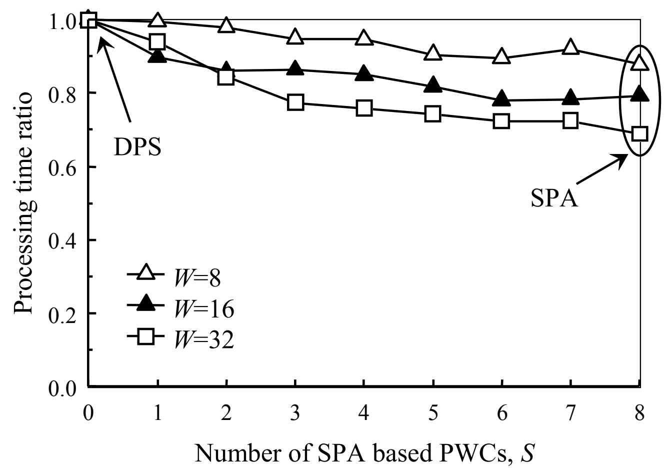

Fig. 7. Processing time ratio of HPC switch at different S values, (N = 16, M = 8, ρ = 0.3).

inputs to outputs therefore has a fixed duration. The computer used had Intel®Core™2 Quad CPU Q9550 @ 2.83GHz with 4GB of DIMM SDRAM memory.

Uniform and non-uniform traffic are considered. In uniform traffic, incoming traffic from input ports is uniformly distributed to all output ports. In non-uniform traffic, an unbalance probability is used to generate skewed traffic.

A. Uniform Traffic

It is assumed that packet arrival at N input ports follows a Bernoulli process. When input traffic load is ρ, an incoming packet arrives with probability ρ, and is the case of no arrival has probability of 1 - ρ. The incoming packets are distributed uniformly to all output ports [12].

Figure 4 shows the packet loss rate at different S values when ρ is 0.3 and 0.5. With the same ρ, the packet loss rate increases with S. The DPS switch has the lowest packet loss rate, S = 0, while the SPA switch has the highest, S = 8.

Figure 5 shows the processing time ratio at different S values when ρ is 0.3 and 0.5. The processing time ratio decreases as S increases. The processing time when ρ = 0.3 is less than that when ρ = 0.5 for the HPC switch. The HPC switch has shorter processing time than the DPS switch, S = 0. However, it is slower than the SPA switch, S = 8. With ρ = 0.3, the actual value of the processing time of the HPC switch with S = 4 is 4.873 ms, while in the corresponding values for the SPA and DPS switches are 3.879 ms and 8.282 ms, respectively. The processing time ratio is 8.282/8.282 = 1 for the DPS switch, 4.873/8.282 = 0.588 for the HPC switch, and 3.879/8.282 = 0.468 for the SPA switch. This means that HPC switch with S = 4 has (1 - 0.588) × 100 = 41.2%, while the SPA switch has (1 - 0.468) × 100 = 53.2% shorter processing time than the DPS switch. In this case, the actual processing time of the HPC switch is 0.994 ms slower than that of the SPA switch. However, it is 3.409 ms faster than that of the DPS switch.

Figure 6 plots packet loss rate of the HPC switch at different S values with W of 8, 16, and 32. The packet loss rate remains unchanged when $S \leq 5$ with W = 8, and $S \leq 3$ with W = 16. However, it is different for every S with W = 32. With $S \geq 3$, the

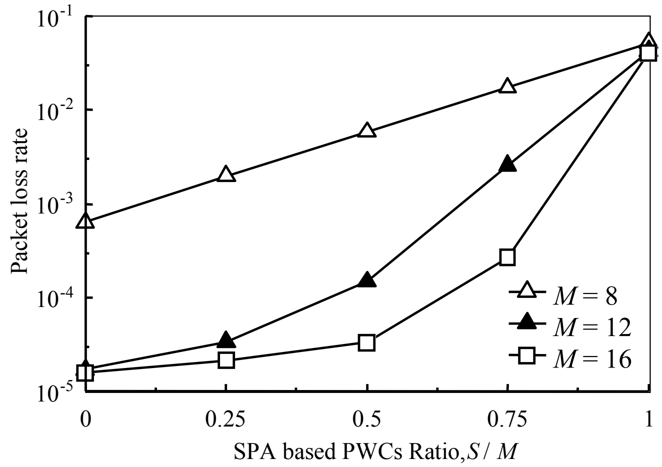

Fig. 8. Packet loss rate at different SPA-based PWC ratios, S/M, (N = 16, W = 32, ρ = 0.3).

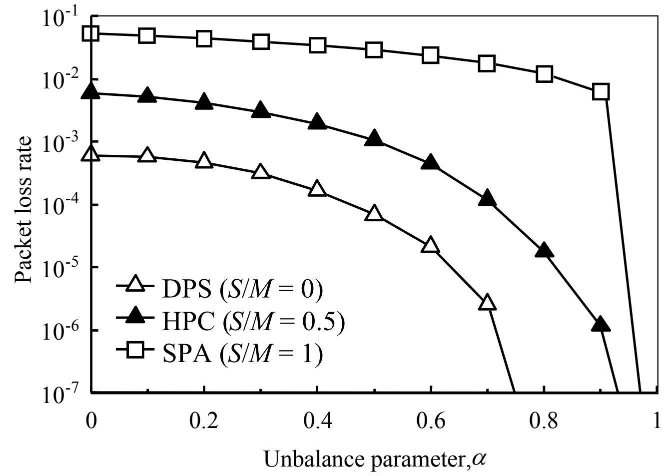

Fig. 10. Packet loss rate of HPC switch under unbalance traffic at different unbalance parameter values, α, (N = 16, W = 32, M = 8, ρ = 0.5).

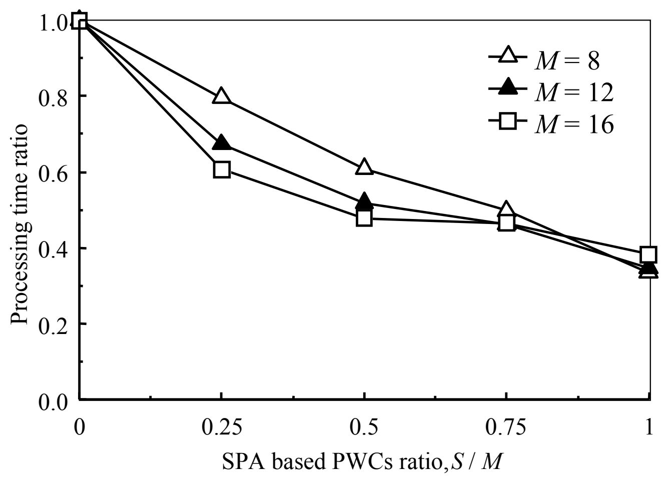

Fig. 9. Processing time ratio at different SPA-based PWC ratio values, S/M, (N = 16, W = 32, ρ = 0.3).

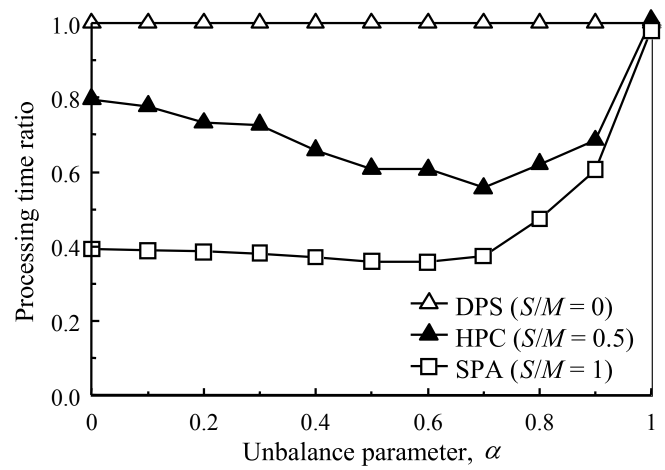

Fig. 11. Processing time ratio of HPC switch under unbalanced traffic with unbalance parameter, α, (N = 16, W = 32, M = 8, ρ = 0.5).

difference in the processing time ratio of the HPC switch compared to that of the SPA switch is tiny, as shown in Fig. 7. The processing time is reduced by at most 30% compared to the DPS switch, when W = 32 and S = 7.

Figure 8 shows the packet loss rate at different SPA-based PWC ratio values, i.e. S/M. The packet loss rate increases with SPA-based PWC ratio. The DPS switch has lowest packet loss rate, S/M = 0, while the SPA switch has the highest. The reason is that increasing S decreases the number of DPS-based PWCs. Wavelengths of the remaining unmatched requests from Phase II have less probability of being converted and switched to the available output ports.

Figure 9 shows the processing time ratio at different S/M values. The processing time ratio decreases as S/M increases. The reason is that the number of DPS-based PWCs decreases, which reduces the processing time needed to complete Phase III.

As mentioned in Section IV, time complexity depends on just the number of DPS-based PWCs. Although the packet loss rate, as shown in Fig. 8, in the case of M = 12, S/M = 0.25 is almost the same as that of M = 16, S/M = 0.5, the former yields a higher processing time ratio than the latter. The number of SPA and DPS-based PWCs in the case of M = 12, S/M = 0.25 are three and nine, respectively, while those in the case of M = 16, S/M = 0.5 are eight and eight, respectively. The former requires more DPS-based PWCs than the latter, which explains its higher processing time ratio.

B. Non-uniform Traffic

Packet loss rates under non-uniform traffic of both the DPS switch and SPA-VR are investigated using the following four well-known traffic models, unbalanced [15], [16], power of two (PO2) [17], diagonal [18], and hotspot [19].

The traffic is uniform if the destinations are uniformly distributed among all output ports [13], [14]. Otherwise, the traffic is non-uniform [20]. For uniform and non-uniform traffic, packets arriving at N input ports follow a Bernoulli process, the input traffic is assumed to be homogeneous, and it is distributed uniformly to all input ports. The unbalanced traffic model

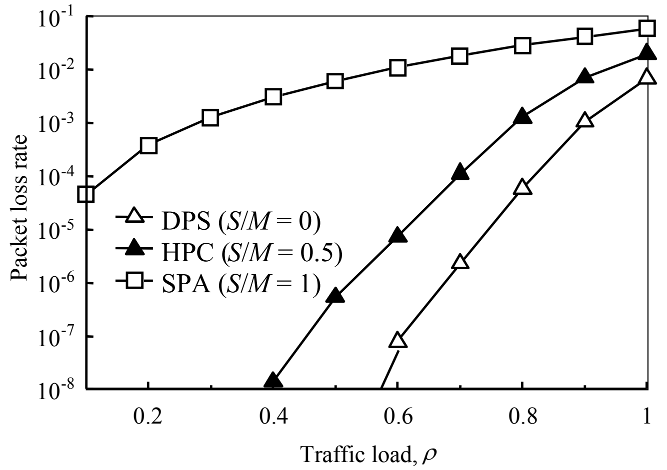

Fig. 12. Packet loss rate of HPC switch under PO2 model, (N = 16, W = 32, M = 8).

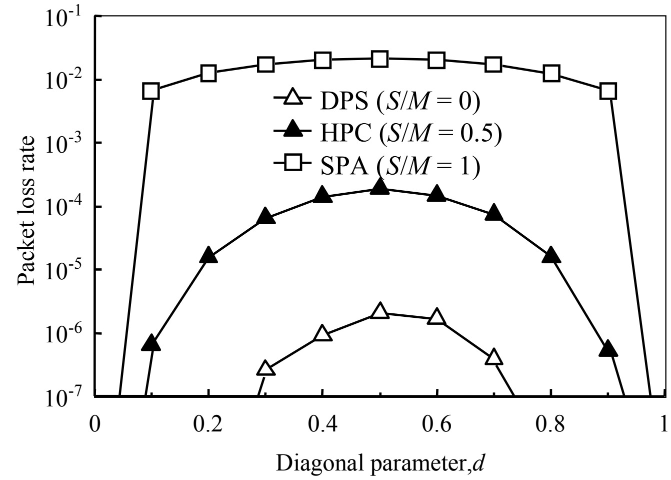

Fig. 14. Packet loss rate of HPC switch under diagonal traffic with diagonal parameter, d, (N = 16, W = 32, M = 8, ρ = 0.5).

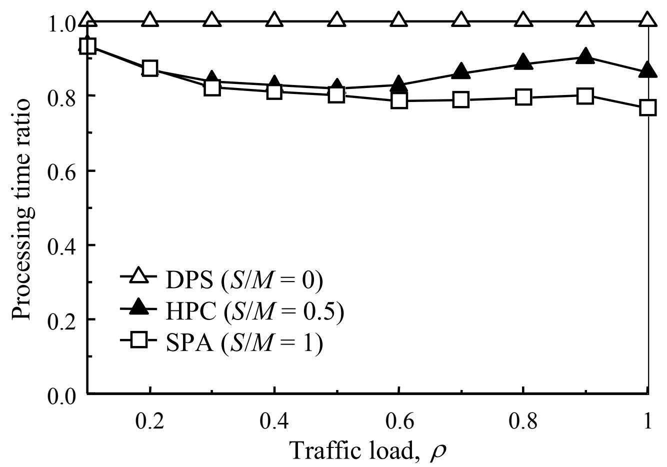

Fig. 13. Processing time ratio of HPC switch under PO2 model, (N = 16, W = 32, M = 8).

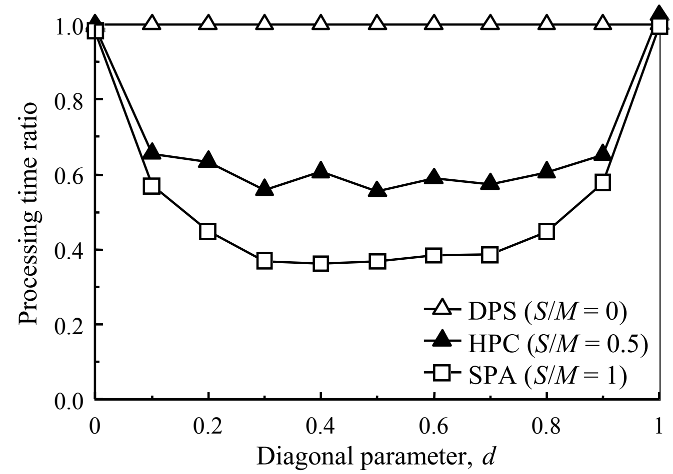

Fig. 15. Processing time ratio of HPC switch under diagonal traffic with diagonal parameter, d, (N = 16, W = 32, M = 8, ρ = 0.5).

presented in [15], [16] is used. The unbalanced traffic is generated by setting the parameter of unbalance probability, α. Considering offered input load for each ith input, ρ, the traffic load from the ith input to the jth output, $\rho_{i,j}$, is given by [15]

$$\rho_{i,j} = \begin{cases} \rho\left(\alpha + \dfrac{1-\alpha}{N}\right) & \text{if } i = j \\ \rho\left(\dfrac{1-\alpha}{N}\right) & \text{otherwise.} \end{cases} \tag{1}$$

The traffic is uniformly distributed when α is zero and the traffic is completely non-uniform when α is one.

Figures 10 and 11 show the packet loss rate and the processing time ratio of the HPC switch under unbalanced traffic at different α values. The packet loss rate of the HPC switch reduces as α increases. It is lower than that of the SPA switch but higher than that of the DPS switch. The HPC switch has a much lower packet loss rate than the SPA switch when α is close to 1.0. This means that the HPC switch achieves higher performance than the SPA switch when the traffic becomes unbalanced. As shown in Fig. 11, the processing time ratio of the HPC switch decreases as α increases when α is less than 0.7. It increases when α is larger than 0.7. Unlike the SPA switch, the processing time ratio is not significantly changed at low α. It is increased when α is larger than 0.7.

The power of two (PO2) traffic model [17] is represented by matrix $\rho_{i,j}$ as:

$$\rho_{i,j} = \rho \begin{pmatrix} \frac{1}{2^1} & \frac{1}{2^2} & \frac{1}{2^3} & \cdots & \frac{1}{2^N} \\ \frac{1}{2^2} & \frac{1}{2^3} & \frac{1}{2^4} & \cdots & \frac{1}{2^1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{1}{2^N} & \frac{1}{2^1} & \frac{1}{2^2} & \cdots & \frac{1}{2^{N-1}} \end{pmatrix}. \tag{2}$$

Figures 12 and 13 present the packet loss rate and the processing time ratio of the HPC switch under PO2 traffic at different traffic loads, ρ. The HPC switch has lower packet loss rate than the SPA switch, but higher rate than the DPS switch. The HPC switch has lower processing time ratio than the DPS switch, but

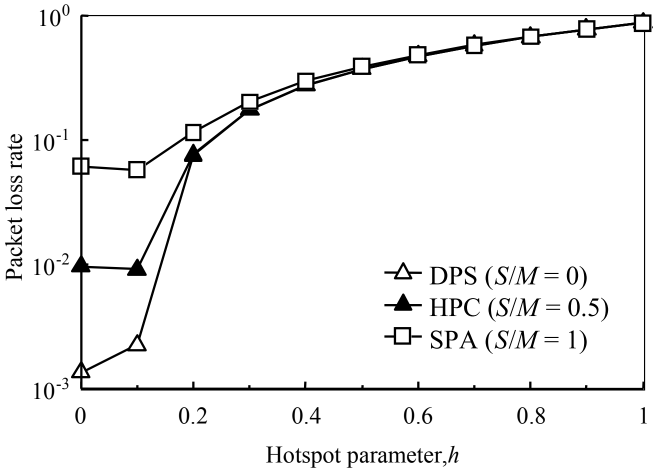

Fig. 16. Packet loss rate of HPC switch under hotspot traffic with hotspot parameter, h, ($N = 16$, $W = 32$, $M = 8$, $\rho = 0.5$).

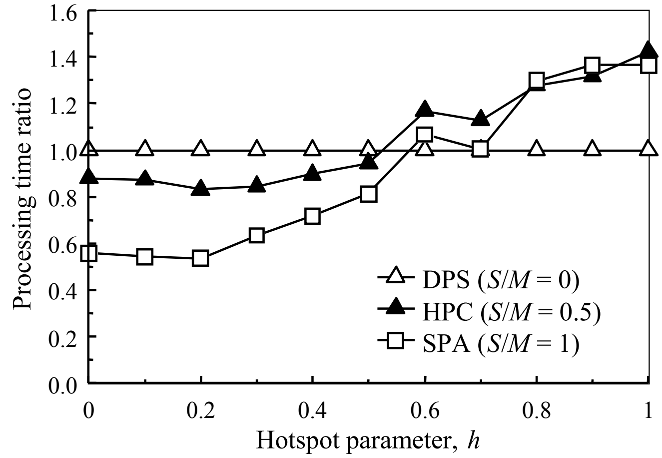

Fig. 17. Processing time ratio of HPC switch under hotspot traffic with diagonal parameter, h, ($N = 16$, $W = 32$, $M = 8$, $\rho = 0.5$).

higher ratio than the SPA switch. It is similar to the SPA switch for ρ values of up to 0.5.

Diagonal traffic [18] is generated by assigning a diagonal probability, d, to represent the traffic from the ith input to jth output, $\rho_{i,j}$, which is given by

$$\rho_{i,j} = \begin{cases} d\rho & \text{if } i = j \\ (1-d)\rho & \text{if } i = j + 1 \text{ MOD } N \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

$\rho_{i,j}$ is written in matrix form as follows.

$$\rho_{i,j} = \rho \begin{pmatrix} d & 1-d & 0 & \cdots & 0 \\ 0 & d & 1-d & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1-d & 0 & 0 & \cdots & d \end{pmatrix}. \quad (4)$$

Figures 14 and 15 plot the packet loss rate and the processing time ratio of the HPC switch under diagonal traffic at different traffic loads, d. The HPC switch has lower packet loss rate than the SPA switch, but higher rate than the DPS switch. The packet loss rates of HPC, DPS, and SPA switches fall when d approaches 0 or 1. They reach their maximum when d is 0.5. The HPC switch has higher processing time ratio than the SPA switch, but lower ratio than the DPS switch.

The hotspot traffic [19], each input distributes all packets among all outputs with equal probability except for a specific output. The traffic is generated by setting the hotspot probability, h, which is the probability that the packet is forwarded from an input to a specific output. $\rho_{i,j}$, which is the traffic load from ith input to jth output, is given by

$$\rho_{i,j} = \begin{cases} h\rho & \text{if } j \text{ is the specific output fiber} \\ \dfrac{1-h\rho}{N-1} & \text{otherwise.} \end{cases} \quad (5)$$

Figures 16 and 17 plot the packet loss rate and the processing time ratio of the HPC switch under hotspot traffic at different traffic loads, h. The packet loss rate increases with h. The HPC switch has lower packet loss rate than the SPA switch but higher rate than the DPS switch at low h. The processing time ratios of the HPC and SPA switches are lower than that of the DPS switch when $h < 0.6$.

VI. CONCLUSION

This paper proposed a hybrid pump wavelengths configuration switch; it combines the advantages of SPA and DPS switches, and provides an effective way of trading packet loss rate off against processing time. The SPA switch has much processing time than the DPS switch. However, the packet loss rate of the SPA switch is higher than the DPS switch. Simulations showed that the HPC switch achieves better performance in term of packet loss rate than the SPA switch. In terms of processing time, the HPC switch achieves better performance than the DPS switch. Numerical results showed that the HPC switch outperforms the SPA switch under both uniform and non-uniform traffic in terms of packet loss rate and outperforms DPS in terms of processing time. The HPC switch is closer in performance to the DPS switch than the SPA switch.

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