Shared-Per-Wavelength Asynchronous Optical Packet Switching: A Comparative Analysis☆

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Abstract

This paper compares four different architectures for sharing wavelength converters in asynchronous optical packet switches with variable-length packets. The first two architectures are the well-known Shared-Per-Node (SPN) and Shared-Per-Link (SPL) architectures, while the other two are the Shared-Per-Input-Wavelength (SPIW) architecture, recently proposed as an optical switch architecture in synchronous context only, which is extended here to the asynchronous scenario, and an original scheme called Shared-Per-Output-Wavelength (SPOW) architecture that we propose in the current article. We introduce novel analytical models to evaluate packet loss probabilities for SPIW and SPOW architectures in asynchronous context based on Markov chains and fixed-point iterations for the particular scenario of Poisson input traffic and exponentially distributed packet lengths. The models also account for unbalanced traffic whose impact is thoroughly studied. These models are validated by comparison with simulations which demonstrate that they are remarkably accurate. In terms of performance, the SPOW scheme provides blocking performance very close to the SPN scheme while maintaining al-

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most the same complexity of the space switch, and employing less expensive wavelength converters. On the other hand, the SPIW scheme allows less complexity in terms of number of optical gates required, while it substantially outperforms the widely accepted SPL scheme. The authors therefore believe that the SPIW and SPOW schemes are promising alternatives to the conventional SPN and SPL schemes for the implementation of next-generation optical packet switching systems.

Key words: optical packet switching, wavelength conversion, shared-per-wavelength optical architecture, Markov chains, fixed-point analysis

1. Introduction

Optical packet switching-based paradigms have recently emerged as a result of a need to more efficiently utilize the fiber capacity using the recent advancements in photonic components [1],[2]. In particular, two particular approaches have attracted the attention of researchers: Optical Packet Switching (OPS) [3] and Optical Burst Switching (OBS) [4]. A significant amount of research and experimentation has been carried out in the last decade on optical packet/burst switching [5],[6],[7],[8].

OPS/OBS can be operated in either synchronous (time-slotted) or asynchronous (un-slotted) mode. Optical packets have fixed sizes in synchronous systems requiring costly synchronization equipment. On the other hand, synchronous systems are known to have better throughput than their asynchronous counterparts due to the alignment of packet arrivals. In asynchronous mode of operation, optical packets have a flexibility of being variable-sized in addition to the lack of a need for costly synchronization equipment. In this paper, we focus on asynchronous optical packet switching architectures that fit well with variable-sized packets of IP networks.

A major problem in both synchronous and asynchronous optical packet switching networks is contention which arises when multiple incoming packets contend for the same output wavelength channel at the same time. Contention can be resolved either in: wavelength domain by wavelength converters (WC) which allows wavelength shifting inside the switch to solve contention by forwarding the packet in a free output wavelength channel [9],[10]; time domain by Fiber Delay Lines (FDLs) which allows packet delay so that the packet is forwarded when the output channel will be available [4];

space domain by deflection routing for which some of the contending packets are sent over an alternative path [11]. We refer the reader to [12] for a unified study of contention resolution schemes in optical packet-switched networks.

If the underlying contention resolution schemes come short of resolving the contention, one or more of the contending packets would be lost that is detrimental for end-to-end performance. Most of the existing research focus on the reduction of loss probabilities in optical networks by using an appropriate combination of existing contention resolution methods. The current article focuses on contention resolution by exploiting the wavelength domain in asynchronous optical packet switches. In such a switch, the key components are wavelength converters which are complex and expensive, therefore a desirable feature for a promising optical switch architecture is its efficient use of such components. Different switch architectures would require different kinds of WCs with different features and cost. The WCs considered in the current article are: full-range Tunable-input/Tunable-output Wavelength Converters (TTWCs) which can convert any input wavelength to any other wavelength, full-range Fixed-input/Tunable-output Wavelength Converters (FTWCs) which convert a predetermined input wavelength to any output wavelength, and Fixed Wavelength Converters (FWCs) which can convert any wavelength to one fixed output wavelength [13],[14]. We refer the reader to [15] for technologies and applications underlying wavelength converters. We also note that wavelength converter implementations at rates over 80 Gbps are reported in [16],[17].

To reduce the number of WCs needed in a switch, the WCs can be configured in a single bank that allows converter sharing across all fiber links, which is referred to as the Shared-Per-Node (SPN) architecture [18]. An approximate analytical model to evaluate packet loss for the SPN scheme is given in [19] for the asynchronous scenario with Poisson input but only for balanced traffic. An alternative organization of the SPN scheme to improve scalability is proposed in [20]. Alternatively, separate WC banks can be dedicated to each output fiber which does not allow WC sharing across multiple output fibers as in SPN. The corresponding scheme is called Shared-Per-Link (SPL) [18]. An exact analytical model and a computationally efficient procedure for the SPL scheme for asynchronous switches is given in [21] for the case of MAP (Markovian Arrival Process) input traffic and phase-type (PH-type) distributed packet lengths. However, the case of unbalanced traffic has not been explicitly studied in that particular work. We note that SPN and SPL schemes require TTWCs.

Recently, an alternative WC sharing scheme, namely the Shared-Per-Input-Wavelength (SPIW), has been proposed and its performance has been evaluated in synchronous context [22]. In this scheme, a bank of FTWCs is dedicated to each input wavelength allowing converter sharing for packets that arrive on the same wavelength. An alternative shared-per-wavelength switch architecture is given in [23]. The SPIW architecture proposed in [22] is a variant of the SPN switch employing FTWCs organized in a modular scheme. In [22], an analytical approach is proposed and validated through simulations in the presence of Bernoulli balanced and unbalanced traffic and the results are also compared with the SPN and SPL schemes.

This paper focuses on the loss performance of the SPIW switch in asynchronous context which has not been addressed before to the best of our knowledge. Furthermore, the current article also introduces a novel architecture, the so-called Shared-Per-Output-Wavelength (SPOW) sharing scheme, which corresponds to the dual of the SPIW. The SPOW scheme dedicates a bank of FWCs for each output wavelength. This paper analyzes both shared-per-wavelength alternatives, providing computationally efficient analytical models based on Markov chains and fixed-point iterations, to evaluate the packet loss probability arising in such converter sharing schemes when the packet arrival process is Poisson and packet lengths are exponentially distributed. These models capture the packet loss for both balanced and unbalanced traffic scenarios. Furthermore, an extension of the model for SPN and SPL schemes is provided to take unbalanced traffic into account. We also provide a complexity evaluation of the four converter sharing schemes.

The paper is organized as follows. Section 2 describes the SPIW and SPOW sharing architectures as well as SPN and SPL. Section 3 presents analytical models for the SPIW and SPOW schemes taking asynchronous packet switching systems into account. In Section 4, we not only validate the proposed models using simulations but also study their performance as a function of the number of converters used in the system, traffic load, and the distribution of traffic intensity over different output fibers. Section 5 also presents a complexity evaluation, in terms of optical components employed, and provides a complexity comparison among the four architectures based on the results of Section 4. Finally, we conclude in Section 6.

2. Wavelength Converter Sharing Architectures

The basic principle of contention resolution in wavelength domain is a shift of one or more packets contending for the same output wavelength channel from their original wavelength to different ones allocated on the same output fiber interface. This operation is performed by wavelength converters (WC). The resulting effect is to increase throughput and output channel utilization and, consequently, reduce output channel blocking. The sharing of WCs in all-optical switching architectures based on strictly non-blocking space switching matrices has been extensively studied in the past [18],[24] with the aim of demonstrating that architectures with limited number of WCs can provide the same performance as fully-equipped architectures. In particular, two types of WC sharing schemes have been thoroughly investigated:

- Shared-Per-Link (SPL) architecture,
- Shared-Per-Node (SPN) architecture.

Both architectures are based on a modular organization allowing easier and less costly implementation. For the purpose of presenting these architectures, we consider N Input and Output Fibers (IFs/OFs) each carrying a WDM signal with M wavelengths. In the SPL scheme [21], each OF has a dedicated bank of r_l WCs (Nr_l WCs in total). This architecture is depicted in Fig. 1 in which the M space switching fabrics (SSF) in the first space stage connect the input wavelength channels (IWC) associated with the same wavelength to the OFs and WCs, so they have N inputs and $N + Nr_l$ outputs. The outputs of each WC bank are directly connected to an output fiber and therefore in this case, a second switching stage is not needed. From a performance standpoint, the SPL scheme suffers from the following:

- In the SPL architecture, a WC bank is dedicated to each OF. When the traffic is asymmetric, then some of the WC banks will be fully utilized whereas others would be idle leading to a waste of WC resources. This situation can be enhanced by deploying WC banks of varying sizes for different OFs based on a-priori knowledge of the traffic demand which is generally hard to obtain.
- Even when the traffic is perfectly symmetric, there will be epochs of high utilization for a fiber n and of low utilization for another fiber m.

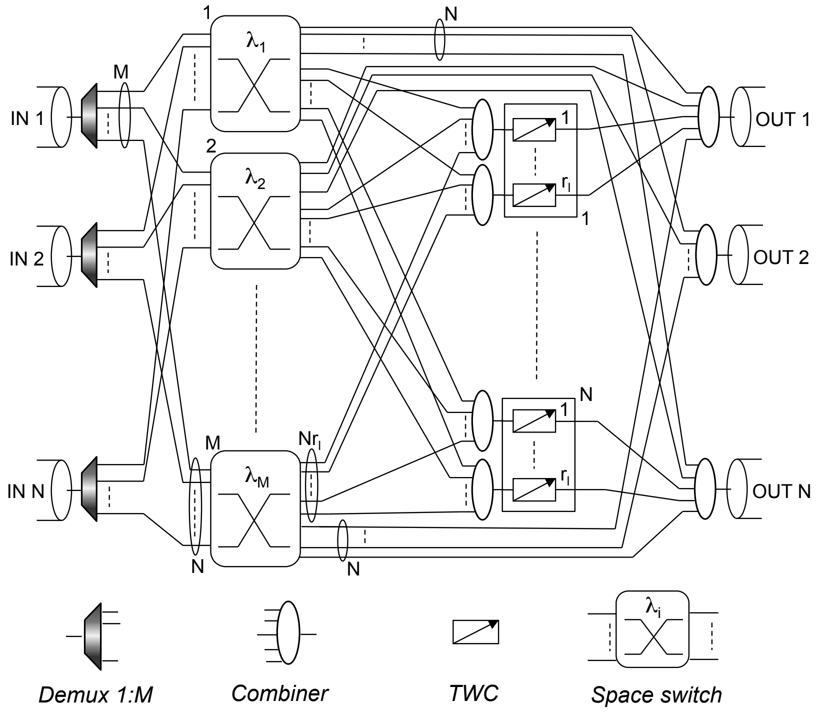

Figure 1: SPL architecture with N input/output fibers each carrying M wavelengths and N banks of r_l converters dedicated to each output fiber interface.

> Due to high correlations between the utilization of an individual OF and its WC bank occupancy, fiber n will be short of WCs but the bank of fiber m would be idle and sharing between these two banks would not take place.

In the alternative SPN scheme (illustrated in Fig. 2), a bank of r_n WCs is shared among all input channels [25] to serve those packets that cannot be forwarded to the OFs in their wavelength channels. In a first space switching stage, M space switching fabrics dedicated to different wavelengths connect the IWCs to the OFs and the WC bank. Each SSF has N inputs and $N + r_n$ outputs so that each IWC can be connected to all OFs and any of the WCs. However, in contrast with the SPL scheme, a second space stage is required to connect the WC outputs to the OFs. The SPN scheme represents the perfect sharing scheme in the sense that each arriving packet to the switch can exploit any of the available WCs in the system, i.e., maximum degree of sharing. For this reason, SPN architecture achieves better throughput than

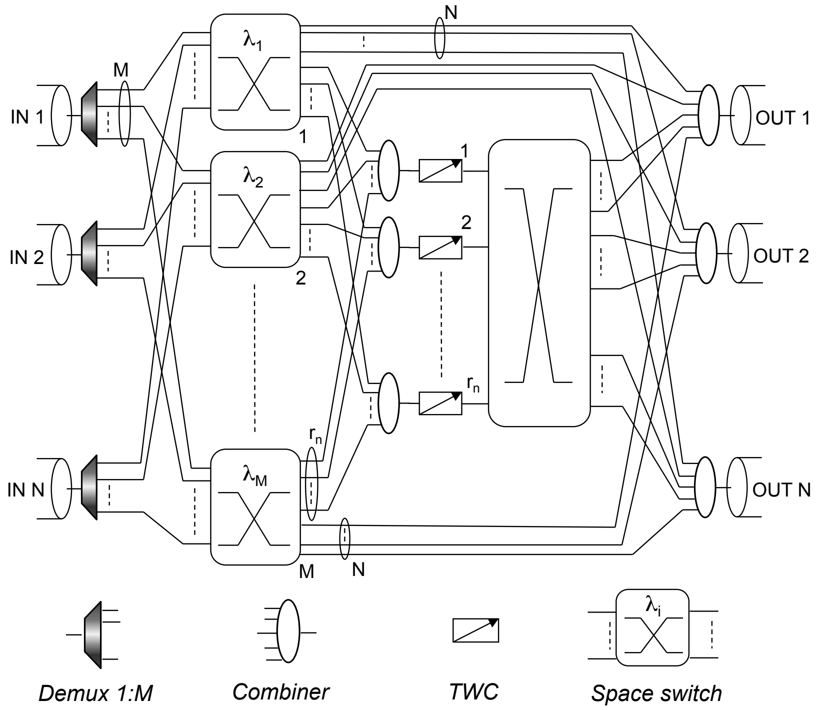

Figure 2: SPN architecture with N input/output fibers each carrying M wavelengths and a bank of r_n converters.

SPL given the total number of WCs employed, at the expense of increased space switch complexity [18]. Both schemes require TTWCs; any of the available WCs in these two schemes must be able to convert a packet from a given wavelength to any other wavelength.

With the aim of employing simpler and less costly WCs, a shared-per-wavelength scheme which employs FTWCs has been presented and evaluated in synchronous context in [22]. A modular and scalable version of this architecture (similar to the one presented in [20] for the SPN scheme), here named Shared-Per-Input-Wavelength (SPIW), is shown in Fig. 3. The target of this section is to present the main features of the SPIW scheme, while a detailed complexity evaluation is proposed in Section 5. The SPIW switch consists of N IF/OFs each carrying M wavelength channels. The N IWCs related to wavelength λ_k ($k = 1, \ldots, M$) in different IFs share a common bank of r_w WCs. In other words, a number r_w of WCs are dedicated to the packets arriving on wavelength λ_1, r_w to the packets coming on wavelength λ_2 and

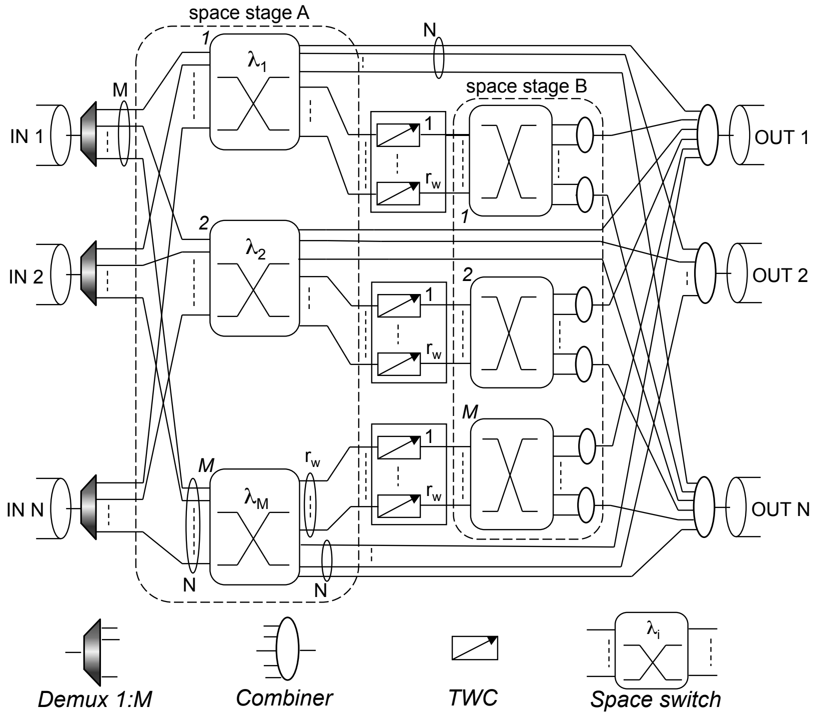

Figure 3: SPIW architecture with N input/output fibers each carrying M wavelengths and M banks of r_w converters dedicated per input wavelength.

so on, for a total amount of Mr_w WCs. Two space switching stages are needed; the first stage to connect the IFs to the OFs and WCs (highlighted in the figure with letter A), and the second to connect the WC outputs to the OFs (highlighted in the figure with letter B). In stage A, after demultiplexing of IWCs, the IWCs associated with the same wavelength λ_k in different IFs are sent to a dedicated SSF. There are M SSFs in total, each with size $N \times (N + r_w)$. In each SSF, the packets not needing conversion are directly sent to the destination OFs while those needing conversion are sent to the corresponding WC bank. Furthermore, as mentioned above, in the SPIW scheme WCs may be FTWCs instead of TTWCs, allowing further savings in cost. The second stage B forwards the packets to the OFs after wavelength conversion. Moreover, there are a total of M SSFs at this stage with each SSF forwarding packets outgoing from a particular WC bank.

In this paper, we also introduce a novel architecture called Shared-Per-Output-Wavelength (SPOW) which can be viewed as the dual of the SPIW.

The SPOW architecture is depicted in Fig. 4. In this scheme, WCs are organized in M banks of r_w WCs dedicated for each output wavelength. All the r_w WCs in the same bank convert the input signal (no matter the wavelength) to a fixed output wavelength (say λ_k). The SPOW switch employs FWCs that are the least complex and expensive WCs [14],[26]. Again, two space switching stages are needed to connect IFs to OFs and WCs (space stage A) and WC outputs to OFs (space stage B). In the space stage A, after wavelength demultiplexing at the IFs, M SSFs dedicated per wavelength (similar to those used for the SPIW scheme) are employed. In this case, the size of these SSFs is $N \times (N + (M-1)\, r_w)$. Indeed, an incoming packet that needs conversion, in principle, is allowed to access any of the $(M-1)\, r_w$ WCs dedicated to the $M-1$ wavelengths except for the one it is coming from. The space stage B relies on M SSFs to forward the converted signals to the destination OFs. It is important to note that these SSFs are here dedicated per wavelength (WCs on the same bank are fixed-output). The size of these SSFs is $r_w \times N$ since the signals on the same wavelength are directed to different OFs. For this reason, both switching stages consist of M parallel planes. In such an architecture, a packet can be forwarded on a given wavelength λ_k after wavelength conversion if and only if that wavelength is free on the destination OF and there is at least one free WC in the corresponding bank k. This architecture provides a good flexibility in terms of conversion capability. As a matter of fact, when a packet cannot be forwarded in a given wavelength because no WC is free for that wavelength, another wavelength can be checked, until a free wavelength on the OF with an available WC in the corresponding bank is found. A packet can, in principle exploit a number of WCs much larger than r_w. Instead, in SPIW, a packet coming on a particular wavelength λ_i can only exploit the r_w WCs in bank i.

To correctly manage packet forwarding in these sharing schemes, scheduling algorithms (SAs) are needed [18]. These algorithms must be designed taking the switching matrix characteristics and the switching context (synchronous or asynchronous) into account. SAs typically aim at minimizing the number of wavelength conversions, thus maximizing the number of packets forwarded. Scheduling problem is especially critical in the synchronous case where a decision for a number of packets arriving at the same time slot needs to be made, while in the asynchronous case a decision will be made for a single packet when it arrives at the switch inputs. SAs which manage packet forwarding for the four architectures considered in this paper have been designed by considering the asynchronous nature of the arrivals and

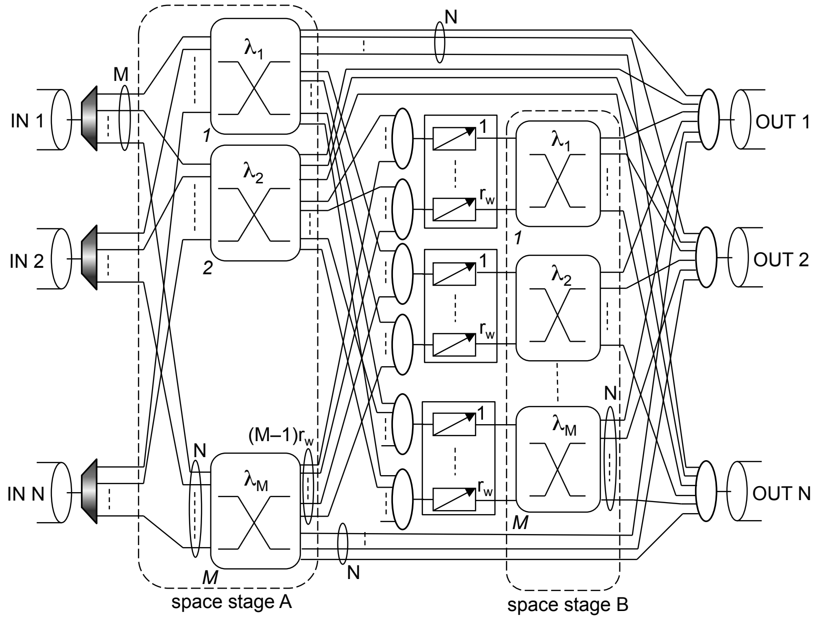

Figure 4: SPOW architecture with N input/output fibers each carrying M wavelengths and M banks of r_w converters dedicated per output wavelength.

the assumption of strictly non-blocking SSFs that are employed. The details of the SAs for the four architectures studied in this article are given below:

- *SPN*: in the SPN architecture, when a packet arrives, the SA first checks if its wavelength is free on the corresponding OF. If so, the packet is forwarded. Otherwise, the SA randomly selects a free wavelength on the destination OF and sequentially checks the r_n shared WCs in the node, until a free WC is found. After then, the packet is forwarded on the selected wavelength. The packet is lost when there is no free wavelength on the destination OF (output blocking) or no WC is available (conversion unavailability).

- *SPL*: the SA only differs from the previous one in the usage of the WCs. When a packet needs conversion, the SA randomly selects a wavelength on the targeted OF and checks whether there is a free WC among the r_l available on the corresponding bank.

- *SPIW*: when a packet coming on wavelength λ_k needs conversion, the SA randomly selects a wavelength on the targeted OF and checks whether there is a free WC among the r_w available within the bank dedicated to λ_k.

- *SPOW*: when a packet needs conversion, the SA randomly selects a wavelength λ_s on the targeted OF and checks whether there is a free WC among those that are able to convert the packet on λ_s (one of the r_w converters in bank s). In case this WC is not found, the SA selects another free output wavelength and tries again, until a WC to convert the packet is found. The packet is lost due to converter unavailability only in case all free wavelengths on the destination OF are checked without finding a WC available to convert the packet.

The SA for the SPOW switch is slightly more complex than the others since in some cases, a number of wavelengths need to be checked before packet forwarding.

3. Analytical Models

In this section, we propose novel analytical models for the wavelength conversion architectures described in the previous section. Asynchronous packet arrivals are considered for the optical packet switch of interest with N IF/OFs carrying M wavelength each. The traffic destined to OF n ($n = 1, \ldots, N$), is assumed to be a Poisson process with intensity $\eta^{(n)}$. The total packet arrival rate to the switch, denoted by η, is given by:

$$\eta = \sum_{n=1}^{N} \eta^{(n)}. \tag{1}$$

The wavelength of an incoming optical packet is assumed to be uniformly distributed over the M wavelengths since edge devices have the freedom to choose a transmission wavelength with uniform probabilities. Packet lengths are assumed to be exponentially distributed with parameter μ. Without loss of generality, the value $\mu = 1$ is considered hereafter, so that the time unit is normalized to the mean packet length. One can model traffic asymmetry across N OFs by choosing $\eta^{(n)}$ differently for different values of n. The traffic asymmetry is considered according to a parsimonious model described in [18], so the values of $\eta^{(n)}$ are given in terms of a single parameter f as:

$$\eta^{(n)} = \eta \tfrac{1-f}{1-f^N} f^{n-1}, \quad 1 \leq n \leq N \tag{2}$$

where $f \geq 1$ is called the traffic imbalance parameter. The traffic tends to get more asymmetric as the parameter f increases. On the other hand, as $f \to 1$, the traffic tends to be symmetric over all OFs. The traffic asymmetry also depends on the total number of OFs, N, so with the same value of f, the traffic gets more asymmetric for high N. It is crucial to study the impact of traffic imbalance on the performance of the switch under different wavelength conversion architectures.

To compare different wavelength conversion sharing schemes, we propose a parameter called *wavelength conversion ratio* r ($0 \leq r \leq 1$) which is defined as the ratio of the overall number of WCs to K which is the overall number of wavelength channels in the switch. Note that $K = NM$. The four WC sharing schemes are then comparatively studied with the same wavelength conversion ratio parameter r to study their loss performance under the same conditions.

Next, we describe the stochastic models we propose for the SPIW and SPOW schemes and provide algorithms to find the packet loss probabilities for both sharing schemes. The analytical models for SPL and SPN sharing schemes already exist in the literature for the symmetric traffic scenario. For the sake of convenience, methods to find the packet loss probabilities for the SPL and SPN schemes with extensions to asymmetric traffic scenarios are given in Appendices A and B, respectively.

3.1. Analysis of SPIW Scheme

In the SPIW scheme, a WC bank of size $r_w = Nr$ is dedicated to each wavelength λ_k ($k = 1, \ldots, M$), totalling NMr WCs. Assume an optical packet arriving on wavelength λ_k which is destined to OF n. If all the wavelength channels on OF n are occupied, then the packet will be blocked. Otherwise, say $l < M$ of the channels are occupied on the destination fiber n. Due to symmetry across wavelengths, the wavelength λ_k will be idle with probability $(M-l)/M$ and the packet will be forwarded over the fiber without a need for wavelength conversion. On the other hand, with probability l/M, the packet will require conversion and will be forwarded to the converter bank for wavelength λ_k. Upon finding an idle wavelength, the packet will be converted to a suitable wavelength so as to be forwarded over the fiber; otherwise, the packet will be dropped due to the lack of a converter. There are two apparent benefits of the SPIW scheme when compared to the SPL scheme:

- In the SPIW scheme, the WCs are FTWCs and therefore they are simpler to implement.
- There is not a high correlation between the utilization of an individual fiber and that of an individual converter bank. Therefore, in epochs of high utilization for a given fiber n and when a packet requires conversion, it would be more likely for the packet to use an idle converter in the SPIW architecture than in the SPL scheme.

For the analysis of the SPIW scheme and based on the second observation above, the fiber occupancy process for a given fiber n and the converter occupancy process for wavelength λ_k are assumed to be independent for all n, k $(n = 1, \ldots, N), (k = 1, \ldots, M)$. When N increases, the dependence between these two processes tends to reduce, which is not only beneficiary for the performance of the overall system but also the problem becomes more suitable for analysis. This assumption will later be verified through simulations. Let us now focus on the OF n. Let $L^{(n)}(t)$ denote the number of occupied wavelength channels for fiber n at time t. Note that $L^{(n)}(t)$ takes values in the set $\{0, 1, \ldots, M\}$ and can be shown to be a non-homogeneous birth-death (BD) type Markov chain based on the independence assumption. The transition diagram for this BD chain is given in Fig. 5. The birth rates of this chain can be written as:

$$\eta_l^{(n)} = \eta^{(n)} \frac{M-l}{M} + \eta^{(n)} \frac{l}{M} (1 - P_{conv}^{SPIW}), l = 0, \ldots, M-1, \tag{3}$$

where P_{conv}^{SPIW} is the probability that a packet directed to the WC bank does not get to find an idle converter. Note that due to symmetry among wavelengths, this quantity is the same for all wavelengths. If P_{conv}^{SPIW} is known, one can find the steady-state probabilities $\pi_l^{(n)}, l = 0, 1, \ldots, M$ of the BD chain which amounts to the steady-state probability that the Markov chain corresponding to fiber n is visiting state l. Because of the PASTA property, $\pi_l^{(n)}$ is the probability that an arriving packet finds l occupied channels on OF n [27]. This procedure is to be repeated for all fibers $1 \leq n \leq N$. The loss probability for a packet directed to fiber n is then written as:

$$P_{loss}^{SPIW,(n)} = \pi_M^{(n)} + \sum_{l=1}^{M-1} \pi_l^{(n)} \frac{l}{M} P_{conv}^{SPIW}, 1 \leq n \leq N. \tag{4}$$

The first term amounts to the case when an arriving packet finds all M channels occupied whereas the second term corresponds to the case when there

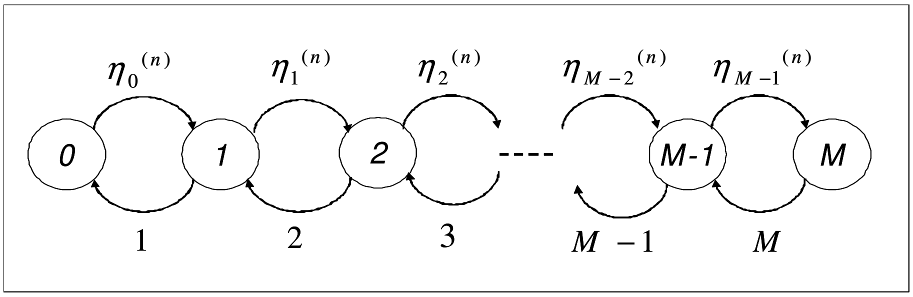

Figure 5: State transition diagram for the birth-death type Markov chain for fiber n arising in the analysis of the SPIW, SPN, and SPOW schemes

are idle channels on the destination fiber and the packet requires conversion but is dropped due to the lack of a converter. It is then straightforward to write the overall loss probability for the SPIW scheme:

$$P_{loss}^{SPIW} = \frac{\sum_{n=1}^{N} \eta^{(n)} P_{loss}^{SPIW,(n)}}{\eta}. \tag{5}$$

However, the quantity $P_{conv}^{SPIW}$is not known yet. To calculate this quantity, note that the intensity of traffic destined to OF n but requiring conversion can be expressed as:

$$\nu^{SPIW,(n)} = \sum_{l=1}^{M-1} \eta^{(n)} \pi_l^{(n)} \frac{l}{M}. \tag{6}$$

The intensity of overall traffic destined to the WC bank k, does not depend on the particular wavelength λ_k and can simply be written as:

$$\nu^{SPIW} = \frac{\sum_{n=1}^{N} \nu^{SPIW,(n)}}{M}. \tag{7}$$

This traffic is assumed as Poisson which is justified when the number of traffic substreams N is large. With this assumption in place, the quantity P_{conv}^{SPIW} can be obtained using the Erlang-B formula [27]:

$$P_{conv}^{SPIW} = B(r_w, \nu^{SPIW}), \tag{8}$$

where:

$$B(C, \rho) = \frac{\rho^C / C!}{\sum_{i=0}^{C} \rho^i / i!}.$$

The equations (4)-(8) dictate a fixed-point relationship and the fixed-point iterative procedure proposed for the SPIW scheme is given in Table 1.

1.	First start with an arbitrary initial probability P_{conv}^{SPIW}.
2.	Given P_{conv}^{SPIW}, for each fiber n construct the BD process depicted in Fig. 5 via (3) and solve for its steady-state probabilities $\pi_l^{(n)}, 0 \leq l \leq M$.
3.	Write $P_{loss}^{SPIW,(n)}$ through (4) for each $n, 1 \leq n \leq N$, and then obtain the overall loss probability P_{loss}^{SPIW} via (5). If the normalized difference between two successive values of P_{loss}^{SPIW} is less than an a-priori given parameter ε, then exit the loop.
4.	Find ν^{SPIW} using (6) and (7).
5.	Given ν^{SPIW}, find P_{conv}^{SPIW} through (8).
6.	Go to step 2.

Table 1: Iterative algorithm to calculate the overall blocking probability P_{loss}^{SPIW} for the SPIW scheme.

3.2. Analysis of SPOW Scheme

In SPOW, a WC bank of size $r_w = Nr$ is dedicated for each output wavelength. Overall, the switch is provided with $W = NMr$ FWCs. The WCs in the same bank convert to a fixed-output wavelength. Assume again an optical packet arriving on wavelength λ_k which is destined to fiber n. This packet will be blocked if all the wavelength channels on fiber n are occupied. Otherwise, when $l < M$ channels are occupied on OF n then the packet will be forwarded over the fiber without a need for wavelength conversion with probability $(M-l)/M$. On the other hand, with probability l/M the packet will require conversion (referred to as a class-$(M-l)$ packet) and will then be randomly forwarded to one of the $M-l$ WC banks that has at least one idle converter. To clarify, a class-i packet is a packet requiring conversion and there are i alternative banks that this packet can be forwarded to. The packet will be dropped if all $M-l$ banks are fully occupied. In this paper, a simple randomized scheme is considered where the output wavelength (and consequently the WC bank) to forward the packet is randomly chosen. Note that the case where the packet is forwarded to the least loaded converter bank among the available ones, is not taken into account in the current paper. Consider the OF n which is again a BD process given in Fig. 5 and its birth rates are written for $l = 0, \ldots, M-1$:

$$\eta_l^{(n)} = \eta^{(n)} \frac{M-l}{M} + \eta^{(n)} \frac{l}{M} (1 - P_{conv}^{SPOW}(M-l)), l = 0, \ldots, M-1, \tag{9}$$

where $P_{conv}^{SPOW}(l)$ is the probability that a class-l, $l = 1, 2, \ldots, M-1$ packet requiring conversion gets lost due to the lack of a suitable WC. Let us find the steady-state probabilities $z_l^{(n)}, l = 0, 1, \ldots, M$ of this BD process for all fibers n. The loss probability for a packet directed to OF n (denoted by $P_{loss}^{SPOW,(n)}$) and the SPOW overall loss probability (denoted by P_{loss}^{SPOW}) can then be written for $1 \leq n \leq N$:

$$P_{loss}^{SPOW,(n)} = z_M^{(n)} + \sum_{l=1}^{M-1} z_l^{(n)} \frac{l}{M} P_{conv}^{SPOW}(M-l), 1 \leq l < M \tag{10}$$

$$P_{loss}^{SPOW} = \frac{\sum_{n=1}^{N} \eta^{(n)} P_{loss}^{SPOW,(n)}}{\eta}. \tag{11}$$

However, the probabilities $P_{conv}^{SPOW}(l), 1 \leq l \leq M-1$ are not yet available. For this purpose, the intensity of class-l traffic generated from packets destined to fiber n can be written as:

$$\nu_l^{SPOW,(n)} = \eta^{(n)} z_{M-l}^{(n)} \frac{M-l}{M}, 1 \leq n \leq N, 1 \leq l < M. \tag{12}$$

The intensity of overall class-l traffic destined to the M WC banks is then easy to write:

$$\nu_l^{SPOW} = \sum_{n=1}^{N} \nu_l^{SPOW,(n)}, 1 \leq l < M. \tag{13}$$

Let us now study the stochastic process underlying the total number of converters in use (denoted by $C(t)$ at time t) in the system. Evidently, the process $C(t)$ is not Markovian and we need to keep track of the occupancy of each converter bank to make it Markovian which would then prohibit us from obtaining a computationally efficient numerical solution. Recall that there are overall W WCs and $r_w = W/M$ WCs per each wavelength. A simplifying assumption is made to make $C(t)$ Markovian. For this purpose, let us assume $C(t)$ takes the value $k, 0 \leq k \leq W$. Let $F(m, k), 1 \leq m \leq M, 0 \leq k \leq W$ denote the number of possible ways that these k WCs in use are distributed over m banks of FWCs. In particular, we are interested in the number of m-tuples, namely $x_1, x_2, \ldots, x_m$ satisfying:

$$\sum_{i=1}^{m} x_i = k, 0 \leq x_i \leq r_w, \tag{14}$$

where x_i is the number of WCs in use at WC bank i. It is not difficult to show that:

$$F(m,0) = 1, F(m,1) = m, 1 \leq m \leq M \tag{15}$$

$$F(1,i) = \begin{cases} 1 & \text{if } 1 \leq i \leq r_w, \\ 0 & \text{if } i > r_w \end{cases} \tag{16}$$

Moreover, the quantity $F(m,k)$ can be obtained through the following recursion:

$$F(m,k) = \sum_{i=\max(0,k-r_w)}^{k} F(m-1,i), k \geq 2. \tag{17}$$

One can obtain $F(m,k), 1 \leq m \leq M, 0 \leq k \leq W$ from the identities (15),(16), and the recursion (17). Since the traffic is symmetric over the M wavelengths, a packet forwarded to the WC bank which finds k overall occupied WCs will see (in the steady-state) one of the $F(M,k)$ possible WC distributions to M banks with uniform probabilities. However, two consecutive packet arrivals will see similar converter distributions and there is actually a correlation among successive distributions. For the purpose of obtaining a numerically efficient algorithm, this correlation is ignored and it is assumed that each arriving packet gets to see the same steady-state distribution of WCs in use among the M WC banks. Under this assumption, the process $C(t)$ becomes Markovian and can be represented by the Markov chain given in Fig. 6 where:

$$\gamma_k = \sum_{l=1}^{M-1} \nu_l^{SPOW}(1 - f(l,k)), 0 \leq k < W, \tag{18}$$

where $f(l,k)$ denotes the probability that a class-l packet arriving at the entire WC bank and finding k overall occupied WCs gets lost due to the lack of a suitable converter.

Since there are $F(M,k)$ possible ways each of which is equally likely, it is possible to write for $1 \leq l \leq M-1, 0 \leq k < W$:

$$f(l,k) = \begin{cases} \frac{F(M-l,k-lr_w)}{F(M,k)} & \text{if } k \geq lr_w, \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

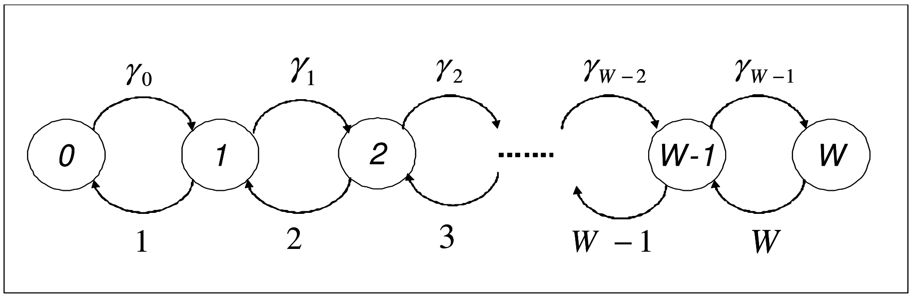

Figure 6: State transition diagram for the converter occupancy process $C(t)$ arising in the analysis of the SPOW scheme

Let us now find the steady-state probabilities $y_k, k = 0, 1, \ldots, W$ of the BD process given in Fig. 6. The probability $P_{conv}^{SPOW}(l)$ can then be written as:

$$P_{conv}^{SPOW}(l) = y_W + \sum_{i=0}^{W-1} y_i f(l, i). \tag{20}$$

The fixed-point algorithm for the SPOW scheme is given in Table 2.

4. Numerical Results

In this section, we provide a comparison of results obtained via simulations and analysis for the four wavelength converter sharing schemes. The proposed sharing schemes are compared in terms of packet loss probability (PLP) by applying the proposed analytical models for SPIW and SPOW, and the models proposed for the SPN and SPL, as a function of the wavelength conversion ratio r. Since the analysis for the SPL scheme is exact, we do not provide simulation results in this case. Simulations are performed with a C-based program with confidence interval at 95% less than or equal to the 5% of the mean. Because of excessive run-time requirements, simulation results for very rare probabilities, i.e., PLP $< 10^{-6}$, are not reported. Consistent with the analytical models, we consider Poisson arrivals on input and apply the SAs described in Section 2. Performance evaluations are presented by introducing the average load per input wavelength $p = \frac{\eta}{NM}$. It is also useful to remind that the conversion ratio r is a discrete variable, with possible values $\frac{i}{N}$ $(i = 0, 1, \ldots, N)$ for SPIW and SPOW, $\frac{i}{NM}$ $(i = 0, 1, \ldots, NM)$ for SPN and $\frac{i}{M}$ $(i = 0, 1, \ldots, M)$ for SPL.

1.	First start with arbitrary initial probabilities $P_{conv}^{SPOW}(l), 1 \leq l \leq M-1$.
2.	Given $P_{conv}^{SPOW}(l), 1 \leq l < M$, for each fiber n construct the BD process depicted in Fig. 5 via (9) and solve for its steady-state probabilities $z_l^{(n)}, 1 \leq n \leq N, 1 \leq l < M$.
3.	Write $P_{loss}^{SPOW,(n)}$ through (10) for each $n, 1 \leq n \leq N$, and then obtain the overall loss probability P_{loss}^{SPOW} via (11). If the normalized difference between two successive values of P_{loss}^{SPOW} is less than a given parameter ε, exit the loop.
4.	Find $\nu_l^{SPOW,(n)}$ and ν_l^{SPOW} using (12) and (13), respectively.
5.	Recursively find the quantities $F(m,k), 1 \leq m \leq M, 0 \leq k \leq W$ using the identities (15),(16) and (17).
6.	Calculate the quantities $f(l,k), 1 \leq l \leq M-1, 0 \leq k \leq W$ using the identity (19).
7.	Construct the BD process given in Fig. 6 using the birth rates given in (18) and solve for its steady-state probabilities $y_l, 0 \leq l \leq W$.
8.	Find $P_{conv}^{SPOW}(l), 1 \leq l \leq M-1$ through (20).
9.	Go to step 2.

Table 2: Iterative algorithm to calculate the overall blocking probability P_{loss}^{SPOW} for the SPOW scheme.

All schemes are compared under balanced $f = 1.0$ and unbalanced $f > 1$ traffic scenarios and for varying loads. The first set of results are depicted in Fig. 7 for the case of $N = 16, M = 16, f = 1$ and in Fig. 8 for the case of $N = 16, M = 16, f = 1.1$, both figures given for two different values of the load parameter p. The second set of results are depicted in Fig. 9 for the case of $N = 32, M = 64, f = 1$ and in Fig. 10 for the case of $N = 32, M = 64, f = 1.05$, both figures given for two different values of the load parameter p.

We observe the following based on Figures 7-10:

- All four figures show that the asymptotic value of the PLP as $r \to 1$ is the same for all four converter sharing schemes, as expected. In fact, this value is due to output contention on the OFs and not related to the sharing scheme applied.

- The analytical results are in accordance with simulation results with slight discrepancies for relatively low loads. However, we believe that the models we propose capture the most crucial characteristics of the associated wavelength converter sharing schemes in all cases. As an example, the newly proposed SPOW and SPIW analytical models allow us to accurately find the minimum conversion ratio required to obtain the asymptotic loss under all the scenarios studied. This minimum conversion ratio obtained via analytical results can be used to dimension converters in optical switches without having to resort to time-consuming simulations especially for rare loss probabilities.

- The SPIW scheme generally outperforms the SPL scheme where the gain in using SPIW relative to SPL increases with increased traffic unbalance characterized by the parameter f. Since one cannot expect the traffic to be uniform over all OFs, the SPIW scheme introduces a significant performance improvement to SPL in realistic traffic scenarios in addition to its architectural advantages, i.e., use of less costly FTWCs as opposed to TTWCs used in SPL. The reason behind this observation is that the traffic can be unbalanced over different fibers but it is uniform across the entire set of wavelengths used in the system.

- When the traffic is balanced, there are cases when SPIW slightly outperforms SPL (such as the $N = 16$ and $M = 16$ scenario) and vice versa (such as the $N = 32$ and $M = 64$ scenario). As M increases, SPL starts to outperform SPIW for balanced traffic cases.

- SPN and SPOW provide loss probabilities which are significantly lower than SPIW and SPL when the conversion ratio is low. This is due to the flexibility provided by these schemes in exploiting the WCs. In fact, in the SPN scheme, an optical packet will exploit any WC available at the node. Quite surprisingly, the SPOW performs very close to the SPN especially for large M, even with FWCs. This can be explained as follows: a packet directed to a particular output fiber can be sent in whatever free wavelength λ_i, provided that at least one WC is available in the corresponding bank; if this is not the case, the packet can be converted to another free wavelength by finding a free wavelength converter in the corresponding bank. This behaves very close to a shared bank of TTWCs which is obtained by groups of FWCs.

5. Complexity Evaluation and Comparison

In this section, the complexities of the switching architectures considered here are evaluated. A first contribution to the complexity is given by the number of optical gates (OGs). In Section 2, modular schemes of the proposed architectures are described. These architectures are based on space switches. The employment of space switches will require a number of OGs which is not as low as possible. The reason is now explained: in all-optical architectures, contention only occurs among those packets on the same wavelength, while packets carried on different wavelengths do not compete each other. Instead, in classic view of a space switch, no more than one packet can access one of the outputs of the switch at the same time. So, in space switches packets on different wavelengths are considered as forwarded in different outputs even if they do not compete. For this reason, the space switches often requires a large number of outputs (and OGs) which are useless to resolve contention. To provide a complete and useful complexity comparison, in this section the architectures are considered as implemented with the lowest number of OGs, through some arrangements where needed.

The second contribution to the complexity is given by the amount of WCs employed. The four schemes are compared here when equipped with the minimum number of WCs needed to reach asymptotic loss performance.

SPIW: by using M SSFs dedicated per wavelength instead of a single large SSF, the number of optical gates needed in the space stage A in Fig. 3 is minimized. Indeed, in this stage contention is resolved in M parallel planes, where space switches are effectively needed to resolve contention among packets on the same wavelength. The M SSFs employed in the space stage A are of size $N \times (N + r_w)$. The number of OGs needed to implement these SSFs (considering single stage implementation) is:

$$N^A_{SPIW} = M\left(N^2 + Nr_w\right) = MN^2\left(1 + r\right) \tag{21}$$

being $r_w = Nr$. A second contribution to the complexity is given by the number of OGs needed implement the switching stage B. The M SSFs depicted in Fig. 3 do not operate on a single wavelength, so they require a large number of OGs. To avoid this extra cost, an SSF has been proposed in [8] in order to connect WC banks to OFs with the lowest number of OGs. To evaluate the complexity of the proposed architecture, this stage with the lowest complexity is considered. It is based on the following observation: each WC may serve a packet which may be directed to any of the N OFs ; so N OGs are needed to connect a WC to the N OFs [8]. For this reason NMr_w OGs are sufficient to connect WCs and OFs and avoid contentions. The complexity of this stage is:

$$N^B_{SPIW} = MNr_w = MN^2 r \tag{22}$$

while the overall complexity for SPIW is:

$$N^{SPIW} = N^A_{SPIW} + N^B_{SPIW} = MN^2 \left(1 + 2r\right) \tag{23}$$

SPOW: the SPOW is organized in a way similar to SPIW, but in this case the M SSFs of space stage A allow the connection between a given input wavelength channel to any WC dedicated to a different wavelength (Fig. 4). The size of each SSF is $N \times (N + (M-1)\, r_w)$ so the complexity of this stage is:

$$N^A_{SPOW} = M\left(N^2 + N\left(M-1\right) r_w\right) = MN^2 \left(1 + \left(M-1\right) r\right) \tag{24}$$

being $r_w = Nr$. In SPOW, each WC bank is connected to the OFs through a SSF dedicated per wavelength (Fig. 4). The number of OGs needed in the space stage B is already minimized, given that each SSF resolves contention among packets converted to the same wavelength. This SSF has r_w inputs and N outputs, given that no more than one packet converted in a given wavelength can be sent to the same OF. Therefore, the overall complexity of the space switch B is $N^B_{SPOW} = rMN^2$. It is worthwhile noting that space stage B for the SPOW requires the same number of OGs as the space stage B in SPIW. The total number of gates for the SPOW results in:

$$N_{SPOW} = N^A_{SPOW} + N^B_{SPOW} = MN^2 \left(1 + Mr\right) \tag{25}$$

By comparing (23) and (25), it is possible to note that the conversion ratio r is here multiplied by M instead of 2.

SPN: the space stage A for SPN architecture can again be realized in a modular way (a similar scheme for SPN can be found in [20]). The input wavelength channels must be connected to all WCs, thus in this case the space stage A requires M SSFs dedicated per wavelength with size $N \times (N + r_n)$. The contribution to the complexity is:

$$N_{SPN}^{A} = M(N^2 + Nr_n) = MN^2 (1 + Mr) \tag{26}$$

being $r_n = NMr$. To connect the WC outputs to the OFs (space stage B) with the lowest number of OGs, N OGs per WC are needed, as in the SPIW. There are r_n WCs in total, so the complexity of the stage B is $N_{SPN}^{B} = Nr_n = MN^2 r$. The overall complexity of the SPN scheme is:

$$N_{SPN} = N_{SPN}^{A} + N_{SPN}^{B} = MN^2 (1 + (M + 1) r) \tag{27}$$

By comparing (25) and (27), the expression of the complexity for SPN and SPOW are very close (the architectures are similarly structured).

SPL: in the SPL scheme the WCs are partitioned among the OFs, so a packet can only exploit the WCs dedicated to its destination OF. The SPL can be structured again in a modular organization, where the space stage A requires M SSFs of size $N \times (N + Nr_l)$ to allow each input channel to be connected to any WC. After that, r_l WCs are directly coupled to OF 1, r_l to OF 2 and so on, so the space stage B is not needed in SPL. The complexity of the SPL scheme is:

$$N_{SPL} = M(N^2 + N^2 r_l) = MN^2 (1 + r_l) = MN^2 (1 + Mr) \tag{28}$$

where $r_l = Mr$.

By comparing (23), (25), (27) and (28) the following remarks can be made: all the complexity expressions are proportional to term MN^2, so the number of IF/OFs, N, significantly affects the complexity. For SPIW, this term is multiplied by $1+2r$ ($1 < 1+2r < 3$), while for the other architectures r is further multiplied by M or $M + 1$. Therefore, the number of OGs in the SPIW is slightly influenced by the conversion ratio r, while in the other architectures r has a relevant impact on the complexity, especially when M is high.

Table 3 shows a comparison among the four architectures in terms of WCs and OGs employed, for $N = 16$, $M = 16$, $f = 1.0$ and $p = 0.25$. The number of WCs employed in each architecture represents the minimum number needed to obtain asymptotic loss performance and are derived from

Fig. 7a. The table shows how the SPN switch provides savings in the number of WCs. The SPL switch requires, in this switch configuration, the highest number of WCs, which also implies a very high number of OGs (high r). The SPIW switch requires a quite high number of WCs but a very small number of OGs are needed compared to the others, thanks to the partitioning of the WCs among the wavelengths, providing significant cost savings. Finally, SPOW requires larger number of WCs than SPN, and consequently also a quite higher number of OGs. For SPOW, two further remarks need to be pointed out: the WCs are fixed output, that are less expensive than TTWCs and FTWCs [26]; even more important, SPOW can be equipped with the same number of WCs as the SPN, with only a small PLP increase (see Fig.7a), and in this case SPOW needs the same number of OGs and WCs as the SPN, but the WCs are fixed-output, that are less expensive. For these reasons, the SPIW and SPOW schemes provide viable alternatives in terms of performance and cost. Further detailed cost consideration should be performed by the knowledge of the cost range of the OGs and fixed/tunable WCs. The range of convenience of each architecture depends on the relative costs of the components employed [28].

	# WCs	# OGs
SPN	48	17.152
SPIW	144	8.704
SPOW	64	20.480
SPL	208	57.344

Table 3: Number of WCs and OGs for SPN, SPIW, SPOW and SPL architectures for $N = 16$, $M = 16$, $f = 1$ and $p = 0.25$.

6. Conclusions

The paper compares four different schemes to share wavelength converters in asynchronous optical packet switches, in terms of performance and complexity. To this end, original analytical models are proposed to evaluate the packet loss probability of SPIW and SPOW switch architectures in asynchronous scenario, with balanced and unbalanced traffic. These models have been validated by comparison with simulations. The proposed models are accurate both for SPIW and SPOW. The SPOW scheme provides performance very close to the SPN scheme while employing fixed-output and thus simpler WCs with almost the same number of switching elements. As a consequence, it provides a promising converter sharing solution in next-generation optical packet switching systems. SPIW and SPL generally perform worse than SPN and SPOW whereas SPIW generally outperforms SPL especially for unbalanced traffic scenarios. We believe that both SPIW and SPOW schemes provide cost-effective alternatives to other conventional converter sharing schemes.

A. Analysis of SPL Scheme

In the SPL architecture, each OF has a dedicated bank of $r_l = Mr$ WCs, totalling NMr WCs. An exact numerical algorithm is given in [21] to calculate the packet loss probability $P_{loss}(M, r_l, \gamma)$ for a single link with M wavelengths and $r_l \leq M$ WCs, loaded with Poisson packet traffic with intensity γ. This algorithm is based on a block tridiagonal LU factorization of a generator of a two-dimensional Markov chain and its computational complexity is $O(r_l M^3)$. Then, the loss probability for the switch under consideration utilizing the SPL scheme can be written as:

$$P_{loss}^{SPL} = \frac{\sum_{n=1}^{N} \eta^{(n)} P_{loss}(M, r_l, \eta^{(n)})}{\eta}. \tag{29}$$

B. Analysis of SPN Scheme

The analysis of the SPN scheme is similar to the one for SPIW. In SPN, a single WC bank of size $r_n = NMr$ is used for the entire node. Assume again an optical packet arriving on wavelength λ_k which is destined to OF n. If all the wavelength channels on fiber n are occupied, then the packet will be blocked. Otherwise, when $l < M$ channels are occupied on OF n, then the packet will be forwarded over the fiber without a need for wavelength conversion with probability $(M - l)/M$ while the packet will require conversion with probability l/M. The packet will be dropped if there is a lack of a WC. Since there is complete sharing of converters, SPN is known to be the most performance efficient but complex wavelength sharing architecture. For the purpose of SPN analysis, a single OF n is considered, leading again to a BD process (see Fig.5) whose birth rates are given by:

$$\eta_l^{(n)} = \eta^{(n)}\frac{M-l}{M} + \eta^{(n)}\frac{l}{M}(1 - P_{conv}^{SPN}), l = 0, \ldots, M-1, \tag{30}$$

where P_{conv}^{SPN} is the probability that a packet requiring conversion gets dropped due to the lack of a WC. Let us find the steady-state probabilities $x_l^{(n)}, l = 0, 1, \ldots, M$ of this BD process for all fibers n. The loss probability for a packet directed to fiber n (denoted by $P_{loss}^{SPN,(n)}$) and the SPN overall loss probability (denoted by P_{loss}^{SPN}) can then be written as:

$$P_{loss}^{SPN,(n)} = x_M^{(n)} + \sum_{l=1}^{M-1} x_l^{(n)} \frac{l}{M} P_{conv}^{SPN}, 1 \leq n \leq N, \tag{31}$$

$$P_{loss}^{SPN} = \frac{\sum_{n=1}^{N} \eta^{(n)} P_{loss}^{SPN,(n)}}{\eta}. \tag{32}$$

In order to find P_{conv}^{SPN}, the following observations are taken into account. The intensity of traffic destined to fiber n but requiring conversion for the SPN scheme is given by:

$$\nu^{SPN,(n)} = \sum_{l=1}^{M-1} \eta^{(n)} x_l^{(n)} \frac{l}{M}. \tag{33}$$

The intensity of overall traffic destined to the single WC bank is then easy to write:

$$\nu^{SPN} = \sum_{n=1}^{N} \upsilon^{SPN,(n)} \tag{34}$$

Again using Poisson approximation for the traffic above, P_{conv}^{SPN} can be found using the Erlang-B formula:

$$P_{conv}^{SPN} = B(r_n, \nu^{SPN}). \tag{35}$$

A fixed-point algorithm for the SPN scheme can also be given as in Table 1 based on the expressions obtained above.

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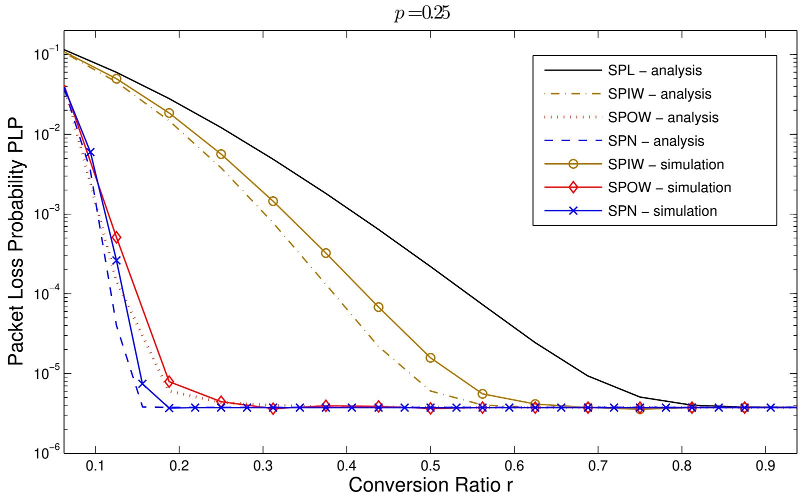

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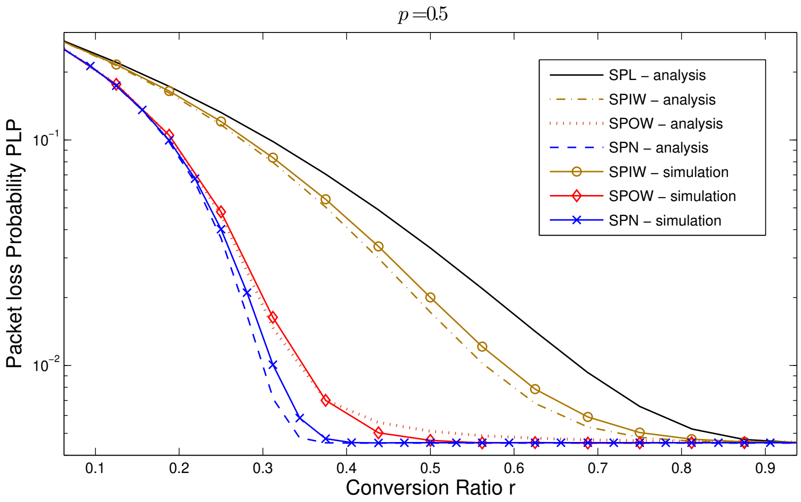
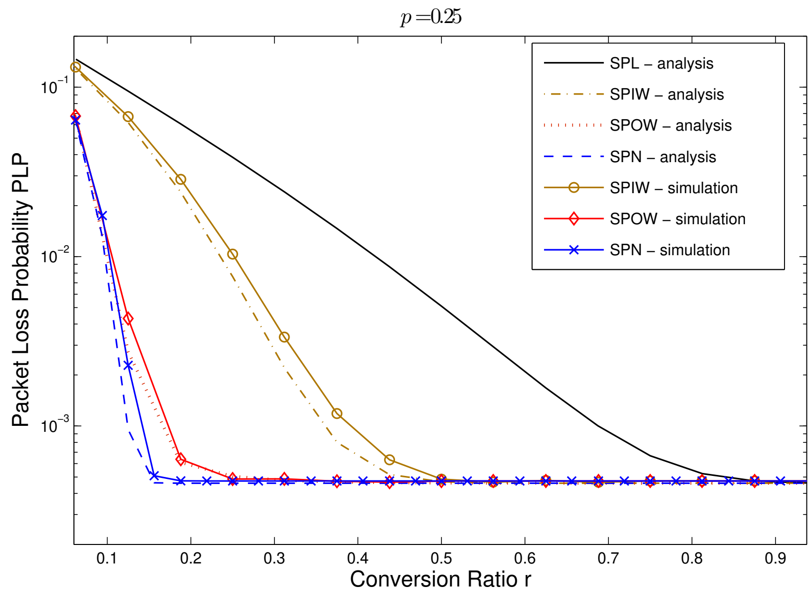


(b)

Figure 7: The packet loss probability PLP as a function of the conversion ratio r for $N = 16$ and $M = 16$ for symmetric traffic scenario $f = 1$ for two different values of load p.



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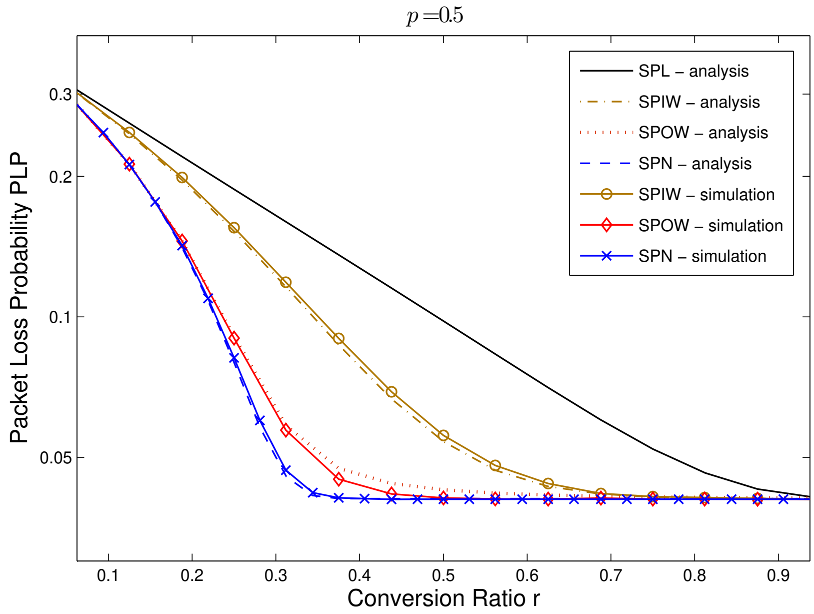
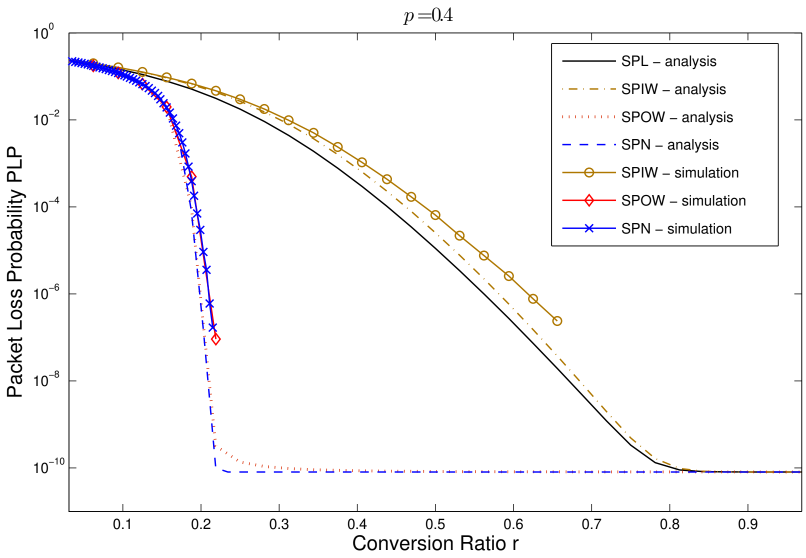


(b)

Figure 8: The packet loss probability PLP as a function of the conversion ratio r for $N = 16$ and $M = 16$ for non-symmetric traffic scenario $f = 1.1$ for two different values of load p.



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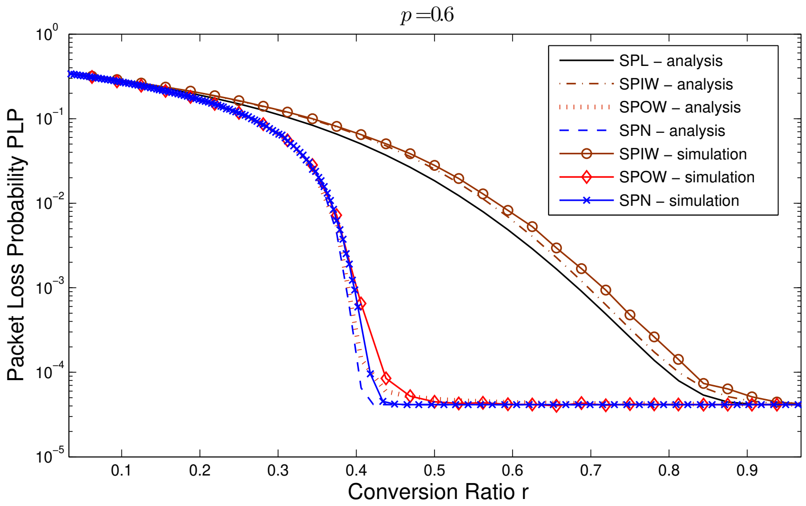
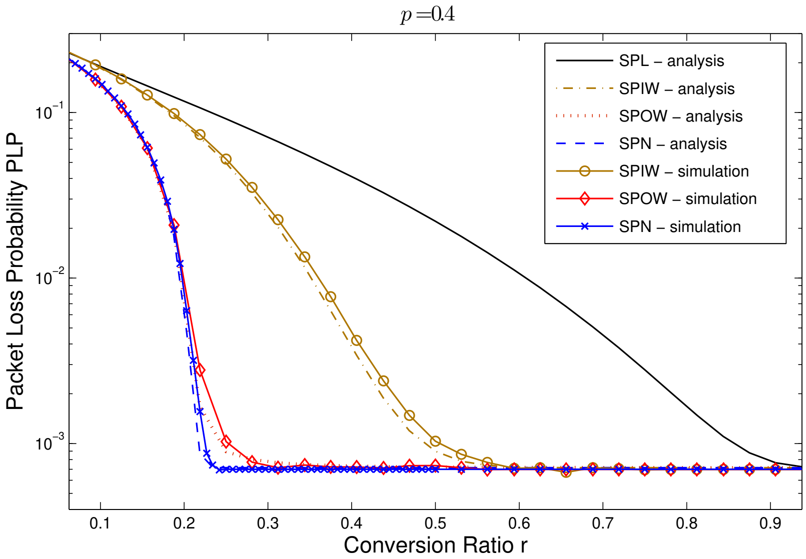
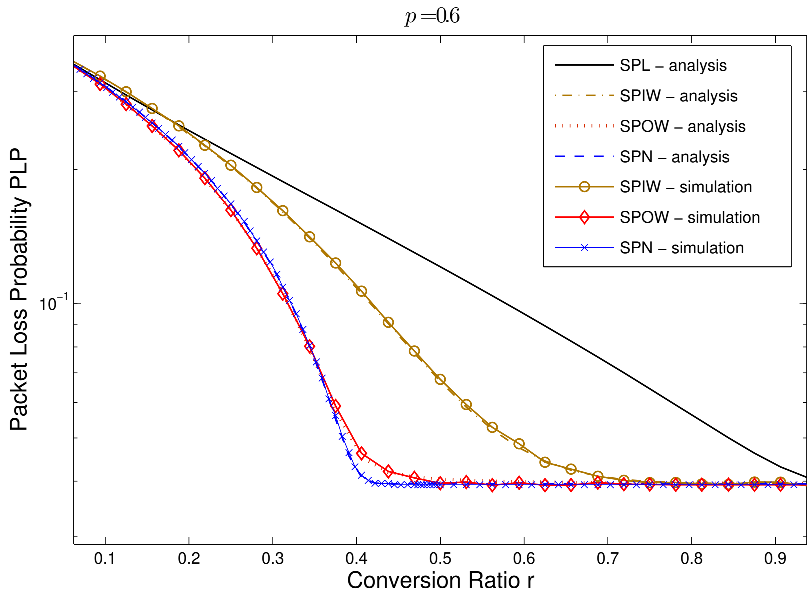


(b)

Figure 9: The packet loss probability PLP as a function of the conversion ratio r for $N = 32$ and $M = 64$ for symmetric traffic scenario $f = 1$ for two different values of load p.



(a)



(b)

Figure 10: The packet loss probability PLP as a function of the conversion ratio r for $N = 32$ and $M = 64$ for non-symmetric traffic scenario $f = 1.05$ for two different values of load p.