Round-robin wavelength assignment: A new packet sequence criterion in Optical Packet Switching SCWP networks

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Abstract

The WASPNET project proposed a packet sequence criterion to preserve end-to-end packet order in Optical Packet Switching (OPS) networks controlled by the Scattered Wavelength Path (SCWP) operational mode. This paper shows that this packet ordering methodology causes performance impairments, related to unbalanced wavelength usage in fiber links. This skewed usage is inherent to the WASPNET sequencing criterion. As a solution, a *round-robin sequence criterion* is proposed. The presented technique eliminates non-uniform wavelength utilization in fiber links for any traffic pattern, as well as the performance impairments associated. We also propose an optimum scheduling algorithm for OPS output-buffered switch fabrics, which preserves packet order by following the new sequencing criterion.

1. Introduction

1.1 WDM Optical Packet Switching Networks

The Optical Packet Switching (OPS) paradigm in Wavelength Division Multiplexing (WDM) networks is similar to traditional electronic packet switching [1][2]. However, the packet payload is transparent in the sense that it remains in the optical domain, while headers are processed electronically. OPS offers high flexibility and bandwidth efficiency, since it operates on packet granularity. Nevertheless, fast packet-by-packet switching operation and optical buffering impose the highest constraints to the photonic switching function. High hardware costs result from state-of-the-art technology. For this reason, although Optical Packet Switching is envisaged as a definitive solution for WDM networks, the deployment of an OPS backbone network is not foreseen in the near future.

An open discussion exists around the optical packet length issue. In this paper, we will focus on synchronous OPS, where time is slotted and the time slot is set to packet transmission time. The adoption of the synchronous approach requires the design of optical synchronizing stages that align packets at input ports. Although synchronization stages raise equipment cost, the associated performance improvement resulting from a better contention behavior has powered the study of this alternative. A synchronous OPS network with a time slot in the order of 1 μs was proposed by the European DAVID project [3], as the most promising option for the WDM backbone network.

When applying Optical Packet Switching in Wavelength Division Multiplexing (WDM) networks, the *networking operational mode* establishes the way permanent higher layer connections (Optical Packet Paths, OPPs) between ingress and egress nodes are mapped onto appropriate link wavelengths. This topic has been addressed by the WASPNET project [4], where two possible methodologies were proposed: Shared Wavelength Path (SHWP) and Scattered Wavelength Path (SCWP). In SHWP, packets from the same OPP follow a fixed sequence of hops to the egress node, such that transmission fiber and wavelength are fixed for each hop. Under these considerations, each packet entering an OPS switch requests a fixed output fiber and a fixed output wavelength. The OPP to which the packet belongs determines these values. Therefore, the scheduling decision of the switch simply assigns the appropriate delay to each incoming packet.

In the SCWP operational mode, an optical path has a fixed sequence of transmission fibers, but the transmission wavelength in each hop may vary. Incoming packets demand known destination output fibers, but the switch may dynamically decide output wavelengths. This extra degree of freedom available for switch schedulers allows a joint decision on packet delay and packet output wavelength, boosting the statistical multiplexing effect. Therefore, SCWP provides OPS switching architectures with higher throughput and lower packet delays than SHWP operation does, yielding simplified architectures according to optical buffering needs [4][5][6]. The authors consider SCWP as the logical operational mode in future OPS networks.

1.2 Packet sequence in OPS networks

In an OPS backbone network, it is necessary to preserve the end-to-end packet sequence to avoid reordering cost at the egress node. Electronic re-sequencing stages would need very large memories due to the high speed of the optical links. Assuming this, the ingress nodes and the interconnection nodes must enforce packet sequence *in each hop* across the network. Thus, packet order information should be available for switching nodes. The solution of adding sequence information into the packet header is not desirable, due to the performance degradation as a consequence of header growth.

Alternatively, it is possible to design an ordering criterion based on packet arrival time and packet arrival wavelength. Packet arrival time is not enough for packet ordering in SCWP networks, because several packets belonging to the same OPP may be simultaneously transmitted using different wavelengths in a given fiber. When these simultaneous packets arrive at a node, the switch scheduler requires extra information to know their order and preserve it in delay/output wavelength assignment.

Packet ordering issues has been the subject of study in unslotted networks [7][8]. However, as far as the authors know, the only existing packet sequence criterion in synchronous SCWP networks was originated in the WASPNET project. The *WASPNET packet sequencing criterion* consists of transmitting simultaneous packets in consecutive wavelengths, starting from the lowest wavelength λ_0, so that lower order packets are transmitted by using lower wavelengths. This is illustrated in Figure 1-a. Chia *et al*. [9] provided a scheduling algorithm for the feedback version of the WASPNET switch fabric [4], which keeps packet sequence according to the WASPNET criterion. In [5], the authors proposed a scheduling algorithm for OPS switch fabrics able to emulate output buffered operation. The advantage of this scheduling algorithm (*basic SCWP scheduler,* in the sequel) is that it provides optimum performance, while preserving packet sequence following the WASPNET criterion for an acceptable processing complexity.

The rest of the paper is organized as follows: In Section 2, the inherent issues/problems associated to the WASPNET order criterion are described. Section 3 proposes a new packet sequence criterion that eliminates the problems in section 2. Section 4 adapts the basic SCWP scheduler to the new sequencing criterion. Section 5 evaluates the performance improvement obtained from the application of the proposed sequence criterion. Section 6 concludes.

2. Non-uniform wavelength selection

Figure 1-a shows an intrinsic consequence of the application of the WASPNET sequencing criterion, namely the unbalanced usage of the wavelengths in the fibers. This is because lower order wavelengths are used more frequently than higher order ones. Every time slot, if wavelength λ_i is occupied, then λ_{i-1} is also occupied, but not conversely. As a result, for any fiber in the network, p_i, the average utilization of wavelength $i=0...n-1$, always holds that $1 \geq p_0 \geq p_1 \geq ... \geq p_{n-2} \geq p_{n-1} \geq 0$.

We have identified impairments in OPS switch fabrics due to unbalanced resources usage. To measure the distribution skew and illustrate the impairments detected, we simulated the SCWP OPS network shown in figure 2. The left side of the figure is a set of N OPS nodes with N input and output fibers and n wavelengths per fiber. The input traffic injected in point (X) for each input fiber, is the aggregation of n Bernouilli uniform sources of load parameter ρ, $0 \leq \rho \leq 1$. Output fiber 0 of each left side node is connected to OPS node A, and output fiber 1 is connected to OPS node B. Left side nodes are $nNxnN$ broadcast-and-select KEOPS switching architectures [10], able to emulate output buffered operation. In the KEOPS switch, fixed wavelength converters assign packets from different inputs to different wavelengths. The combined optical signal of all input packets is broadcast to M delay lines. At the outputs of those lines, all packets that arrived at the switch in any of the last M time slots are eligible for transmission. The packet delivered to each output port is selected by two sets of optical gates. The first set selects a particular delay-line, and thus the time the packet entered the switch. The second set of optical gates selects packet wavelength, and thus the packet input port. The SCWP scheduling algorithm performs these selections.

To measure the imbalance in resources usage in point (Y), the *basic SCWP scheduler* proposed in [5] was applied to the KEOPS switches. We estimated the wavelength selection probabilities by means of simulation (Batch Means method [11], 99% confidence intervals, 1% tolerance, upper limit $5 \cdot 10^{10}$ packets), under uniform Bernoulli input traffic with average load ρ and for $N \in \{2,4,8\}$, $n \in \{2,4,8,16,32,64\}$. A maximum number of 8 input/output fibers suffices to evaluate backbone WDM network topologies, where each node is usually connected to less than 5 neighbors. Delay depth in the switch was set large enough to avoid packet losses for all (ρ, N, n) tuples. As a measure of wavelength selection unbalance, figure 3 plots the ratio between the highest utilization (corresponding to λ_0), and the lowest utilization (corresponding to λ_{n-1}), for every (ρ, N, n) tuple. It can be observed that the unbalance effect is stronger in low and medium loads, and grows with n. Also, the results show a slight improvement in selection uniformity for higher values of N. Note that the values can become extremely high for usual network loads (i.e., $\rho=0.5$).

The first impairment detected due to the unbalanced wavelength selection is related to the hardware of KEOPS switch architectures, but it is also present to some extent in other OPS switching fabrics. The problem arises because in Semiconductor Optical Amplifier (SOA)-based OPS architectures like the KEOPS switch, unbalanced wavelength selection leads to unbalanced power dissipation. If wavelength selection is non-uniform, ON-state probability will be higher in SOAs corresponding to the most frequently demanded output wavelengths (in the space switching stage, and in the fixed wavelength converters at the outputs). SOAs in ON state are driven with high injection currents to amplify the optical input signals, and dissipate more power, whereas SOAs in OFF state -driven by low injection currents- block optical input signals. Thus, on average, some modules will dissipate more heat than others. For quasi-uniform input traffic patterns, a robust design should enforce similarly distributed injection current rates in all devices. The results in Figure 3 reveal that this would not be the case for medium and low input loads.

If we ignore these facts, it can be argued that the non-uniform wavelength distribution issue may not be critical, since it does not affect either packet loss or packet delay in the output-buffered switch. This is due to the non-blocking switching stage that is present at the input of these architectures, making *input* wavelength distribution irrelevant to the assignment of delays and output wavelengths. Examples of switching architectures with this property are the monoplane WASPNET switch [4] and the OPS switching fabrics capable of output-buffered operation (such as the KEOPS switch in Figure 2), the space switch, or the Output-Buffered Wavelength-Routed switch (see [5] for details).

Nevertheless, we have also identified a severe performance degradation in other OPS switching architectures, where a non-uniform wavelength distribution in input traffic (like the one caused by the WASPNET sequence criterion) implies higher packet delays. The sensitivity to input wavelength distribution is related to the lack of a non-blocking switching module at the input stage of these architectures. The right side nodes in figure 2 represent two architectures where we have observed this performance degradation: the Input-Buffered Wavelength-Routed switch [12], and the multiplane WASPNET switch [4].

A. ***Input-Buffered Wavelength-Routed* switch:** Node A in Figure 2 has an *Input-Buffered Wavelength-Routed* (IB-WR) switch architecture, first introduced in [12]. It consists of a buffering section connected to a non-blocking switching section. The buffering section has $n \cdot N$ Tunable Wavelength Converters (TWC) with a tuning range of $\lambda_0 \ldots \lambda_{K-1}$, $K = max\ (n \cdot N, M)$ (1) and two KxK Arrayed-Waveguide-Gratings (AWG) [13] (2) interconnected by M delay lines of lengths 0 to $M-1$ slots (3). The routing properties of AWG devices [13], make that packets from input port i, after going through the two consecutive AWGs, leave the buffering section at the i-th output port. This occurs independently from the wavelength conversion applied. Wavelength conversion is then employed to determine the delay line the packet will go through. The switching section is composed of a set of $n \cdot N$ TWCs, followed by a $nNxnN$ AWG which routes the packet to the appropriate output port. The major benefits of the IB-WR architecture, when compared to other switching architectures, are its lower cost and a more scalable hardware. The application of the SCWP operation mode to this architecture was presented in [6]. It exhibits quasi-optimum switch performance (compared to output buffered OPS architectures). These good results confer the IB-WR architecture a prominent position in the OPS switching fabrics field.

In an IB-WR switch, the decision on packet delay is constrained by two conditions: 1) At most n packets can be scheduled to leave the switch in the same output fiber and time slot (output fiber contention), 2) two packets from the same input port can not be scheduled to leave the switch in the same time slot (input port contention). Input port contention exists because two simultaneous packets leaving the buffering section through the same port, would collide in the TWC in the switching section, which can only operate with one packet at a time. Therefore, the set of eligible delays for each input packet is the intersection of the sets of allowed delays according to input port contention and allowed delays according to output fiber contention. As a consequence, the distribution of input packets wavelengths may influence switch performance. Many packets arriving in lower-wavelengths input ports find more delays unavailable because of input contention, and thus suffer higher delays. Of course, the impact on performance may depend on the scheduling algorithm applied. In our tests (section 5), we choose the sequential algorithm proposed in [6] for the SCWP operational mode.

B. ***Multiplane switching architectures*****:** Multiplane OPS switching fabrics are composed of *n* identical switching planes, one for each input wavelength. Switching planes can be based on any OPS *NxN* switch fabric, *N* being the number of input/output fibers. In these architectures, arriving packets are distributed among the switching planes by passive wavelength demultiplexers. Then, the unbalanced distribution of input traffic makes lower-wavelength planes receive a higher average load than higher-wavelength ones.

One multiplane architecture proposed in the open literature is the multiplane WASPNET switch [4][9], depicted in node B of Figure 2. In our trials we have evaluated the consequences of unbalanced wavelength usage in this fabric. Each plane of the architecture basically consists of a WASPNET feed-back switch, composed of a *2Nx2N* AWG device, *4N* Tunable Wavelength Converters, and an optical gates-based *NxN* space switch module. Arriving packets suffer a wavelength conversion that determines if they will leave the switch in the current time slot or suffer further delay. The constraints for the delay and wavelength scheduler due to the multiplane structure are: (1) No more than n packets can simultaneously leave the switch via the same output fiber, (2) no more than N packets can leave a switching plane each time slot. At the outputs, the space switch allows a plane to even transmit all N packets (in different wavelengths) through the same output fiber. The scheduling algorithm in our tests (section 5) is the one proposed in [9].

3. Round-robin sequencing criterion

This section describes the round-robin sequencing criterion proposed in this paper. Its main properties are:

- It does not require sequence information in the packet header.
- It guarantees a uniform wavelength utilization in all the fibers of the network, for any traffic pattern.

Let p_i and p_{i+1} be ordered and consecutive packets, transmitted in a WDM link in time slots $t(p_i)$ and $t(p_{i+1})$, and wavelengths $\lambda(p_i)$ and $\lambda(p_{i+1})$, respectively. The round-robin criterion specifies that: 1) $t(p_{i+1}) \geq t(p_i)$, and 2) $\lambda(p_{i+1})=(\lambda(p_i) + 1) \bmod n$, where n is the number of wavelengths in the fiber, and ($a \bmod b$) is the remainder of a/b for any two integers a and b.

The result, as shown in figure 1-b, is an exact round-robin packet spread across the wavelengths, for any traffic pattern in the fiber. If k_i is the total sum of packets transmitted in wavelength λ_i, $i=0,\dots,n-1$ of a fiber along T time slots, it holds that $|k_i-k_j| \in \{0,1\}$, $\forall\ i,j=0,\dots,n-1$, $\forall T>0$. In other words, across any series of time slots, the amount of packets transmitted in any two different wavelengths differs at most by one.

This "uniformity" property, and the performance results observed in the previous section, suggest the adoption of the round-robin sequencing criterion for SCWP OPS networks. Let us now consider the changes in OPS networking this assumption implies. A first consequence is a necessary modification of the SCWP scheduling algorithms of OPS switching architectures, in order to satisfy the new ordering specifications. As can be deduced from figure 1-b, the criterion requires each switching node to "remember" the wavelength of the last packet received/transmitted in the sequence, across different time slots. A trivial implementation of this functionality requires a set of round-robin pointers to track packet sequence:

1) One round robin pointer per input fiber, tracking the wavelength of the next packet in the input traffic sequence. When a new packet appears in this wavelength, the pointer is incremented in a round-robin fashion.
2) One round robin pointer per output fiber, determining the output wavelength of the next packet to be transmitted. When a new packet is transmitted, the pointer is incremented in a round-robin fashion.

This method also requires pointer synchronization during equipment start-up: The pointer of each input fiber of a node should be synchronized with the pointer of the output fiber of the previous node. The implementation of the round-robin criterion is not immediate and must be studied independently for each scheduling algorithm. The next section presents the *uniform SCWP scheduler* for OPS output buffered architectures, which is an adaptation of the *basic SCWP scheduler* to satisfy the new sequencing criterion.

Another relevant concern of accepting the round-robin sequence criterion is related to performance evaluation methodology: The specific characteristics of wavelength distribution should be considered when generating traffic to evaluate the performance of SCWP architectures. Evaluating a SCWP switching architecture assuming independent sources for each input wavelength is not accurate. The (beneficial) correlation of traffics in different wavelengths of the same fiber, imposed by the round-robin distribution, should be considered in the analysis of wavelength-sensitive architectures.

4. Uniform SCWP scheduler

In a previous work [5], the authors proposed the *basic SCWP scheduler* for output buffered OPS switching architectures. This scheduler achieves optimum performance, preserving packet sequence by means of the WASPNET order criterion. Our goal has been to modify the algorithm proposed in [5] to fulfill the new round-robin criterion, while maintaining optimum switch performance. This is accomplished by the algorithm proposed in Figure 4.

Algorithm Description:

- *Input ports scanning*: To maintain packet order, each node requires a round-robin wavelength scanning pointer per input fiber (λ_{in} $[f_{in}]$) that tracks packet sequence. To fairly consider all traffic sources (i.e. all input fibers), the algorithm rotates the index of the first input fiber checked each time slot (`f`$_0$).
- *Delay and output wavelength assignment:* Variable `delay[f`$_{out}$`]` tracks what we call *active delay for output fiber* f_{out}: The delay that is currently being assigned to packets destined to f_{out}. Variable `lastDelayOccup` stores the number of packets being assigned the active delay. Optimum performance is achieved since *i*) any packet gets the shortest delay available (active delay, line 7), *ii*) when n_{out} packets

are assigned, the algorithm uses the next delay (lines 9-11), *iii*) as a consequence, a packet destined to output fiber f_{out} is lost (line 6) only when all M delays for that output fiber have n_{out} packets. The algorithm satisfies the sequence criterion, as consecutive packets transmitted in output fiber f_0 get output wavelengths (lines 13-14) from the round-robin pointer $\lambda_{\mathtt{out}}$`[`$\mathtt{f}_{\mathtt{out}}$`]`.

5. Evaluation results

To estimate the performance improvement obtained from the application of the round-robin sequence criterion, we compare the average delay of IB-WR and multiplane switch fabrics, in two scenarios:

A. Applying the WASPNET sequencing criterion to the network. This implies the implementation of the basic SCWP scheduler in the KEOPS switches in the left side of figure 2, leading to an unbalanced wavelength distribution of input traffic in nodes A and B.
B. Applying the round-robin sequencing criterion proposed in section 3. This implies the implementation of the *uniform SCWP scheduler* in the KEOPS switches, as proposed in section 4. As shown below, the uniform SCWP scheduler provides optimum performance to output buffered OPS architectures, preserving packet sequence according to the new round-robin criterion. Under this criterion, the wavelength utilization in all fibers in the OPS network is exactly the same for any traffic pattern.

Let $D^{nw}(n,N)$, $D^{uw}(n,N)$, be the packet delay (packet slots) in a node A or B, receiving traffic from sources with a non-uniform or uniform wavelength distribution, respectively. Let $L(n,N)=D^{nw}(n,N)/D^{uw}(n,N)$, be the *relative* increase in packet delay in a node A or B (i.e. taking the uniform wavelength distribution as a reference). Figures 5-a and 5-b show $log_2\ L(n,N)$ for input loads of 50% and 80% in an IB-WR architecture, and Figures 5-c and 5-d depict $log_2\ L(n,N)$ for the same input loads in a WASPNET multiplane architecure. Note that $L(n,N)>1.0\ \forall n,N$. The values of $L(n,N)$ may be as bad as $L(32,8)= 8\cdot 10^3$ for $\rho=50\%$ in node A, $L(64,2)= 21.14$ for $\rho=80\%$ in node A, $L(32,4)= 1.8\cdot 10^3$ for $\rho=50\%$ in node B and $L(64,2)= 381.42$ for $\rho=80\%$ in node B. These results reveal a high impact of non-uniform input wavelengths distribution in architectures without a non-blocking switching module at the input stage.

6. Conclusions

This paper shows the performance impairments resulting from the application of the WASPNET sequence criterion to a SCWP OPS network. These degradations are due to imbalanced wavelength usage, an intrinsic consequence of the aforementioned criterion. To avoid them, we propose a *round-robin sequence criterion*. The new sequencing technique preserves end-to-end packet sequence without requiring a specialized sequence field in packet headers, and guarantees uniform wavelength usage in every fiber in the network, under any traffic pattern. This paper proposes a *uniform SCWP scheduler* for OPS output-buffered architectures. The new algorithm achieves optimum performance, preserving packet sequence according to the proposed round-robin sequence criterion.

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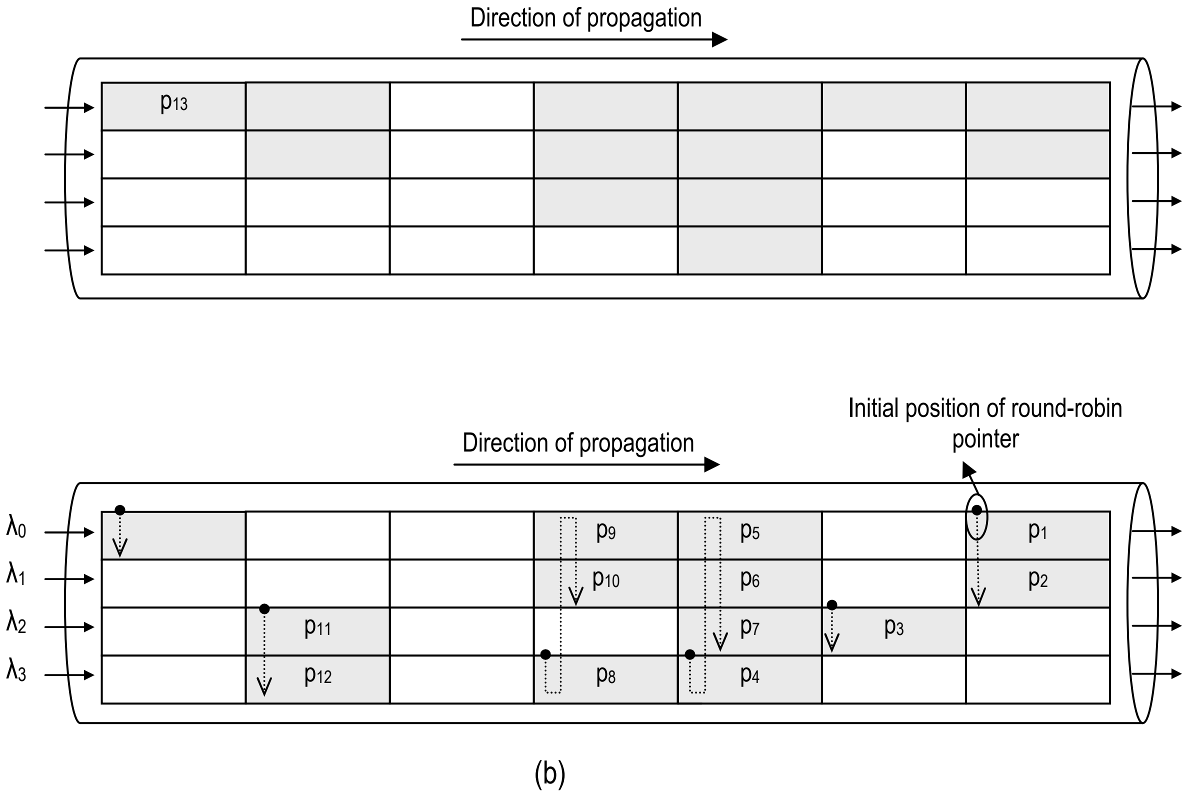

Figure 1. Comparison of wavelength distribution in a fiber (*4* wavelengths, $\lambda_0,\ldots,\lambda_3$).
(a) WASPNET sequence criterion, (b) round-robin sequence criterion

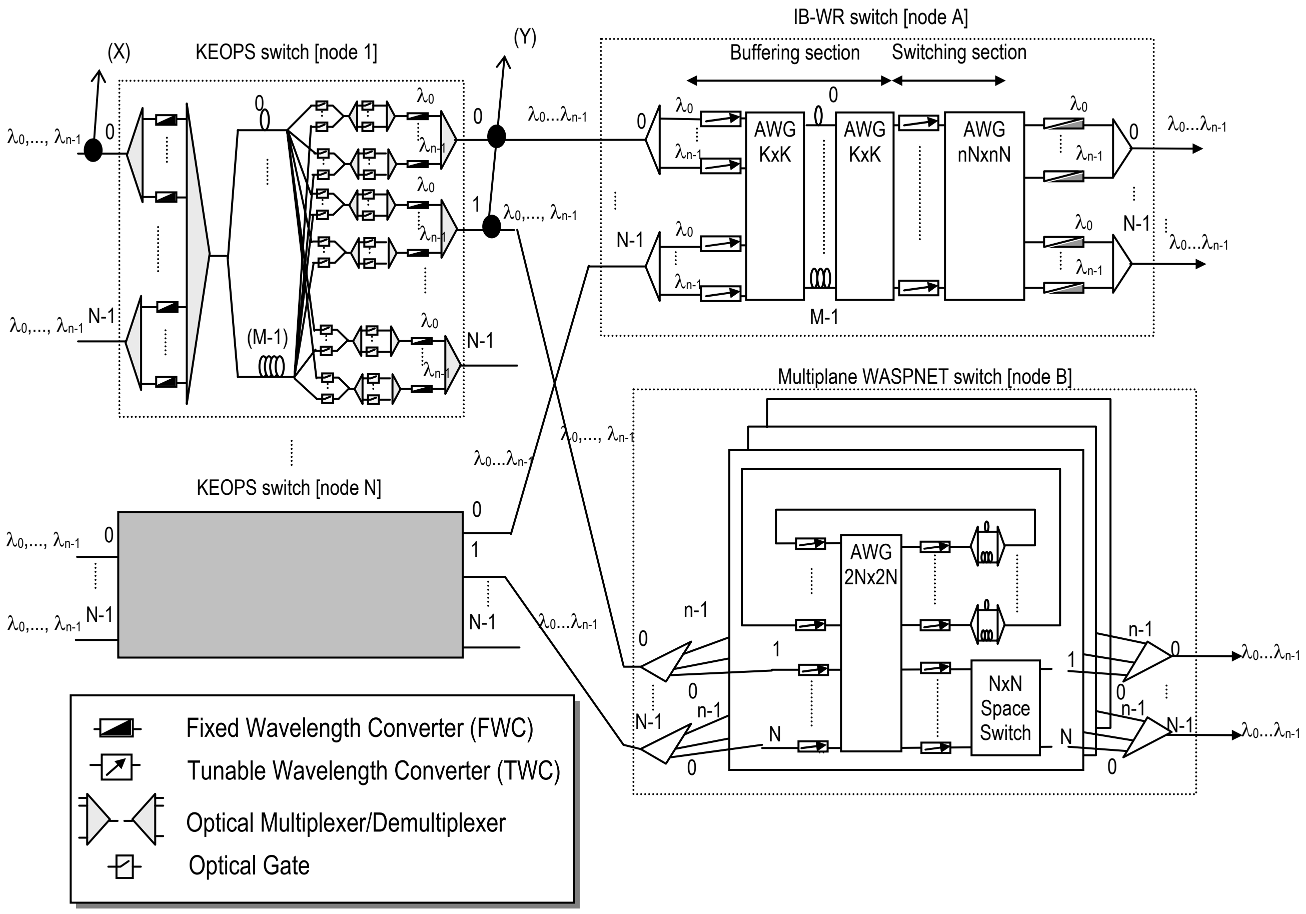

Figure 2. Diagram of the OPS SCWP network evaluated

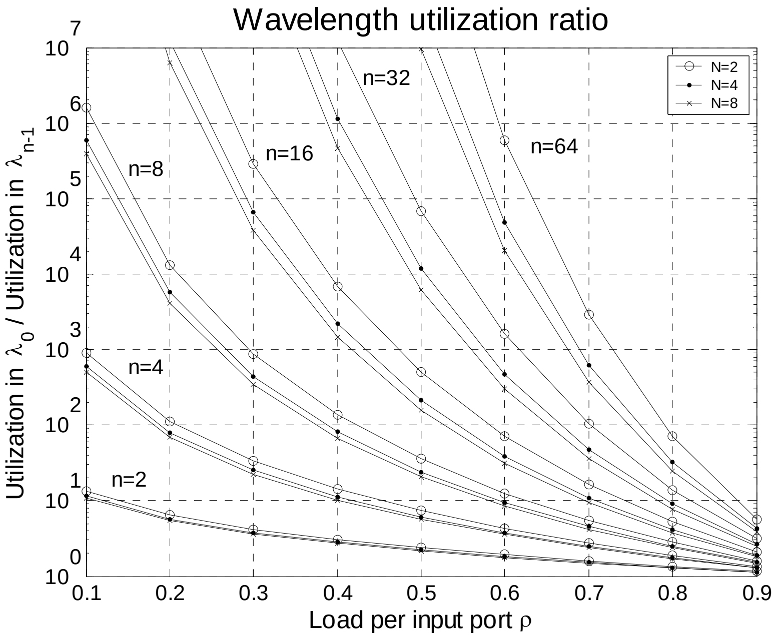

Figure 3. Wavelength utilization ratio: utilization (λ_0) / utilization (λ_{n-1}), in the output fibers of an output buffered OPS switch, in a network designed to follow the WASPNET sequencing criterion. $N=\{2,4,8\}$, $n=\{2, 4, 8, 16, 32, 64\}$, $\rho=\{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$, $M=\infty$

Uniform SCWP scheduler

```
for fiberCounter = 0 to $N$-1 do
  $f_{in}$ = ($f_0$ + fiberCounter) mod $N$
  for wavCounter = 0 to $n$-1 do
    if (packet p in input ($f_{in}$ , $\lambda_{in}$ [$f_{in}$]) then
      $f_{out}$ = output fiber p ( = opp (p) )
      if (delay [$f_{out}$] < $M$) then
        associate delay [$f_{out}$] to packet p
        lastDelayOccup [$f_{out}$] ++
        if (lastDelayOccup [$f_{out}$] == $n$) then
          lastDelayOccup [$f_{out}$] = 0
          delay [$f_{out}$] ++
        endif
        associate $\lambda_{out}$ [$f_{out}$] to packet p
        $\lambda_{out}$ [$f_{out}$] = ($\lambda_{out}$ [$f_{out}$] + 1) mod $n$
      endif
      $\lambda_{in}$ [$f_{in}$] = ($\lambda_{in}$ [$f_{in}$] + 1) mod $n$
    else
      /* for each input fiber, wavelength indexes are selected
      until an "empty" wavelength is found, or $n$ wavelengths have
      been selected */
      break;
    end
  endfor
endfor

/* Process performed at the end of every switching slot */
$f_0$ = ($f_0$ + 1) mod $N$  /* to guarantee input scanning fairness */
for $f_{out}$ = 0 to $N$-1 do
  if (delay [$f_{out}$] == 0)
    lastDelayOccup [$f_{out}$] = 0;
  else
    delay [$f_{out}$] --;
  endif
endfor
```

Figure 4. *Uniform SCWP scheduler* for output-buffered SCWP OPS switching architectures

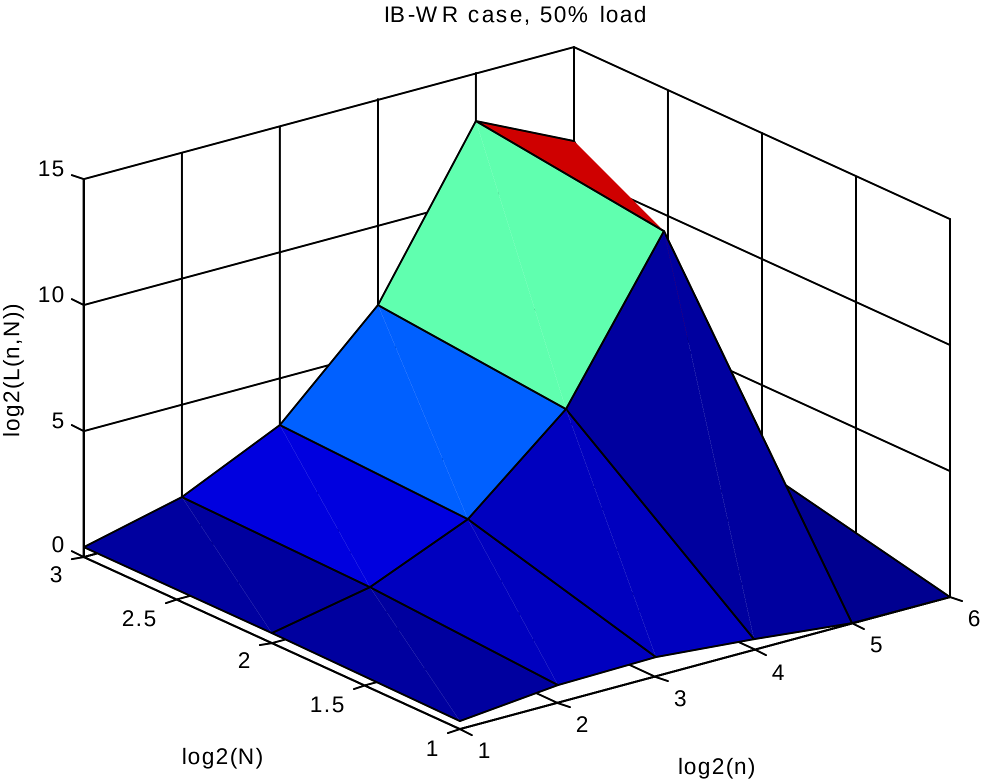

Figure 5-a. *log₂(L(n,N))*, *ρ=50%*, node A (IB-WR switch)

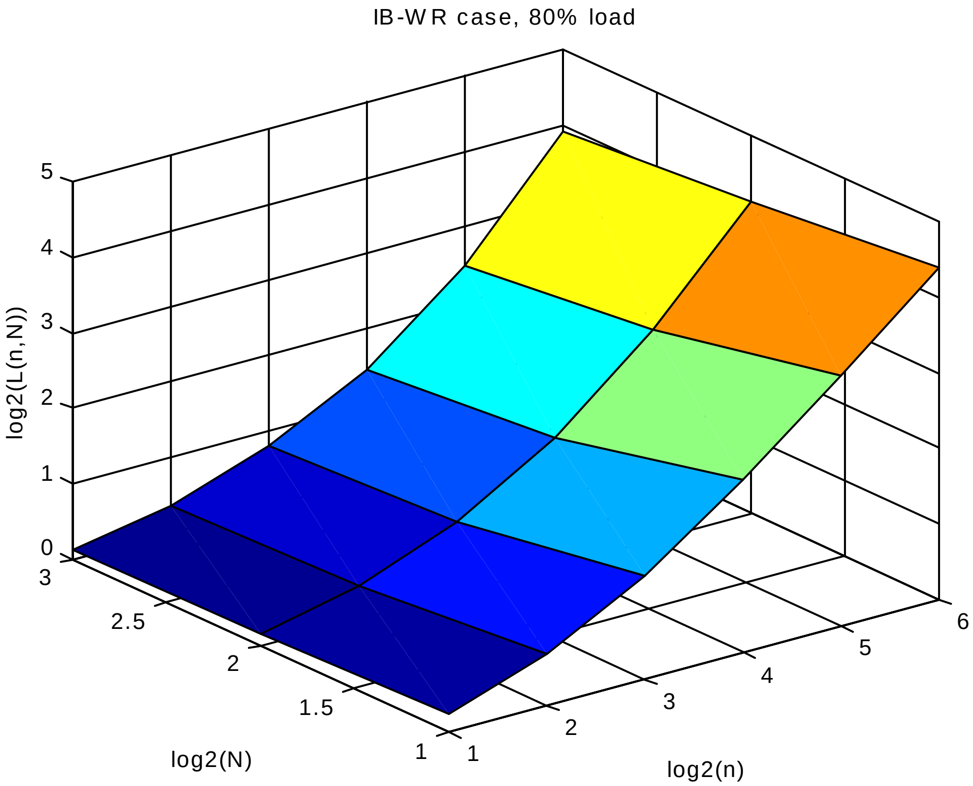

Figure 5-b. *log*$_2$*(L(n,N))*, $\rho=80\%$, node A (IB-WR switch)

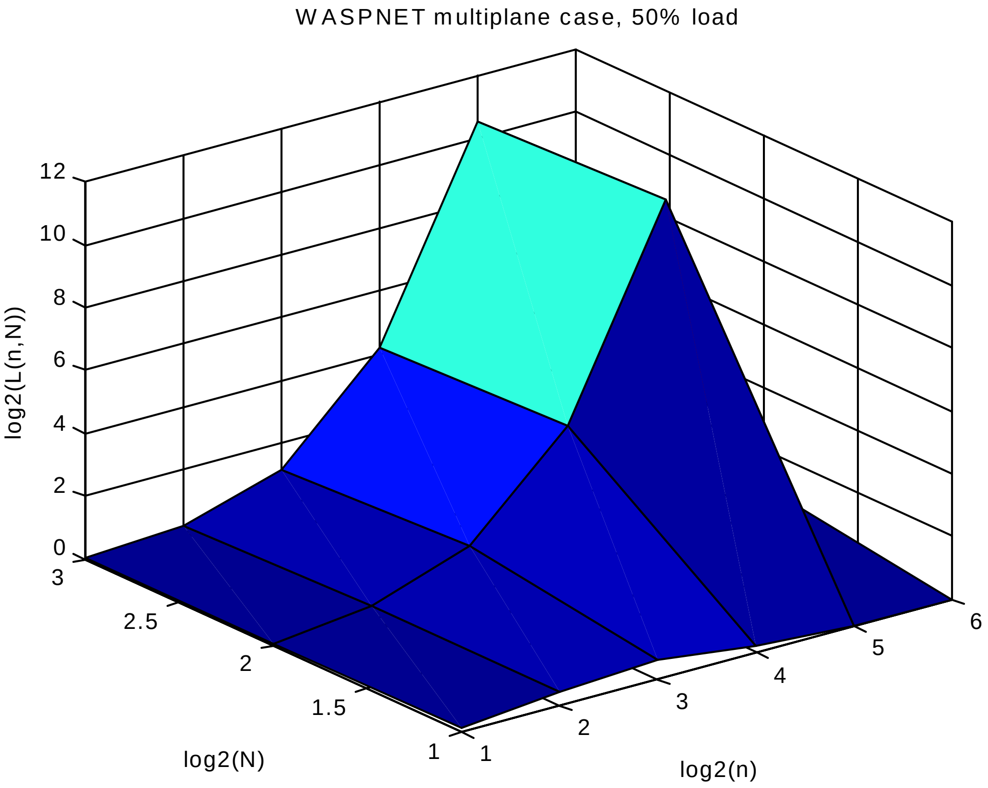

Figure 5-c. *$log_2(L(n,N))$*, *$\rho=50\%$*, node B (WASPNET multiplane switch)

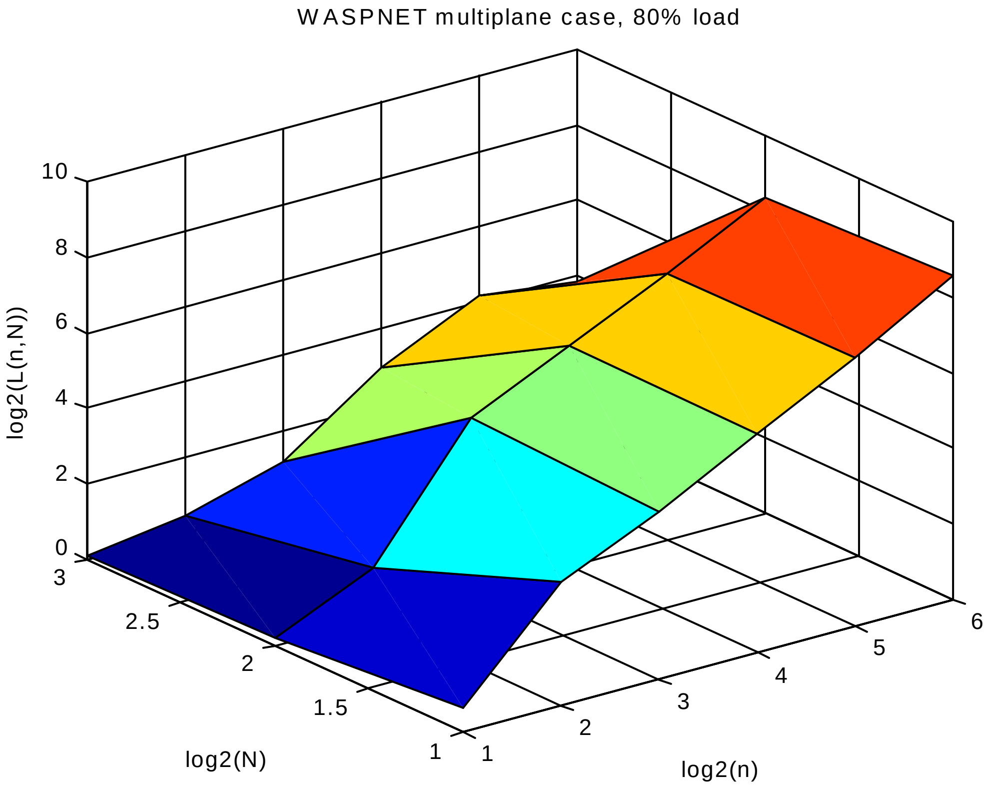

Figure 5-d. *$log_2(L(n,N))$*, *$\rho=80\%$*, node B (WASPNET multiplane switch)