Deflection Routing and Wavelength Conversion in Asynchronous Optical Packet Networks

Raul C. Almeida Jr., Jefferson U. Pelegrini and Helio Waldman

***Resumo*— Este artigo analisa comutadores ópticos assíncronos quando se utiliza resolução de contenção por conversão de comprimento de onda ou roteamento por deflexão. Para ambos mecanismos, propomos modelos analíticos exatos que permitem o cálculo da probabilidade de bloqueio de pacotes, mesmo quando tais mecanismos são usados conjuntamente. Além disso, um modelo analítico aproximado baseado na granularidade infinitamente fina dos canais de entrada é proposto para comutadores sem mecanismos de resolução de contenção ou equipados apenas com conversão de comprimento de onda.**

***Palavras-Chave*— Comutação óptica de pacotes, resolução de contenção, conversão de comprimento de onda, roteamento por deflexão, Modelos de Markov.**

***Abstract*— This paper analyzes asynchronous optical packet switches when wavelength conversion and deflection routing capabilities are used as contention resolution mechanisms. For both mechanisms, we propose exact analytical models that enable the calculation of packet blocking probability, even when they are considered in combination. In addition, a very simple approximated analytical model based on infinitely fine input granularity is proposed for switches without any contention resolution mechanism or equipped only with wavelength conversion.**

***Keywords*— Optical packet switching, contention resolution, wavelength conversion, deflection routing, Markov modeling.**

I. INTRODUCTION

In a WDM optical packet switching network, data packets are modulated on a specific wavelength and may travel several hops before reaching their destinations. In each hop, a switching node is used to direct the packet to the correct output fiber link. Output contention occurs when arriving packets on the same wavelength and overlapped in time are designed to be at the same output port. In optical packet switching, there are three ways to handle output contention: buffering, deflection routing and wavelength conversion. These techniques exploit respectively the time, space and wavelength domains [1], [2].

Buffering in optics cannot be implemented in the same way as with electronic memories. The most convenient optical functionality that resembles buffering results from the use of delay line arrays that provide, for each packet, a delay from a discrete, normally small, set of delays. Such optical delay line banks are called optical delay line buffers or, for short, optical buffers [3]–[7]. This type of buffer is usually small, being limited by the number and length of the delay lines.

The authors are with Optical Networking Laboratory (OptiNet) DECOM/FEEC/UNICAMP. Caixa Postal 6101, 13083-852, Campinas, SP, BRAZIL. URL: http://www.optinet.fee.unicamp.br. E-mails: {rcamelo, jpelegri and waldman}@decom.fee.unicamp.br. This work was supported by Ericsson Telecomunicações do Brasil, CAPES and CNPq.

Deflection routing aims at trying to send packets that are contending for the same output to some other output link(s). By doing so, the packet dropping is reduced, although deflected packets may end up following a longer path to its destination. Deflection routing is an interesting contention resolution mechanism as it does not require great efforts to be implemented neither in terms of hardware components, nor in terms of control complexity [8]–[10].

The wavelength domain exploitation is also a potential method in reducing external blocking, which is based on the fact that several wavelengths run on the same fiber link that connects two optical switches. Therefore, on the arrival of a new packet, if its wavelength is already being used on the destination output link, it may be converted to other potential free wavelength, such that it can still be transmitted [11]–[13].

Notice that these techniques can be perfectly combined by using the necessary components and control requirements for each of them [9]–[11]. In the literature, the existent works that focus on studying and modeling these contending methods are usually based on synchronous networks. In optical domain, however, maintaining synchronization is not a simple task, since signal processing at bit level is not readily available. Additionally, assuming an Internet environment, fixed-length packets imply the need to segment IP datagrams at the edge of the network and reassemble them at the other edge, which can be a problem at very high speeds. For these reasons, it is worth investigating switch block performance in the case where variable-length packets are routed without alignment (asynchronously).

In this paper we examine the space and wavelength domains and propose exact analytical models that are able to evaluate the external packet blocking probability of asynchronous optical packet switches under uniform and memoryless traffic. The models enable us to evaluate the impact on the performance of optical switches using wavelength conversion and deflection routing, even when they are considered in combination. In addition, we propose bounds that may be very useful for studying such switches under generic traffic and wavelength conversion capability. Analytical models are very useful mainly for low packet blocking probability, where simulations become time expensive.

The paper is structured as follows: Section II describes the general considerations used in our analyzes and the traffic definition for the switch modeling. In Section III we deal with the optical packet switch without any contention resolution capability and introduce a Markovian model that will be useful when wavelength conversion and/or deflection routing are considered. Section IV exploits the wavelength conversion capability and, in Section V, we present and infinitely fine granularity bound for the situations specified in sections III and IV. Deflection routing is handled in Section VI and, finally, we make our conclusions in Section VII.

II. General Considerations

Figure 1 shows a space switch fabric architecture, analyzed in [12], that will be reported for a better understanding of our analysis. The switch consists of N incoming and N outgoing fiber links, with W wavelengths running on each fiber link. Thus, there are a total of NW input and output wavelength channels. The switch is able to implement any of the contention methods. For example, in the packet encoder part, after the demultiplexers there are tunable wavelength converters (TWC) that may convert wavelengths and then exploit the wavelength domain. The space switch part may choose to send the packet for the output fiber that is the first option in the routing table or send it to some other outputs and then perform deflection routing. Finally, the packet buffer portion shows a dedicated output buffer, composed by B fiber delay lines (FDL), that may deal with the time domain contention option, which will not be considered in this paper. Some analytical buffer models for asynchronous optical networks have been proposed in [5]–[7].

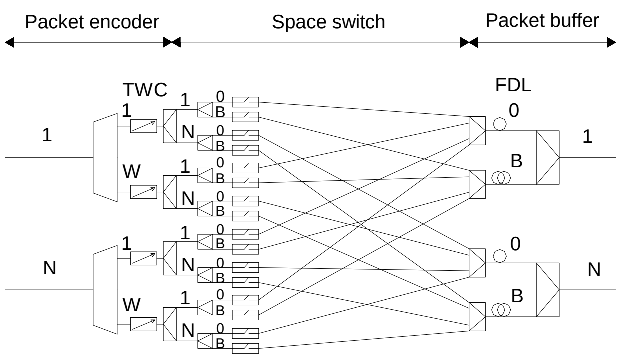

Fig. 1. An architecture with a space switch fabric.

As arriving traffic to the switch, it will be assumed that the input channels are independent of each other and that each of them has the same input load. The traffic partitioning inside the switch will be considered uniform, i.e., a packet arriving in any input fiber has the same probability of being transmitted to any output, which can be written as $p_{i,j} = 1/N$, i, $j = 1, 2, ..., N$. In addition, when deflection routing is considered, it will be assumed that apart from the first output link option in the routing table, D other output links may be assigned in a priority based way. Here, we assume that such alternate links are randomly chosen.

For the purpose of building an exact, analytical model for the blocking performance of the switch, it is usually useful to consider a memoryless model for the arrival and service of packets on each independent input. Each input may be in two states:

a) Active state, during which a packet is present in the input channel under consideration. During the active state, the rate of arrivals of new packets in such input channel is of course zero;
b) Waiting state, during which the input channel under consideration is idle. Under the waiting state, we shall assume that the next arrival may occur in any small interval dt with probability λdt, where λ is a stationary arrival rate.

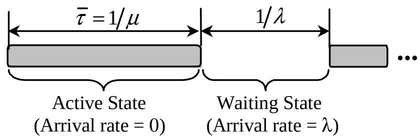

Fig. 2. Active state and waiting state representation for determination of λ.

The interval between two successive arrivals is the sum of two components: service of the last arrived packet, with average duration $\overline{\tau}$ (death rate μ); and wait for the next packet, with average duration $1/\lambda$, as shown in Figure 2. Therefore, the input load, which is identified as the fraction of time the channel is transferring data, will be given by:

$$\rho = \frac{1/\mu}{1/\lambda + 1/\mu}. \qquad (1)$$

The arrival rate during the waiting state may then be expressed as a function of the load and packet death rate by:

$$\lambda = \frac{\rho\mu}{1-\rho}. \qquad (2)$$

III. Switch Without Contention Resolution Capability

In this Section we will focus on the optical switch without any contention resolution capability. This implies that if two or more packets on the same wavelength contend for the same output fiber (and also channel), just one will be permitted to be transmitted, while the others will be blocked. Since there is no wavelength conversion capability, it is possible to study each wavelength separately and therefore two vectors I and J, which represent respectively which input and output fibers are transmitting a packet, would be sufficient to exactly model the switch: $I = \{i_1, i_2, \ldots, i_N\}$ and $J = \{j_1, j_2, \ldots, j_N\}$, where each element $i_k, j_k = \{0, 1\}$, $k = 1, 2, \ldots, N$ and $\sum_k (i_k - j_k) \geq 0$, as the number of active inputs must be at least equal to the number of packets being transmitted to the outputs. However, even with such simplification, the number of states may still become very large when N increases. As solution, since we assume that each input provides the same load ρ and the traffic partitioning inside the switch is uniform, the model may be severely simplified so that a total of $2N + 1$ states is sufficient to exactly model the switch, as depicted in Figure 3 for $N = 4$.

We define the tuple (i, j) as a state of the switch, where $i = 0, 1, \ldots, N$ represents the amount of inputs that are in active state, while $j = 0, 1$ focus on an arbitrary output and inform if such output is transmitting a packet ($j = 1$) or not ($j = 0$). The transition rates may be obtained in the following way: on the arrival of a packet, it has the probability $1/N$ of being transmitted to the referred output and $1 - 1/N$ to any

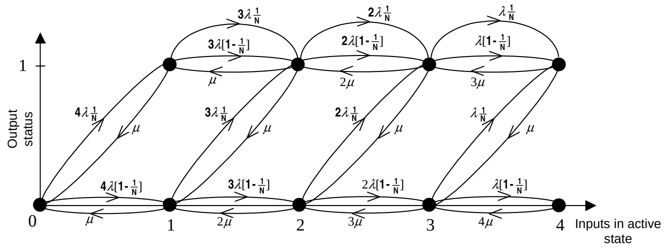

Fig. 3. Transition diagram for $N = 4$.

other. In addition, the total arrival rate given that i inputs are in the active state will be $(N-i)\lambda$. Therefore, if the output is idle ($j = 0$) on the arrival of a packet, the switch will transit from state $(i, 0)$ to state $(i + 1, 1)$ or $(i + 1, 0)$ with transition rates $(N - i)\lambda\frac{1}{N}$ and $(N - i)\lambda[1 - \frac{1}{N}]$, respectively. On the other hand, if $j = 1$, any arriving packet will lead the switch from state $(i, 1)$ to state $(i+1, 1)$ with transition rate $(N-i)\lambda$, which is the contribution of blocked packets rate $(N - i)\lambda\frac{1}{N}$ plus the rate of those packets that are sent to any other output $(N-i)\lambda[1-\frac{1}{N}]$. If we consider the packet deactivation (death), it is easy to see that, if $j = 0$, the switch will transit from state $(i, 0)$ to state $(i - 1, 0)$ with transition rate $i\mu$. Otherwise, if $j = 1$, two kinds of deactivation may occur: a packet that has just been serviced on the referred output, which will make the switch transit to state $(i - 1, 0)$ with transition rate μ; or a packet that does not fit into this case, which will lead the switch to state $(i - 1, 1)$ with transition rate $(i - 1)\mu$.

The steady state probability of any state $Q_{(i,j)}$ may be calculated by numerically solving the stationary equations for the continuous-time Markov process ($\mathbf{QT} = \mathbf{0}$), where $\mathbf{Q}$ is the steady state probability vector and $\mathbf{T}$ is the matrix of transition rates [14]. Finally, the packet blocking probability may be obtained by focusing only on those packets sent to the considered output, being written as:

$$P_B = \frac{\sum_{i=1}^{N-1}(N-i)\lambda\frac{1}{N}Q_{(i,1)}}{\sum_{i=0}^{N-1}(N-i)\lambda\frac{1}{N}Q_{(i,0)} + \sum_{i=1}^{N-1}(N-i)\lambda\frac{1}{N}Q_{(i,1)}} \quad (3)$$

Figure 4 compares the packet blocking probability P_B calculated from our Markovian model with estimates obtained through simulations, for different values of input load ρ and fibers N. As can be seen, the calculations fit the simulations very well, showing the exactness of the model. In addition, it can be seen that: the packet blocking probability increases with N; and even for very low input load ($\rho = 0.1$), the packet blocking probability is still extremely high, thus requiring some contention resolution method to improve the switch performance.

IV. The Wavelength Domain Contention Resolution Capability

In this section we will evaluate the switch performance improvement provided by the use of wavelength converters. We will focus on full range wavelength converters, which can convert a wavelength to any other wavelength in the pool. Again, if the load in the inputs and the traffic distribution inside the switch are non-uniform, the number of states required will be very high and will increase severely with the number of wavelengths. We propose a reduced state model that is able to exactly evaluate the switch when the input load and the traffic distribution inside the switch are uniform. For representing the number of inputs in active state, we chose $i = 0, 1, \ldots, NW$, since that in such context the instantaneous arrival rate of packets will depend on the number of active channels among the NW existents. As before, it is possible to focus on a single output fiber, but now all wavelengths must be taken into account, which implies $j = 0, 1, \ldots, W$.

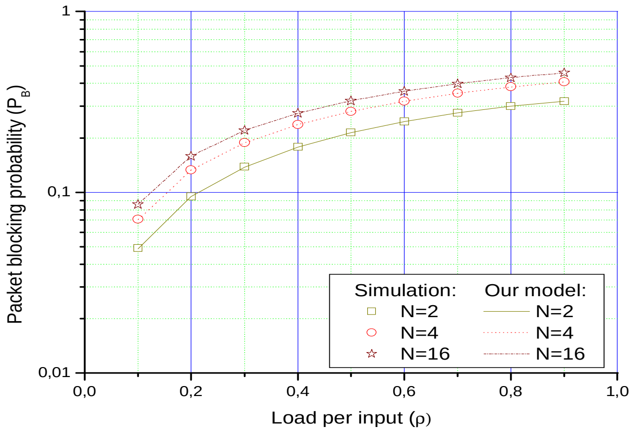

Fig. 4. Packet blocking probability versus load per input ρ for a switch without any contention resolution capability. The packet is assumed exponential and $N = 2, 4, 16$

The transition rates may be obtained as follows: suppose that the switch is at state (i, j). On the arrival of a packet, if the number of occupied channels in the referred output fiber is smaller that W $(j < W)$ and the switch selects such output fiber as forward output, the packet will obviously be transmitted. The switch will then transit to state $(i + 1, j + 1)$ with transition rate $(NW - i)\lambda\frac{1}{N}$. On the other hand, if either $j = W$ or the switch does not select such output fiber as forward output, the switch will transition to state $(i+1, j)$ with transition rates given respectively by $(NW - i)\lambda$ (composed by the sum of blocked packets and packets that are not chosen to be forwarded to that output) and $(NW-i)\lambda[1-\frac{1}{N}]$. Finally, if one of the packets in the referred output is deactivated, the switch will transit to state $(i - 1, j - 1)$ with rate $j\mu$ and if one of the packets that is not being transmitted to the referred output deaths, there will be a transition to state $(i - 1, j)$ with rate $(i - j)\mu$.

In this way, after obtaining the steady-state probabilities $Q_{(i,j)}$ of states (i, j), the packet blocking probability may be obtained as:

$$P_B = \frac{\sum_{i=W}^{NW-1}(NW-i)\lambda\frac{1}{N}Q_{(i,W)}}{\sum_{i=0}^{NW-1}\left[\sum_{j=0}^{min(i,W)} Q_{(i,j)}(NW-i)\lambda\frac{1}{N}\right]}, \quad (4)$$

where $min(x, y)$ is the minimum value between x and y.

Figure 5 compares the packet blocking probability (P_B) versus the load per input (ρ) obtained through our model and simulations. The latter were evaluated until 10^{-6} due to the long time that would be required to obtain reliable results. It can be seen that the model is also exact and that for low to moderate input loads the switch performance is sensitively improved as the number of wavelengths increases. However, above moderate values of input load $(\rho > 0.5)$, another contention resolution method shall probably be necessary to be used (alone or together with wavelength conversion) in order to improve the switch performance.

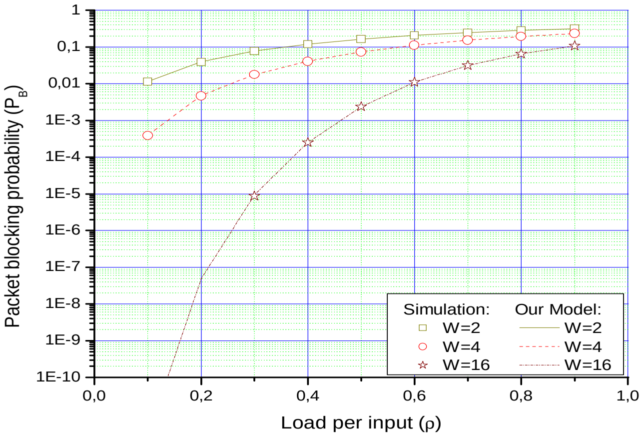

Fig. 5. Packet blocking probability versus load per input ρ for a switch with wavelength conversion contention resolution capability. The packet is exponentially distributed, $N = 4$ and $W = 2, 4, 16$

V. An Infinitely Fine Granularity Bound

In this Section we will present an upper bound on the blocking probability of the switch when the number of input channels is taken to infinity. The bound is based on the fact that, when the number of inputs is made large enough and they are independent, the arrivals tend to be Poissonian. Consequently, the Erlang's first formula (shown in Appendix I) may be used to evaluate the packet blocking probability of the switch.

When there is no wavelength conversion capability, the packet blocking probability will be given by Erlang's loss formula making $c = 1$ and $\lambda'/\mu' = \sum_{n=1}^{N} \rho \frac{1}{N} = \rho$.

Figure 6 shows the packet blocking probability for the switch without wavelength conversion when the packet length distribution is Pareto $(\alpha = 1.5)$ and $N = 2, 4, 16$. As can be seen, the simulations approximate the infinitely fine granularity bound (IFG) quite well when the number of input fibers exceeds ten.

TABLE I

Pareto distribution: $p_\tau(\tau) = \frac{\alpha t_{min}^{\alpha}}{\tau^{\alpha+1}} u(\tau - \tau_{min})$,

where $u(\cdot)$ is the unit step function and $\tau_{min} = \frac{\alpha-1}{\alpha}\bar{\tau}$, for $\alpha > 1$.

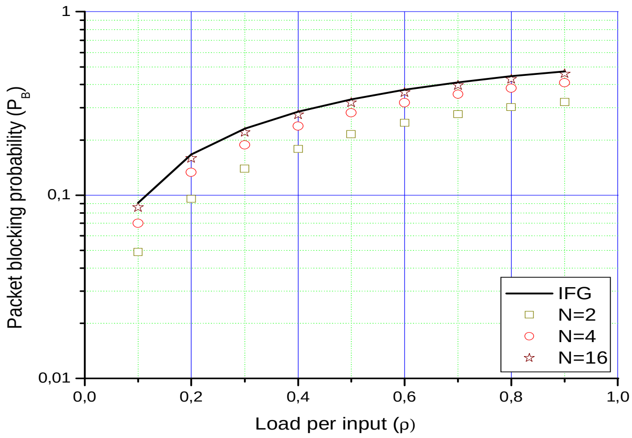

Fig. 6. Packet blocking probability versus load per input ρ for a switch without wavelength conversion. The packet length is Pareto$(\alpha = 1.5)$ and $N = 2, 4, 16$.

On the other hand, if wavelength conversion is available, the packet blocking probability will be given by the same expression, but with $c = W$ and $\lambda'/\mu' = \sum_{n=1}^{N} \sum_{w=1}^{W} \rho \frac{1}{N} = \rho W$. In Figure 7 we fixed $N = 4$ and made $W = 2, 4, 16$. The simulations approximate the infinitely fine granularity bound (IFG) satisfactorily. However, depending on the number of wavelengths and input load, the approximations may be a little bit scant.

It is interesting to notice that the IFG bound is valid for any packet length distribution for the switch with or without wavelength conversion.

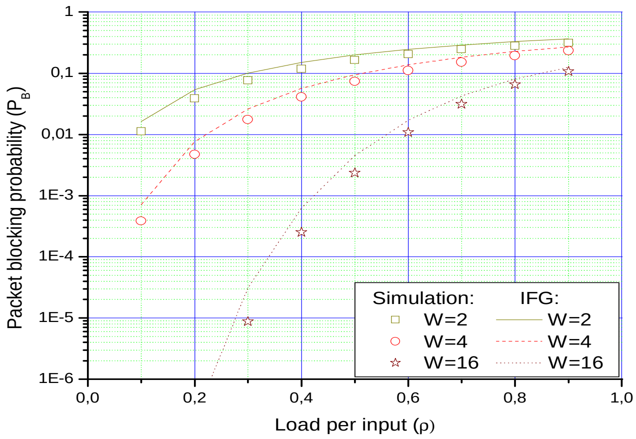

Fig. 7. Packet blocking probability versus load per input ρ for a switch with full wavelength conversion. The packet length is Pareto$(\alpha = 1.5)$, $N = 4$ and $W = 2, 4, 16$.

VI. The Deflection Routing Contention Resolution Capability

In this section, we will study the switch performance under deflection routing contention resolution capability. First, we will analyze it when the switch does not have wavelength conversion capability, in order to evaluate its individual influence on the switch performance. After that, the switch performance under deflection routing coupled with wavelength conversion capability will be studied and analyzed.

The basic principle of deflection routing is to assign more than one output link to incoming packets in a priority based way. Thereby, eventual contentions can be resolved by deflecting some of the contending packets to eventual free links. In our analyzes, it will be assumed that apart from the output link as the first option in the routing table, D other output links may be assigned in a priority based way. Such assignment will depend on the routing algorithm used by the optical switch. Here we assume that the output links will be randomly defined for each contending packet.

If we do not consider wavelength conversion, we may again focus on a single wavelength and then represent the switch states as (i, j), $0 \leq i \leq N$, $j \leq i$, where i and j represent, respectively, the number of input and output fibers that are transmitting a packet on the referred wavelength. On the arrival of a packet, if $j \leq D$, the switch will certainly transit to state $(i+1, j+1)$ with transition rate $(N-i)\lambda$, as D output fibers may be chosen as deflected output. On the other hand, if $j > D$, the probability that a packet is not accepted is given by the probability that all $D+1$ possible output fibers for the packet are blocked, which is given by $\prod_{d=0}^{D}\left(\frac{j-d}{N-d}\right)$. This implies that, if $j > D$, the switch will transit either to states $(i+1, j)$ and $(i+1, j+1)$ with transition rates $(N-i)\lambda\prod_{d=0}^{D}\left(\frac{j-d}{N-d}\right)$ and $(N-i)\lambda\left[1-\prod_{d=0}^{D}\left(\frac{j-d}{N-d}\right)\right]$, respectively. When we assume the packet deactivation, the switch will transit to states $(i-1, j-1)$ and $(i-1, j)$ with transition rates given respectively by $j\mu$ and $(i-j)\mu$.

Such equations permit that the matrix of transition rates $\mathbf{T}$ may be obtained and thereby the steady-state probabilities $Q_{(i,j)}$ of the switch states (i, j). The packet blocking probability may be written as:

$$P_B = \frac{\sum_{i=D+1}^{N-1}\sum_{j=D+1}^{i} Q_{(i,j)}\mathbf{T}_{(i,j),(i+1,j)}}{\sum_{i=0}^{N-1}\sum_{j=0}^{i} Q_{(i,j)}\left[\mathbf{T}_{(i,j),(i+1,j+1)}+\mathbf{T}_{(i,j),(i+1,j)}\right]}, \quad (5)$$

where $\mathbf{T}_{(a,b),(c,d)}$ represents the transition rates from state (a, b) to state (c, d).

Figure 8 shows the packet blocking probability versus the load per input ρ when only deflection routing is considered in a switch with $N = 8$ and $D = 1, 2, 4$. In the same way as with wavelength conversion, the performance gain is as high as lower is the input load. In addition, differently from wavelength conversion, the number of possible deflections is limited to the number of inputs N, the network topology, the routing algorithm, maximum end-to-end delay, etc.

In order to obtain better performance, we will consider deflection routing together with wavelength conversion: a packet coming from an input fiber at a specific wavelength can be switched to any of $D+1$ selected output fibers on any wavelength. We propose an analytical model where the states will be represented by $(i; j_1, j_2, \ldots, j_N)$, where $0 \leq i \leq NW$ represents the amount of input channels that are transmitting a packet and $0 \leq j_n \leq W$ represents the amount of packets

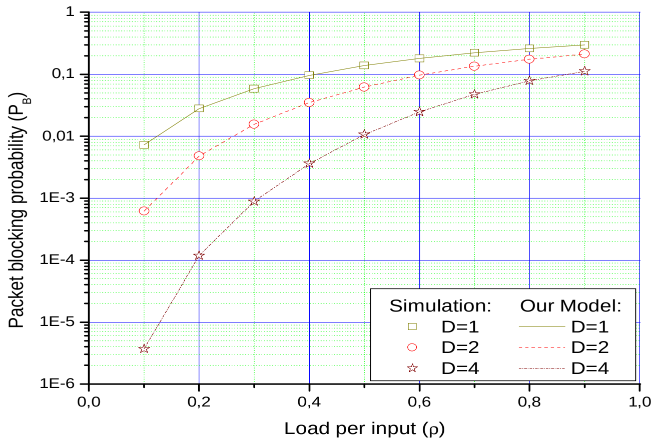

Fig. 8. Packet blocking probability versus load per input ρ for a switch with deflection routing contention resolution capability. The packet is exponentially distributed, $N = 8$ and $D = 1, 2, 4$

that are being transmitted at output fiber $1 \leq n \leq N$. Since we assume that the traffic is uniformly distributed among the output fibers, in order to reduce the number of states, it is possible to consider $j_1 \leq j_2 \leq \ldots \leq j_N$. Let F be the number of fibers that are transmitting W packets, i.e., that do not have any free (available) channel and let $(i; j_1, j_2, \ldots, j_N)$ be the current state of the switch. As i input channels are in active state, the packet arrival rate to the switch will be given by $(NW-i)\lambda$. If $F \leq D$, any arriving packet will certainly be accepted in one of the $N-F$ available fibers. Thereby, $\forall\ n \mid j_n < W$, the switch will then transit to state $(i+1; sort\{j_1, j_2, \ldots, j_n+1, \ldots, j_N\})$ with transition rate given by $(NW-i)\lambda/(N-F)$, where $sort$ is the required non-decreasing sort function applied to the output vector, in order to follow our proposed state reduction criterion. If $F > D$, the packet may be blocked or not. It will be blocked if all $D+1$ randomly selected output fibers are not available, which happens with probability $\prod_{d=0}^{D}\left(\frac{F-d}{N-d}\right)$. In this way, the switch will transit either to states $(i+1; j_1, j_2, \ldots, j_N)$ and $(i+1; sort\{j_1, j_2, \ldots, j_n+1, \ldots, j_N\})$ with transition rates $(NW-i)\lambda\prod_{d=0}^{D}\left(\frac{F-d}{N-d}\right)$ and $(NW-i)\lambda\left[1-\prod_{d=0}^{D}\left(\frac{F-d}{N-d}\right)\right]/(N-F)$, respectively. After finding the steady state probabilities, the packet blocking probability will be given by:

$$P_B = \frac{\sum_{i=0}^{NW-1} Q_{(i;\vec{j})}\mathbf{T}_{(i;\vec{j})(i+1;\vec{j})}}{\sum_{i=0}^{NW-1} Q_{(i;\vec{j})}\left[\mathbf{T}_{(i;\vec{j})(i+1;\vec{j})}+\sum_{n=1}^{N}\mathbf{T}_{(i;\vec{j})(i+1;sort\{\vec{j}+\vec{l}_n\})}\right]}, \quad (6)$$

where $\vec{j}$ is the output state vector $(j_1, j_2, \ldots, j_N)$ and $\vec{l}_n$ is the vector $(0, 0, \ldots, 1, \ldots, 0)$ with a 1 in the n-th position.

Figure 9 shows the packet blocking probability versus the load per input (ρ) for $N = 4$ and the possible combinations among $D = 0, 1, 2$ and $W = 1, 8$. $D = 0$ and $W = 1$ represent, respectively, absence of deflection routing and wavelength conversion. It can be seen the gain in performance when deflection routing ($D = 1, W = 1$ and $D = 2, W = 1$) and wavelength conversion ($D = 0, W = 8$) are used alone and when they are used jointly ($D = 1, W = 8$ and $D = 2, W = 8$). As expected, the combination of both mechanisms can improve the switch performance. However, such performance is not yet acceptable for input load near 0.8, which is usually assumed for typical packet-switched network planning. Therefore, as deflection routing is limited by the facts already mentioned and if the number of wavelengths is not large, another contention resolution mechanism (buffering) may be necessary to be used together with those herein studied.

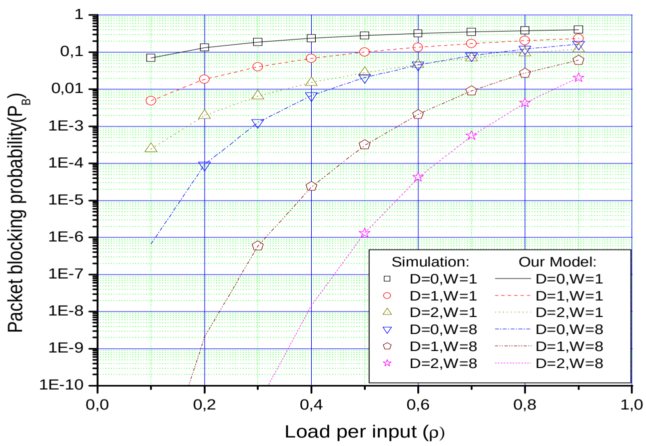

Fig. 9. Packet blocking probability versus load per input ρ for all the cases here considered. The packet is exponentially distributed, $N = 4$, $W = 1, 8$ and $D = 1, 2$

Finally, it would be of great interest if an asymptotic bound for deflection routing could be obtained for the cases with and without wavelength conversion.

VII. Conclusions

In this paper we propose exact analytical models for optical packet switches in asynchronous networks. Such models enable the evaluation of the switch performance when deflection routing and wavelength conversion are used as contention resolution mechanisms. We can see that such mechanisms are capable of providing satisfactory results when they operate together, with reasonable number of wavelengths and moderate input loads. As deflection routing is limited by some factors (e.g., number of fibers N, network topology, routing algorithm, maximum end-to-end delay), wavelength conversion appears as a more flexible solution, mainly if the number of wavelengths can evolve. For small to moderate number of wavelengths, however, the employment of a complementary contention resolution mechanism becomes necessary, so that the switch can achieve performance similar to current electrical packet-switched networks (packet blocking probability below 10^{-10}). Therefore, an expansion of this work considering buffering is an important topic to be investigated.

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Appendix I
The Erlang's First Formula

For $M/G/c$ systems with no waiting space, the steady-state probabilities are identical for the corresponding $M/M/c$ system [14], which are given by Erlang's first formula. Thus, independently of the service distribution, the probability of having n customers being served is written as:

$$P_n = \frac{(\lambda'/\mu')^n/n!}{\sum_{i=0}^{c}(\lambda'/\mu')^i/i!}, \quad 0 \leq n \leq c\,, \tag{7}$$

where λ' is the constant arrival rate and μ' is the inverse of the mean service time. The resultant formula for P_c is itself called Erlang's loss formula and corresponds to the probability of a full system at any time in the steady state.