Design-Dimensioning Model for Transparent WDM Packet-Switched Irregular Networks

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Abstract—A detailed analytical traffic model for all-optical wavelength division multiplexing (WDM) photonic packet-switched networks is presented and the requirements for buffer size and link dimensions are analyzed. This paper shows that due to the topology, packets may generate traffic bottlenecks produced by a tendency of the routing scheme to send packets with different destinations through preferred paths. This effect increases the traffic load and, hence, the probability of blocking at the output links of specific routers in the network and, therefore, a large buffer depth is required or an increment in the number of fibers per link. Three router architectures are analyzed and it is shown that WDM all-optical router architectures with shared contention resolution resources are the best candidates to reduce hardware volume and cost of all-optical networks. It is shown that routers with a bank of completely shared wavelength converters (WCs) require a fraction of WCs compared to router architectures that use a WC per wavelength. This fraction depends on the location of the router, the network topology, and the traffic load in the network. However, in general terms, about 50% to 90% of WCs can be saved by architectures with shared wavelength-conversion resources. Also, it is shown that limited wavelength conversion degrees \(\theta = 8\) and \(\theta = 10\) in packet-switching routers with 16 and 32 wavelengths give the same probability of packet loss performance as full wavelength conversion.

Index Terms—Network architecture and performance, network dimensioning, transparent networks, wavelength conversion, wavelength routing.

I. INTRODUCTION

ONE OF the major problems in the design of all-optical packet-switching routers [1] is reduction of the number of components and the number of components a signal has to traverse without affecting the teletraffic performance of a network. The number of components in a router is driven by the degree of blocking probability desired. Blocking occurs when two or more competing packets at the input of a router desire the same output. Buffering [2], multipath routing [3], wavelength translation [4], [5], and link dimensioning [6] are some of the techniques that can be used to solve the conflict of packets. The teletraffic performance and the optimization of the number of components in a router have been analyzed assuming an isolated node [7]. Usually, a uniform distribution is assumed to assign the outlet destination to the incoming packets. The consequence of this kind of assumption is that router architectures require a balanced buffer depth per outlet. Therefore, due to this assumption, the number of components used in the router increases. In this paper, it is shown that, due to the nonuniform network traffic behavior [8], routers require asymmetric buffering capacity to solve contention. This paper shows that an integrated analysis by considering the network topology, routing scheme, dynamic traffic distribution, and multiplexing gain of the routers into a single optimization model, leads to an optimum all-optical router architecture and network design.

This paper presents a wavelength division multiplexing (WDM) packet-switched network model that adequately represents the queuing behavior of the traffic in irregular mesh networks. Models that can effectively describe the behavior of the traffic in terms of a minimum number of parameters are of great practical significance. Several efforts have been demonstrated in [5] and [9] to model regular mesh networks under uniform traffic. Fig. 1 shows a flow diagram of the model presented here. The analytical model requires information of the traffic matrix (information of the source–destination load distribution), number of inlets used to inject packets into the network, network topology, and routing tables. Using a path-decomposition approach, described in this paper, the method computes the traffic load per wavelength and per fiber in all links of the network. Also, the method computes packet-forwarding probabilities of the routers. These forwarding probabilities are associated with routing in the node and consist of the proper selection of output wavelength and fiber both for transiting and
for locally generated packets. After this procedure, a method for network dimensioning embedded into the analytical model is presented. Router and network dimensioning are the processes of identifying where and when to add bandwidth or expand contention resolution resources, routing, or switching capacity. Router dimensioning is used to quantify the buffer size and the number of output fibers to achieve a specific probability of packet loss per router. After dimensioning a router, the traffic load per fiber in the network has to be recomputed; hence, the method is recursive in nature. Iterations terminate when none of the routers in the network require dimensioning, i.e., a certain probability of packet loss has been achieved.

We compare three router architectures. In the first, the output optical buffers are completely partitioned (CP) among the outlets. In the second, the output optical buffers are completely shared (CS) by the outlets. In the third, the output optical buffers and the wavelength converters (WCs) are completely shared by the outlets. The analytical results are compared to simulation results assuming noncorrelated traffic. Also, we assume that the router operations are time slotted, and fixed size packets are aligned at the node inputs. Each router performs access and routing functions. Access consists of the possible transmission of up to \( n_{w} \) wavelengths, of which the node is source. For the comparison analysis, we assume full wavelength conversion, i.e., every packet can be converted to any of the \( n_{w} \) available wavelengths. However, via simulations, we demonstrate that limited wavelength conversion, i.e., incoming packets that are converted to only a restricted number of wavelengths, performs as good as full wavelength conversion. The restricted wavelength conversion results are mainly beneficial for architectures in which WCs are completely shared.

Analysis shows that WDM all-optical router architectures with shared contention resolution resources are the best candidates to reduce hardware volume and cost of all-optical networks. This is due to the fact that the contention resolution resources are used in a more efficient way. This paper also shows that increasing the buffer depth is a more effective way of solving contention than using wavelength conversion. In this strategy, the number of WCs in use (converting packets in every time slot) reaches a maximum and, to reduce the probability of packet loss, it is preferable to increase the buffer depth or to increase the number of fibers per link (link dimensioning) than to increase the number of WCs. Results also show that limited wavelength conversion is as effective as full wavelength conversion; WCs with conversion capacities of eight and 10 wavelengths perform as well as full wavelength conversion. The restricted wavelength conversion degree is \( \lambda_{w} \) of the \( n_{w} \) wavelengths, of which the node is source. For the comparison analysis, we assume full wavelength conversion, i.e., every packet can be converted to any of the \( n_{w} \) available wavelengths. However, via simulations, we demonstrate that limited wavelength conversion, i.e., incoming packets that are converted to only a restricted number of wavelengths, performs as good as full wavelength conversion. The restricted wavelength conversion results are mainly beneficial for architectures in which WCs are completely shared.

The remainder of the paper is organized as follows. Section II presents the three router architectures. Section III details the path decomposition scheme. Section IV presents a detailed analysis for router dimensioning. Section V gives results of the maximum number of WCs required in a router and the degree of wavelength conversion. Section VI analyzes the average propagation delay in irregular networks and Section VII contains the conclusions.

II. ROUTING SCHEME AND ROUTER ARCHITECTURE

Optical packets must be routed through a network from the origin and through intermediate nodes to reach the destination. The decision of the path to be followed is made by a control unit, which most often is implemented with electronic techniques. The routing algorithm is closely related to the network topology and, thus, to the type of switching routers in use. Routers in irregular meshed networks use predefined lookup tables to forward-arriving packets. Usually, a shortest path or least number of hops algorithm is used to define the optimum output at every router in the network. There is normally a single path and, therefore, one output for every packet that arrives to the router. Analysis of the router performance in terms of packet loss, number of delay lines, size of the router, and number of wavelengths has been studied for the case of single-path routing and uniform-router traffic [7].

The router architecture, demonstrated in [10], is one of the architectures used in this analysis and is shown in Fig. 2(a). The demultiplexer (DEMUX) selects the packets arriving on wavelengths \( \lambda_{1}, \ldots, \lambda_{n_{w}} \) on each of the \( N \) input fibers. Optical-to-electrical interfaces located after the DEMUX are used to read the packet headers. Also, after the demultiplexer, tunable WCs are utilized to solve blocking of packets. The space switch consists of optical gates that control the flow of packets to the designated output and fiber-delay lines in the output buffer. Fiber-delay lines provide the packet buffering and are present at the output of the router [7]. In Fig. 2(a), \( B \) is the number of fiber-delay lines, each capable of storing \( n_{w} \) packets. There is at least one inlet to inject up to \( n_{w} \) packets into the network and at least one outlet to absorb up to \( n_{w} \) packets from the network. Logically, the router has the functions of packet dropping (absorption), adding (injection), wavelength switching (\( \lambda \) conversion), routing (space switch), and buffering. Observe that architecture in Fig. 2(a) has completely partitioned buffers because fiber-delay lines are distributed among the outlets. Fig. 2(b) shows an all-optical router similar to the architecture shown in Fig. 2(a), but the optical buffer has access to all outlets; hence, the buffer is said to be completely shared by all outlets. The dots in Fig. 2(b) indicate that more than one completely shared buffer might be in place. Fig. 2(c) shows a router architecture with a completely shared buffer and wavelength conversion module with \( C \) WCs. The number of wavelength converters \( C \) and the conversion degree \( d \) in the architecture shown in Fig. 2(c) are important parameters to optimize and will be analyzed in Section V.

III. TRAFFIC MATRIX

This section explains how a traffic matrix given in bits per second can be transformed for use in the method described. Consider the traffic matrix given in Table VI.

From Table I, we can compute the number of fibers used to inject traffic into the network. Let us assume that the bit rate of the \( n_{w} \) transmitters per fiber is fixed so that the number of injection fibers is given by \( F_{\text{injection}} = \left\lceil \frac{\phi_{x} \times \text{bit rate}}{n_{w}} \right\rceil \) where \( \lceil \cdot \rceil \) represents the ceiling function and gives the smallest integer larger than the argument. \( N \) in Table I is the total number of routers in the network.

In order to modify the traffic matrix of Table I for use in this method, we have to multiply each cell of the traffic matrix by
TABLE I

<table>
<thead>
<tr>
<th>Source/Destination</th>
<th>Node 1</th>
<th>Node 2</th>
<th>...</th>
<th>Node R</th>
<th>Total traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>0</td>
<td>φ_{1,2}</td>
<td>...</td>
<td>φ_{1,R}</td>
<td>φ_1 = \sum_{d=1}^{R} φ_{1,d}</td>
</tr>
<tr>
<td>Node 2</td>
<td>φ_{2,1}</td>
<td>0</td>
<td>...</td>
<td>φ_{2,R}</td>
<td>φ_2 = \sum_{d=1}^{R} φ_{2,d}</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Node R</td>
<td>φ_{R,1}</td>
<td>φ_{R,2}</td>
<td>...</td>
<td>0</td>
<td>φ_R = \sum_{d=1}^{R} φ_{R,d}</td>
</tr>
</tbody>
</table>

Each cell of this traffic matrix is a percentage of the total injection capacity per node and can be also envisioned as the probability of sending a packet from source $s$ to destination $d$ ($\beta_{s,d}$), provided that $\beta_{s,d} \leq 1$, or, equivalently, $\varphi_x \leq \text{(bit rate)} \cdot n_{in}$. In general, a multilayer multihop network can be thought of as a stack of $n_{in}$ identical parallel networks, one per wavelength. Packets are routed from one network to the other through wavelength conversion at each node. The fact that a node may have two or more injection fibers can be also thought of as the colocation of two or more parallel routers that are joined together by the space switch. In cases where $\beta_{s,d} > 1$, it is necessary to consider that more than one fiber is used to inject packets into the network in that specific source node. Hence, the traffic has to be divided by the number of injection fibers. This is equivalent to adding more rows to the traffic matrix, one per injection fiber of the node. The total traffic is then divided by the number of injection fibers. However, in order to simply our analysis, let us assume that $\varphi_x \leq \text{(bit rate)} \cdot n_{in}$.

IV. PATH DECOMPOSITION

In this section, we describe the computation of input slot utilization, output slot utilization, and router forwarding probabilities. In this paper, we assume that the traffic load per link is uniformly distributed among the wavelengths and that the total traffic load per fiber is the sum of the traffic loads of the wavelengths carried by the fiber. We assume, additionally, that the number of local packet arrivals per clock $0 \leq C \leq n_{in}$ is a binomial random variable with trial number $n_{in}$ and success probability $g_s = \sum_{d=1}^{R} \beta_{s,d}$, which we denoted by $\text{Bin}(n_{in}, g_s)$. This corresponds to having $n_{in}$ independent Bernoulli fluxes of intensity $g_s$. We assume that the destinations of the packets are independent and are given by the traffic matrix of Table II. Let us define $\mu_{i,x,y}$ as the input load per wavelength, i.e., the probability that a time slot at inlet $i$ (input fiber) of router $y$ carries a packet. Define $\mu_{j,x,y}^\prime$ as the output utilization, i.e., the probability that a time slot at output $j$ of router $y$ carries a packet. Also, define $\rho_{i,j}$ as the probability that a packet at inlet $i$ exits through outlet $j$. These parameters are shown in Fig. 3.

Now, let us determine the input slot utilization $\mu_i$. This parameter can be computed using a path decomposition method. Basically, by decomposing paths that packets traverse in the network into the set of links that form that specific path, it is possible to compute $\mu_i$. For example, Table III shows the source-destination paths of packets injected at node 16 of the Pan-European topology shown in Fig. 4. Table III was obtained by applying the least number of hops routing scheme using the topology given in Table IV. Observe that paths are composed of a set of logical links. For example, the path from node 16

\[
(1/\text{(bit rate)} \cdot n_{in})
\]
Fig. 3. Pan-European topology.

more than one fiber; hence, $L(x, y)$ may be composed by fibers $F_{x,y}^1, \ldots, F_{x,y}^n$ where $i$, arbitrarily assigned, is the router’s input fiber number. We are also assuming bidirectional links, i.e., there is a fiber carrying data from $x$ to $y$ and another fiber carrying data from $y$ to $x$.

By computing the routing paths for the whole network, it is possible to obtain the set of links used for each path. Using the link information, it is also possible to compute the input fiber utilization, packet-forwarding probabilities, and output fiber utilization of node $y$. The input fiber utilization $u_{i,y}$ can be obtained by the following algorithm.

/*BEGIN*/

Step 1) Compute all the source-destination routing paths in the network using a routing scheme, for example, least number of hops or shortest distance.

Step 2) Assuming that at the beginning of the network dimensioning, there is only one fiber per link per direction, enumerate these links, i.e., index the fibers with logical numbers to associate each fiber with a logical inlet of a router. This association of fibers to inlets is important in order to compute the forwarding probabilities explained below.

/*END*/
Step 3) From the pool of paths of the network, find those that use link \( L(x, y) \). Each path is characterized by a load probability \( \beta_{n,d} \). Therefore, each path contributes \( \beta_{n,d} \) traffic to link \( L(x, y) \). The sum of the \( \beta_{n,d} \) of the paths using link \( L(x, y) \) is performed to obtain the link’s total traffic load \( \gamma_{x,y} = \sum \beta_{n,d} \).

Step 4) Condition the total traffic \( \gamma_{x,y} \) to be lower than a threshold parameter \( \tau \). If \( \gamma_{x,y} \leq \tau \) for \( \tau \leq 1 \), then only one fiber is required for link \( L(x, y) \). However, if \( (F_{x,y} - 1)\tau \leq \gamma_{x,y} \leq F_{x,y} \tau \), then we need to divide the total traffic by the number of fibers \( F_{x,y} = \lceil \gamma_{x,y}/\tau \rceil \). The result is the traffic per fiber \( u_{i,y} \).

Stating this algorithm in an equation, we have for, \( u_{i,y} \)

\[
 u_{i,y} = \frac{\gamma_{x,y}}{F_{x,y}}. 
\] (1)

The value \( \tau \) is a traffic load threshold for a given probability of packet loss \( \text{PPL}(d_l) \) desired for a specific outlet. \( \tau \) may be different per router as it depends on the topology, distance to the next router, and number of fiber delay lines the network designer wants to add to the router, because \( \text{PPL}(d_l) \) depends on the number of delay lines \( F_{x,y} \). A discussion of the value of \( \tau \) follows in .

In cases where \( F_{x,y} > 1 \), it is necessary to consider the addition of fibers per link because, initially, one fiber per link was assumed. The traffic load in the added fibers will have the same traffic load per fiber \( u_{i,y} \). However, we need to assign logical router input numbers to the added fibers. In order to assign the input numbers, we can use \( u_{f,y} = u_{i,y} \) where subscript \( f = N_y, N_y + 1, \ldots, F_{x,y} \) indicates inlet number. Here, \( N_y \) is the number of inlets for router \( y \) and it continually updates during the link dimensioning process. After dimensioning a link, \( N_y \) is augmented with additional inlets, as is given by \( N_y = N_y + F_{x,y} \).

Let us now find the probability of packet forwarding \( \rho_{i,j} \) from inlet \( i \) to outlet \( j \). This parameter can be computed as

\[
 \rho_{i,j} = \frac{I_{(i,j),y}}{K_{i,y}}. 
\] (2)

where \( I_{(i,j),y} \) is the number of occurrences that the internal router link \( I_{(i,j),y} \) appears in the routing tables. \( K_{i,y} \) is the number of occurrences inlet \( i \) is selected for forwarding. To illustrate the preceding discussion, let us consider one example. Assume that inlet \( i \) is related to link \( L(16, 5) \) and outlet \( j \) is related to link \( L(5, 6) \) in Table III. Because link \( L(5, 6) \) appears only twice, \( I_{(i,j),y} = 2 \); because link \( L(16, 5) \) appears five times, \( K_{i,y} = 5 \). Then, \( \rho_{i,j} = 2/5 \) for this partial list of paths. In case of dimensioning a link to a different number of fibers, the forwarding probabilities will be the same for the additional fibers.

### Table V

<table>
<thead>
<tr>
<th>CF</th>
<th>input/output</th>
<th>CT</th>
<th>( u_i )</th>
<th>( u_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>16</td>
<td>16</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>16</td>
<td>0.833</td>
<td>0.333</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>5</td>
<td>0.222</td>
<td>0.500</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>17</td>
<td>0.500</td>
<td>0.500</td>
</tr>
<tr>
<td>18</td>
<td>5</td>
<td>15</td>
<td>0.333</td>
<td>0.500</td>
</tr>
<tr>
<td>17</td>
<td>6</td>
<td>1</td>
<td>0.500</td>
<td>0.833</td>
</tr>
<tr>
<td>15</td>
<td>7</td>
<td>4</td>
<td>0.222</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The output fiber utilization is given by

\[
 u'_{i,j,y} = \sum_{i=1}^{N_y} u_{i,y} \rho_{i,j}. 
\] (3)

Because we can compute the input fiber utilization of all of the links in the network from (1), (3) serves to validate the results of equation (1), because the input fiber utilization of one node is the output fiber utilization of the previous node.

Note that this is a recursive method. What we know about the input–output link utilization is initialized as a traffic matrix parameter. We must then dimension the link by the number of required fibers in order to compute the traffic load per fiber as a probability of a packet occupying a time slot. Then, by dimensioning the network, the probability of packet loss is reduced in the network. Considering that a probability of packet loss below \( 10^{-6} \) is required in an optical network for an acceptable performance, we can assume that the packet loss throughput is negligible. Therefore, the injection throughput is equal to the absorption throughput, where we understand that absorption throughput means the amount of traffic correctly received at the destination node.

### V. ROUTER DIMENSIONING

This section continues with the network model presented in the introduction of the paper. To facilitate the explanation of the model, we present results and analyze one of the routers of the Pan-European topology (see Fig. 4 and Table IV). This analysis can be extended to other router nodes within the network.

Table V shows the input link utilization, output link utilization, logical inlet, and outlet indexes for node 16. Table V also contains information that characterizes the connections that node 16 has with other nodes in the network incoming fibers and outgoing fibers. Incoming fibers are referred to as \( \text{connected from (CF)} \) and outgoing fibers are referred to as \( \text{connected to (CT)} \). For example, \( \text{CF} = 1 \) means link \( L(1, 16) \), and \( \text{CT} = 18 \) means link \( L(16, 18) \). Link \( L(1, 16) \) uses inlet 2 and link \( L(16, 18) \) uses outlet 2. Observe that inlet 2 and outlet 6 have a traffic load of 0.833. This indicates that there is a network bottleneck and, therefore, the outlet will require a higher number of delay lines or more fibers per link, as will be shown later. Also, note that when \( \text{CF} = \text{CT} \), the link utilizations \( u_i \) and \( u_o \) are also equal; this is because we assume uniform bandwidth for the network, i.e., \( \beta_{n,d} = 1/(8-1) \) and \( g_s = 1 \). However, information of asymmetric traffic (source
destination) can be observed if we apply an asymmetric traffic matrix. It is important to note that this model can be extended to a complete network design and dimensioning by using a set of different traffic matrices and provisioning the network resources for this set of traffic matrices. In this way, we can capture different dynamic random events that affect the performance of the network. Table VI shows the packet forwarding probabilities $\rho_{i,j}$ of node 16. Observe that there are several inlets that do not send packets to specific outlets $\rho_{i,j} = 0$, i.e., the forwarding probabilities are asymmetric. The routing tables (which, in turn, depend on the network topology) produce this effect. This suggests that many of the switching components of the switching matrix can be eliminated because many of them are not used. For instance, input fiber 3 connected from node 4 only sends data to outlets 1 and 4. Considering that the switching matrix will require the use of semiconductor optical amplifiers (SOAs) [11] for fast packet switching, one can design the switching matrix with an asymmetric layout. Asymmetric switching matrices have been shown to reduce the number of SOAs required for switching [8].

With the analysis of link dimensioning based on the traffic matrix thus explained, we need to develop an analysis for router dimensioning. Router dimensioning involves determining the number of fiber delay lines and number of output fibers required for a specific probability of packet loss. We can improve the probability of packet loss by changing wavelength, adding more delay lines to the buffers, or by decreasing the traffic load per outlet. To decrease the traffic load per outlet, it is necessary to increase the number of fibers per link so that the traffic is distributed among more fibers [10].

Because any of the inlets in a router can contribute a packet to an outlet, the probability that $k = r_1 + r_2 + \cdots + r_N$ packets are going to a given outlet $(j)$ $a^j_k$ is given by the following multinomial equation:

$$a^j_k = \binom{N_j \eta_{w}}{k} \prod_{i=1}^{N} (\eta_{w} \rho_{i,j})^{r_i} \prod_{i=2}^{N} r_i!$$

where $N_j$ is the total number of inlets that may send packets to outlet $j$ (specified at the bottom of Table VI), $\eta_{w}$ is the number of wavelengths per fiber, and $N$ is the total number of input fibers after the link dimensioning process explained in Section IV.

### Table VI

<table>
<thead>
<tr>
<th>CF/I/CT-O</th>
<th>16-1</th>
<th>18-2</th>
<th>5-3</th>
<th>17-4</th>
<th>15-5</th>
<th>1-6</th>
<th>4-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-1</td>
<td>0.00</td>
<td>0.11</td>
<td>0.27</td>
<td>0.16</td>
<td>0.16</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>1-2</td>
<td>0.20</td>
<td>0.26</td>
<td>0.06</td>
<td>0.26</td>
<td>0.20</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>4-3</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>5-4</td>
<td>0.55</td>
<td>0.00</td>
<td>0.00</td>
<td>0.33</td>
<td>0.11</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>18-5</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00</td>
<td>0.66</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-6</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00</td>
<td>0.44</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-7</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00</td>
<td>0.53</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The probability of packet loss of outlet $j$ is given by [7]

$$PPL^j = 1 - \frac{\sum_{k=0}^{n_{w}} \sum_{l=0}^{n_{w}-1} q^j_k (\eta_{w} - (k+l))}{n_{w} \eta_{w}}$$

where $q^j_k$ is the probability of finding $k$ packets in queue $j$ and can be determined using the principles provided in [7].

### A. Complete Partitioning

Fig. 5 shows the probability of packet loss versus the number of delay lines for router 16 of the Pan-European topology, assuming four wavelengths in the network and using the data given in Tables V and VI. Observe that the number of delay lines required depends on the output traffic load. Therefore, the buffer depth per outlet will be difficult to optimize, in practical terms, for this type of architecture. Also, note that the traffic load of output link 1 is one, so that more than one fiber is required to absorb packets from the network. If two fibers are used, the performance of link 1 will be similar to that of link 4, considering that the outgoing traffic is divided by two. To split the traffic, the entries in column 16–1 must be divided by two. Considering that the outgoing traffic is divided by two.

By adding an output fiber, Table VI is in effect adding another output fiber ($O = 8$) to the router. In this case, the fiber is used to absorb packets from the network destined to router 16. The total traffic load per fiber is then halved, to a value of 0.5. Hence, approximately three delay lines per outlet are needed for $PPL < 10^{-9}$. Observe that link 1 is used to absorb packets from the network because it is labeled as a connection to node 16. This means that this fiber is physically connected to an adjacent edge router. If we assume that the distance from node 16 to the edge routers is short, more than two fibers to absorb packets from the network would be preferred.

### B. Complete Sharing

Let us analyze the case where the router output buffer is completely shared by all outlets, as shown in Fig. 2(b) and (c). This architecture has been analyzed previously in [12]–[14]. Here, we consider the more general problem caused by the spatial traffic asymmetries of the network and asymmetric traffic probabilities. In the case of the completely partitioned...
buffer discussed in Section V-A, the random variable $q_j$ denotes the number of packets addressed to output $j$ in the buffer. The random variable representing the sum of packets in all the buffers given by $s = \sum_{j=1}^{N} q_j$ is an approximation to the random variable representing the number of packets in a completely shared buffer. Now, we can approximate the distribution of $s$ by a gamma distribution, which can be characterized by its mean and variance as in [13]. The probability of packet loss for a router with completely shared buffers is then given by

$$PPL = \sum_{j=1}^{N_{out}} \sum_{l=0}^{n_{in}+N} a_k^j s_l^j \frac{(k-(B+n_{in}-l))}{k \cdot O_l}$$ (6)

$$O_l = \sum_{j=1}^{N_{out}} s_l^j$$ (7)

where $s_l$ is the probability of finding $l$ packets in the shared buffers, $N_{out}$ is the number of output fibers after the link dimensioning process; $N$ is the number of input fibers after the link dimensioning, $B = n_{in} \cdot d_i$ is the number of packets that can be stored in one of the shared buffers, and $R$ is the number of shared buffers. An alternative approximation for the computation of the $PPL$ is demonstrated in [12], where $PPL = \sum_{l=0}^{\infty} S_l$ assumes an infinite buffer size. Note that, in the case of completely shared buffers, the $PPL$ is for the complete router, as opposed to completely partitioned buffers, where $PPL$ is given per outlet.

Fig. 6 shows the router probability of packet loss against the number of delay lines in the case of a completely shared buffer architecture for router 16 of the Pan-European topology with four wavelengths, using the data given in Tables V and VI. Note that the $PPL$ is approximately $10^{-2}$ when one fiber is used in link 1. If two fibers are assumed, and the traffic of link 1 is divided by two, then the $PPL$ is reduced and about 12 delay lines are required for $PPL < 10^{-5}$. Also, if two shared buffers are used ($R = 2$) along with two fibers in link 1, the number of delay lines per shared buffer is 7 to achieve a $PPL < 10^{-5}$.

**VI. NUMBER OF WAVELENGTH CONVERTERS**

Now, we turn our attention to another important design parameter that is represented in the architecture of Fig. 2(c). This is the number of WCs that are active in each time slot, converting packets to resolve outlet contention. For the architecture shown in Fig. 2(c), a critical design parameter is the number of wavelength converters $C$. Fig. 7 shows simulation results of the number of WCs versus the buffer depth for an 8 × 8 architecture in Fig. 2(c) with four, eight, 16, and 32 wavelengths. Note that $C$ does not depend on the buffer depth. The number of WCs does not increase with the number of delay lines. This is because of the queuing behavior of delay-line buffers. The number of available slots for wavelength conversion of packets is a constant in average regardless of the buffer depth; hence, the number of WCs does not increase, because there is no need to wavelength convert more packets. Therefore, in order to improve the PPL, it is necessary to increase the buffer depth [5] or provide more fibers per link. The results, shown in Fig. 7(a), assume uniform distribution for the outlet destination of packet traffic with an uniform traffic load of 0.85 per wavelength. Fig. 7(b) shows simulation results for router 16 of the Pan-European topology using traffic Tables V, and VI with the modification of two fibers in
link 1. Note that, as shown in Fig. 7(b), with a use of four fibers in link 1 when \( n_{\text{eff}} = 32 \), the number of WCs can be reduced. For more network simulation results under self-similar traffic, refer to [8].

A. Limited Wavelength Conversion

Another important design parameter for architecture in Fig. 2(c) is the degree of wavelength conversion in packet-switched networks. The degree of wavelength conversion \( d \) is defined as the number of wavelengths that the WCs can translate a packet. Because the WCs that have been demonstrated in laboratories to date have a limited wavelength conversion capability [15], it is essential to investigate the performance of packet-switched routers with the same wavelength-conversion constraints. A natural question that arises is whether or not an acceptable PPL can be obtained by using WCs with limited wavelength conversion in a packet-switched network. Several efforts [15] and [16] have targeted the analysis of limited wavelength conversion in circuit-switched networks. However, to the best of the author’s knowledge, there is no literature that addresses wavelength conversion limits for packet-switched networks.

Fig. 8 shows simulation results of the probability of packet loss versus the buffer depth for an 8 \( \times \) 8 router (architecture of Fig. 2(c) with \( R = 1 \), with 16 wavelengths [see Fig. 8(a)] and 32 wavelengths [see Fig. 8(b)]. The simulation was performed with a traffic load of 0.85 assumed for Fig. 8(a) and a load of 0.9 for Fig. 8(b). We assumed that the WCs can convert wavelength to a set of consecutive wavelengths. Also, we assume that wavelengths are distributed uniformly among the WCs. One should note that the number of WCs is fixed; in Fig. 8(a), it is fixed at 63, and in Fig. 8(b), it is fixed at 125. As shown in Fig. 8(a), with a wavelength conversion degree \( d \) of eight, the router performance is the same as with full wavelength conversion. With \( d = 8 \), the simulation yields a probability of packet loss below \( 10^{-6} \). Also when \( d = 2, 4, 6 \) the probability of packet loss maintains a minimum value starting at a certain number of delay lines. This is due to the wavelength-conversion limitation; there is a restricted set of wavelengths per WC and, therefore, the WCs are not able to translate packets to available slots in the buffers. In the case shown in Fig. 8(b), a \( d \) of 10 is required to perform similarly as full conversion. A greater conversion degree is required in Fig. 8(b) than in Fig. 8(a), mainly because of the greater traffic load used in the former. It is important to mention that these results are upper bounds, because we are assuming noncorrelated traffic and uniform priority scheduling to forward the packets to the output links and the buffer. In the case of having correlated traffic, the PPL limit is imposed by the characteristics of the traffic and, therefore, a lower conversion degree may be needed.

VII. PROPAGATION DELAY

Let us now analyze the network’s average propagation delay in terms of the number of hops necessary to reach a destination. The average propagation delay of a mesh network can be ob-

Fig. 8. Probability of packet loss against the buffer depth for a 8 \( \times \) 8 router with one completely shared buffer (\( R = 1 \)). (a) Sixteen wavelengths (load = 0.85, 63 WCs) and (b) 32 wavelengths (load = 0.9, 125 WCs). The wavelength-conversion degree is represented by \( d \).

\[
H = \frac{1}{N} \sum_{s=1}^{N} \sum_{d=1}^{N} h_{s,d} \beta_{s,d} \tag{8}
\]

where \( N \) is the number of routers in the network and \( h_{s,d} \) is the number of hops between router \( s \) and router \( d \). A partial list of \( h_{s,d} \) values is shown in Table III. To clarify this computation, assuming \( \beta_{s,d} = 1/(N - 1) \) for all source-destination nodes of the Pan-European topology, then the average propagation delay is 2.1 hops. Also, it is possible to compute the network’s average propagation delay in units of time by the following equation:

\[
T = \frac{1}{N} \sum_{s=1}^{N} \sum_{d=1}^{D_{s,d}} D_{s,d} \beta_{s,d} \frac{\eta}{C} \tag{9}
\]

where \( D_{s,d} \) is the source-destination distance, \( \eta \) is the fiber index of refraction, and \( C \) is the speed of light. Note that we are
neglecting the possible average queueing delay imposed by the optical buffers, which is expected to be minimal.

VIII. CONCLUSIONS

The model presented in this paper assumes noncorrelated traffic and, therefore, gives a lower bounds characterization for the number of delay lines required in all-optical routers. This model adequately represents the queueing behavior of the traffic in terms of a minimum number of parameters; further work is required to investigate the impact of correlated traffic on the queueing performance of the routers, and the network growth produced in providing protection and restoration resources in the network. Three router architectures are analyzed, and it is shown that WDM all-optical router architectures with shared contention resolution resources are the best candidates to reduce hardware volume and costs of all-optical networks. It is shown that routers with a bank of completely shared WCs require a fraction of WCs in comparison to router architectures that use a WC per wavelength. This fraction depends on the location of the router, the network topology, and the traffic load in the network. However, in general terms about 50% to 90% of WCs can be eliminated by architectures with shared-wavelength conversion resources [8]. Also, it is shown that wavelength-conversion degrees $d = 8$ and $d = 10$ in an $8 \times 8$ packet-switching router with 16 and 32 wavelengths yield the same probability of packet-loss performance as full wavelength conversion.

REFERENCES


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