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Wavelength Conversion in Optical Packet Switching

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(Invited Paper)

***Abstract*—A detailed traffic analysis of optical packet switch design is performed. Special consideration is given to the complexity of the optical buffering and the overall switch block structure is considered in general. Wavelength converters are shown to improve the traffic performance of the switch blocks for both random and bursty traffic. Furthermore, the traffic performance of switch blocks with add–drop sports has been assessed in a Shufflenetwork showing the advantage of having converters at the inlets. Finally, the aspect of synchronization is discussed through a proposal to operate the packet switch block asynchronously, i.e., without packet alignment at the input.**

***Index Terms*—Frequency conversion, optical communications, optical fiber delay-lines, optical signal processing, packet switching, photonic switching systems, semiconductor optical amplifiers (SOA's), wavelength division multiplexing.**

I. Introduction

THE growth of existing and new broadband services is continuing to increase the traffic flow in the telecommunication networks and thus push for larger and larger bandwidth. As a first step to overcome the increased bandwidth demand, a massive deployment of wavelength division multiplexing (WDM) in the transmission network has taken place.

As a next step, future networks are expected to utilize WDM techniques for optical functionalities capable of handling multigigabit signals and in this way reduce the amount of complex electronics and thus the cost [1]. Therefore, it is envisaged that optical cross-connects (OXC's) [2]–[6] as well as optical add–drop multiplexers (OADM's) [7], [8] will be implemented in the future transport networks to perform routing and switching [9]–[11]. Additionally, the introduction of a bit rate and transfer mode transparent optical packet switched network layer will bridge the granularity gap between the high speed wavelength channels in the optical WDM transport network and the electrically switched network partitions [12]–[16]. This improves the bandwidth utilization and the flexibility of the network by allowing switching of frequently changing high bit rate connections with diverse traffic characteristics without affecting the OXC's in the transport network. Moreover, an optical packet layer can support and transport any service without prior addition of framing and control bits (such as in, e.g., SDH, Synchronous Digital Hierarchy), thereby offering a potential cost competitive solution for the future telecommunication network.

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Optical packet switches require buffering and synchronization of optical packets. Both functionalities can be realized with fiber delay-line arrangements combined with gates for correct access [17]–[22]. Although the use of passive fibers is very simple, the number of delay-lines and thus gates increases dramatically with the traffic load. As an example, more than 40 delay-lines are needed for a packet loss probability of 10^{-10} at a load of 0.8 [23]. To avoid these large numbers, various fiber loop type buffers have been suggested [24]–[27]. In this paper, however, the focus will be on an alternative approach: it uses the wavelength dimension for contention resolution by converting packets that are addressing the same switch outlet to different wavelengths [28]–[32].

So far, synchronous operation of the packet switch blocks has been proposed with packet alignment at the input in analogy with an electronic packet switch [33]. However, in contrast to the electrical domain the major advantage of photonic networking is the easy handling of large bandwidths rather than signal processing at the bit level. Therefore, a nonaligned packet control scheme is presented [34]. Since it is envisioned that the buffering with this scheme is less efficient, we perform an analysis of the traffic performance also assessing the flexibility offered by the wavelength domain.

The paper is organized as follows. First, a motivation for packet switching is given (Section II). Next, the basics of optical packet switching is described together with different switching architectures (Section III). Then the traffic performance of optical packet switches without add–drop functionality is analyzed both with random and bursty traffic including the influence of tuneable wavelength converters on the number of fiber delay-lines (Section IV). Section V gives an analytical model for assessment of the traffic performance of optical packet switches with add–drop functionality. Moreover, results are presented considering add–drop nodes with and without wavelength converters. Finally, Section VI presents investigations of optical packet switching without packet alignment.

II. Why Optical Packet Switching?

The upgrade from electronics to photonics to deal with the throughput bottleneck has lead to the suggestion of an optical cross-connected backbone network as described briefly in the introduction. A further step in the evolution would include an optical packet switched layer between the electrically switched layer and the backbone layer operating at channel bit rates of possibly 2.5 or 10 Gb/s (see Fig. 1) [12], [15], [16]. Whereas optical cross-connects are already demonstrated in field trials

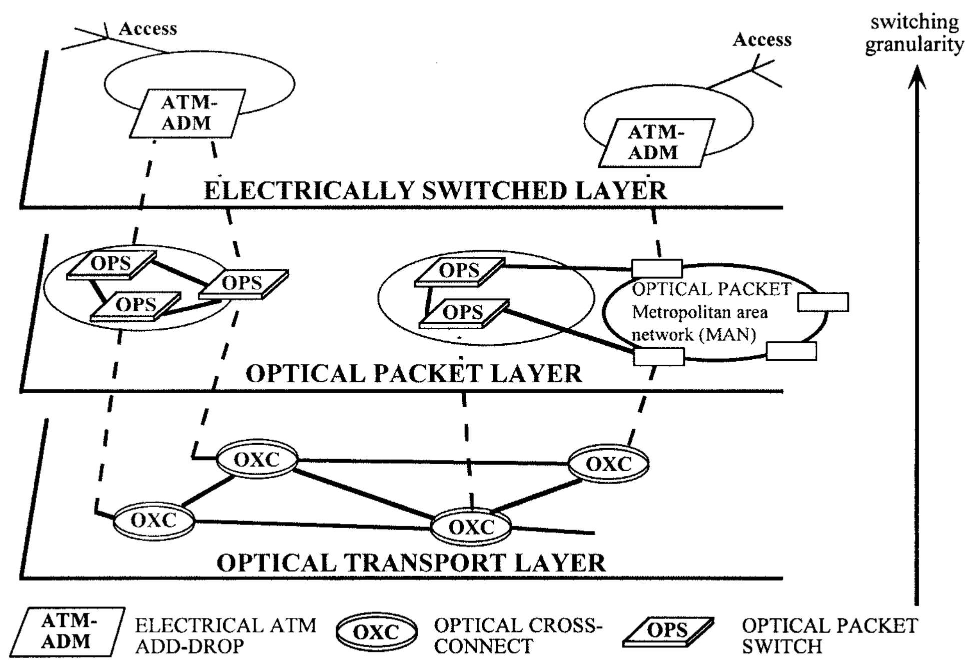


Fig. 1. The layered network reference model. At the top the access networks are depicted. The second layer is a transparent optical packet switched layer with optical packet switches as well as optical packet switched metropolitan area networks (MAN's). The third layer is an optical transport layer with optical circuit switched cross-connects.

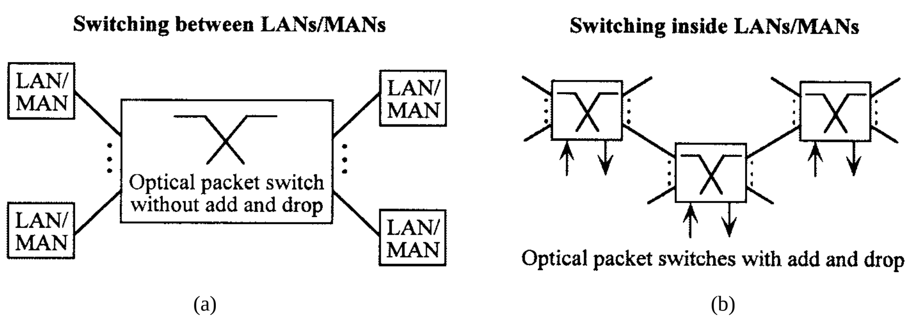


Fig. 2. The use of optical packet switches in optical networks. (a) Packet switch without add and drop for connection MAN's or large. (b) Packet switches with add and drop functions situated inside the LAN's or MAN's.

worldwide [1], [35], the implementation of the optical packet switched layer is on a longer term.

The advantage of having such a layer is that it will bridge the granularity gap between the existing electrical layers using, e.g, Asynchronous Transfer Mode (ATM) at 155/622 Mb/s and the optical channels in the backbone. Simultaneously, it will allow fast switching of frequently changing connections at a bit rate much higher than provided by the electrical layer without directly effecting the backbone cross-connects.

Using the layered reference model in Fig. 1, the next step is to consider architectures for the optical packet switches and identify the subblocks and components needed to realize them.

III. Basic Optical Packet Switching Architectures

It must be pointed out that some packet switch nodes require add–drop drop functions while others do not, depending on the required functionality of the switch node. To illustrate this, Fig. 2(a) shows an optical packet switch that is used to switch data streams between MAN's or large LAN's. In that case, the switch does not require add and drop functions since this is handled within the LAN's or MAN's. If, however, the switch node is part of a "local" network as shown in Fig. 2(b), the add and drop functions are required. The basic building block of the two switch types are the same, though, and for simplicity the switches presented in the following assume no add and drop functions. Later, in Sections IV and V the traffic performance for the switch nodes and networks is investigated.

A. The ATMOS Switch Architecture

The packet switch architecture suggested for the packet layer in the RACE ATMOS (ATM optical switching) project [15] is given in Fig. 3. The switch is not all-optical in the strict sense since the control is handled by electronics. The switch consists of three stages: 1) the first stage is the wavelength encoding section where the packet headers at each of the M inlets are detected with photo detectors (PD) in order to extract routing information. Based on this information, each packet is assigned the wavelength that fits the bandpass filter

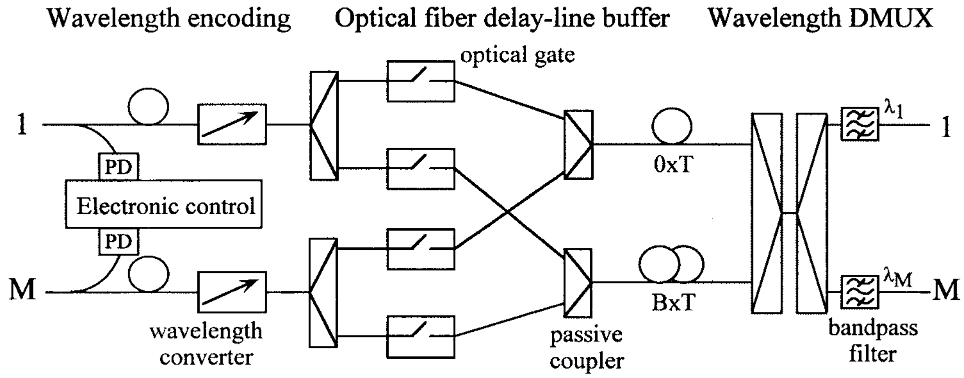


Fig. 3. The packet switch suggested in the European RACE research project, ATMOS.

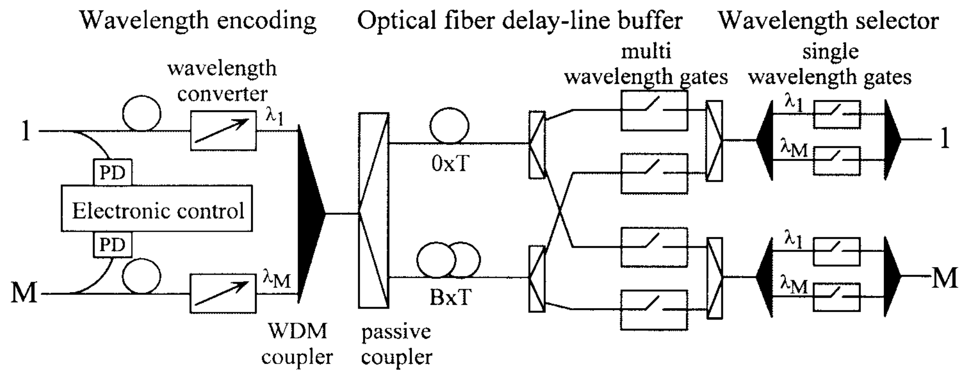


Fig. 4. The packet switch suggested in the European ACTS research project, KEOPS.

at the desired outlet by all-optical wavelength conversion; 2) contention resolution is achieved by a buffer section that uses optical fiber delay-lines with lengths corresponding to a multiple of the packet duration, T. To access the fiber delay-lines fast optical gates are used; 3) Finally, a wavelength demultiplexing stage with bandpass filters is selecting the packets.

B. The KEOPS Switch Architectures

In 1995 the European ATMOS project was succeeded by the KEOPS (KEys to Optical Packet Switching) project [12], [16] in which the study of the packet switched optical network layer has been extended. This has lead to the suggestion of an optical packet that has a fixed duration in time of about 1.7 μs. The packet header carrying information at 622 Mb/s is electronically processed while the payload carried by the packets can have a variable bit rate. The fixed packet duration ensures that the same switch node can switch the variable bit rate packets. Consequently—and in contrast to the electronic network in the upper layer of Fig. 1—the optical packet network layer proposed in KEOPS can be considered both bit rate and to some degree also transfer mode transparent, e.g., both ATM cells, IP (Internet Protocol) packets and SDH frames can be switched.

In addition to the variable bit rate packets, the switch architecture proposed in the KEOPS project allows for broadcasting of incoming data packets [36]. The switch is illustrated in Fig. 4 and basically consists of the same sections as the ATMOS switch. The main difference is that packets from a given inlet are always converted to the same wavelength. Combined with the use of multiwavelength gates following the fiber delay-lines as well as fast wavelength selectors at the output, broadcasting is enabled.

In more detail, the principle of operation can be described as follows [36]. Each incoming packet is assigned one wavelength through wavelength conversion identifying its input port and is then fed to the packet buffer. By passive splitting, all packets experience all possible delays. The role of the optical multiwavelength gates at the output of each delay-line is to select the packet belonging to the appropriate time slot determined by the queuing situation. It is noted that all wavelengths are gated simultaneously by these gates. The role of the fast wavelength selector is to select only one of the packets, i.e., one wavelength. This operation scheme provides the means for selecting the same wavelength at all or some outputs at the same time, i.e., broadcasting/multicasting.

With the description of basic packet switch architectures and the involved subblocks, we now turn to the analysis of the traffic performance which in turn will give design guidelines regarding the number of gates, wavelengths and input–output ports.

IV. Traffic Performance of Optical Packet Switches Without Add–Drop Functionality

The absence of an efficient way to store packets in the optical domain, reduces the realistic buffer capacity of the packet switches. As an example, a packet loss probability

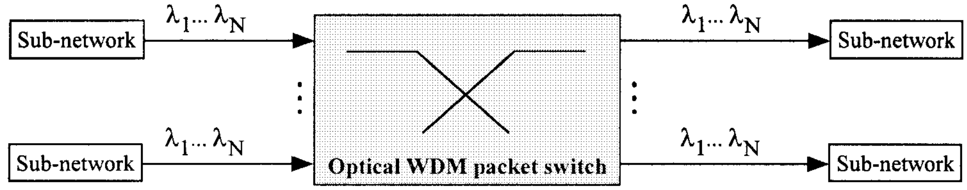


Fig. 5. WDM packet switch for interchanging packet data between subnetworks. N wavelength channels are used to transmit between the subnetworks and the switch.

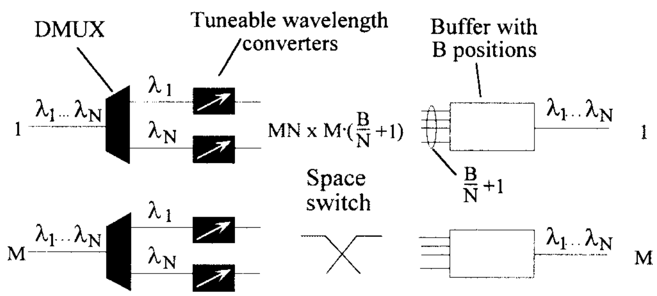


Fig. 6. WDM packet switch block with buffers realized by fiber delay-lines and with tuneable wavelength converters to address free space in the buffers (one buffer per outlet).

(PLR) of 10^{-10} at a random traffic load of 0.8 requires a buffer capacity of 48 packets per switch outlet for a 16×16 switch [23]. Realizing the optical buffer by fiber delay-lines requires fiber lengths up to ~15 km for a packet duration of 1.7 μs, which is the packet length considered in the KEOPS project [12], [16]. This is of concern for reasons of switch node complexity as well as compactness.

This section describes the use of the wavelength dimension for contention resolution proposed in [28] and recently demonstrated theoretically and experimentally in [29], [37]–[39]. The investigation considers the optical packet switches needed for interconnecting networks as shown in Fig. 2(a). It reveals that by exploiting the wavelength dimension by using WDM and employing tuneable optical wavelength converters (TOWC's) the required number of fiber delay-lines in optical packet switches can be reduced compared to switch architectures without wavelength converters [37], [38].

A. Network and WDM Switch Architecture Description

The optical WDM packet network considered in this section is shown in Fig. 5. The optical packet switch interchanges data between subnetworks that could be MAN's, large LAN's and in principle also wide area networks (WAN's). The network resembles a star network and N different wavelengths, $\lambda_1 \cdots \lambda_N$ per fiber, are used to carry the traffic.

In Section III, the ATMOS and KEOPS switch architectures with single channel input ports were described. Here, a generic realization of a WDM packet switch node is considered as shown in Fig. 6. The switch consists of three main blocks: 1) The input section where a demultiplexer (DMUX) selects the packets arriving at the N fixed wavelengths, $\lambda_1 \cdots \lambda_N$, and TOWC's address free space in the fiber delay-line output buffers, 2) a nonblocking space-switch to access the desired outlet as well as the appropriate delay-line in the output buffer, 3) packet buffers, that are realized by fiber delay-lines. As seen from the figure, the size of the space-switch is $N \cdot M \times M \cdot (B/N+1)$ where B is the number of packet positions in the buffer, N the number of wavelengths, M the number of in- and out-lets and B/N the number of delay-lines. Note that the last of the $B/N+1$ connections from the space switch through the buffer to each outlet is a fiber with an infinitesimal small length. In the following the term $B/N+1$ is denoted α for simplicity and it is stressed that for a given number of fiber delay-lines the number of packet positions, B, is a multiple of N so that α is an integer.

Not shown in the architecture are optical to electrical interfaces situated just after the demultiplexers at the switch inlets. As for the ATMOS and the KEOPS switches in Section III, these interfaces are used to extract the header of each packet by which the destination and thereby switch outlet can be found. Together with the knowledge of the queuing situation this is used to control the output wavelength of the converters as well as the state of the gates within the space switch. To illustrate the physical realization of the packet switches using fiber delay-lines and optical gates, Fig. 7 gives a more detailed view of the configuration in Fig. 6. In this paper the wavelength converters are assumed to be ideal. That means that no signal distortion or noise is introduced. The bandwidth of the converters is also assumed to be sufficiently high not to result in any impairments due to cascading. All of these assumptions have been shown reasonable by the experimental work carried out on, e.g., all-optic interferometric wavelength converters such as the Mach–Zehnder and the Michelson structure. As an example, such devices have been demonstrated to work at bit rates of up to 40 Gb/s [56] and in cascade of up to 20 converters [57].

B. Influence of Tuneable Wavelength Converters on the Number of Fiber Delay-Lines: Random Traffic

Tuneable wavelength converters are essential for the performance of the packet switch block. This is illustrated in Fig. 8 that shows the buffering process with and without tuneable wavelength converters. The TOWC's reduce the number of fiber delay-lines by storing multiple packets with different wavelengths in the same fiber. Note, that using the wavelength dimension in this way the sequence of packets belonging to the same connection may be disturbed [37]. This will cause the packets to arrive in an order different from that in which they were transmitted, thereby breaking the packet integrity rule. However, as described in [37], the statistical nature of this phenomenon only vaguely influences the traffic performance

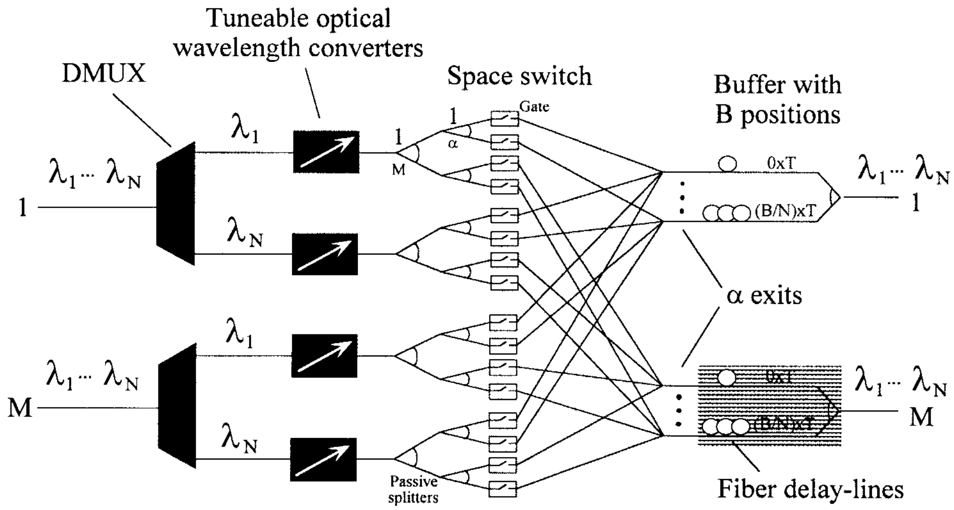


Fig. 7. WDM packet switch configuration (a) with buffers realized as fiber delay-lines and with tuneable optical wavelength converters to address free space in the buffers. T corresponds to the duration of a packet.

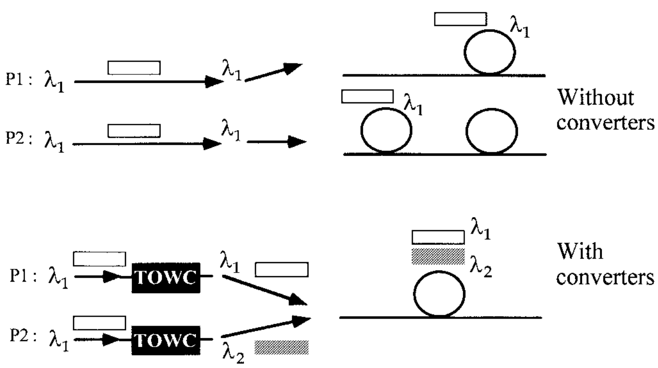


Fig. 8. Buffer filling process with and without wavelength converters. Two packets, P1 and P2 destined for the same outlet, arrive simultaneously and have the same wavelength, λ_1. Without converters, two fiber delay-lines are needed to store the packets, whereas with converters, only one delay-line is needed since one packet can be converted to another wavelength, λ_2.

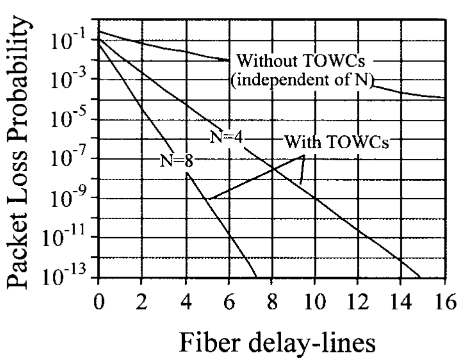


Fig. 9. Packet loss probability with and without tuneable wavelength converters versus the number of fiber delay-lines, B/N, at a load per wavelength channel of 0.8 for a 16 $\times$ 16 switch with four and eight wavelengths per inlet.

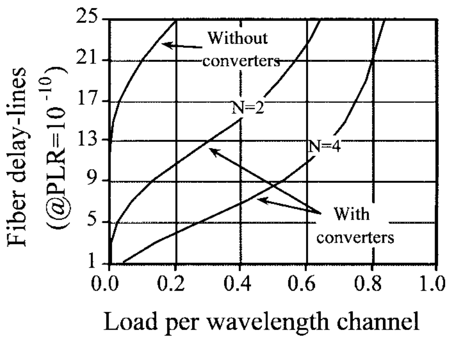
even for a worst case situation. Consequently, this behavior will not be accounted for in the following.

The reduction of the number of delay-lines by use of converters is confirmed in Fig. 9 using the traffic model for random traffic developed and verified in [37]. The figure shows the packet loss probability versus the number of delay-lines, B/N. The results are for a 16 $\times$ 16 switch with a load of 0.8 for each of the N wavelength channels per inlet. Without converters the performance is independent of N, and the queue can be viewed as consisting of N separate and independent queues, each being unique for one wavelength. This means, that without converters, the calculations can be carried out by setting $N = 1$. With converters, the switch performance in terms of the PLR is improved as the number of wavelengths is increased: When N is increased the total number of input and output channels also increase and both of these numbers are equal to $N \cdot M$. Despite the increase in the number of input channels, each output channel receives the same mean load ρ independent of N, and the buffer positions needed to ensure a given PLR is therefore almost unchanged. On the other hand, if the number of fiber delay-lines B/N is fixed, then the number of buffer positions increases with N. Consequently, the packet loss probability decreases with the number of wavelength channels when TOWC's are used. For comparison, 12 and 6 delay-lines are needed for N equal to 4 and 8, respectively, while 48 are needed for the case without wavelength converters (for PLR $< 10^{-10}$).

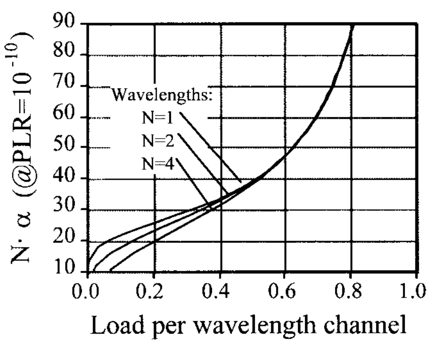
C. Influence of Tuneable Wavelength Converters on the Number of Fiber Delay-Lines: Bursty Traffic

To account for more realistic traffic, i.e., bursty traffic, an analytical model including bursty traffic conditions based on [40] has been implemented and verified as shown in [38]. Basic calculations for the single channel per fiber situation reveals that the accepted load is much lower for bursty traffic compared to random traffic. However, by going into the WDM regime this problem can be reduced as also illustrated for random traffic in the previous subsection.

For a burstiness of two (burstiness: average number of successive packets from a traffic source) Fig. 10(a) illustrates the reduction of the required number of fiber delay-lines due to the TOWC's that enable WDM packet switching. The figure gives the number of delay-lines for a fixed PLR of 10^{-10}. Clearly, the required number of fiber delay-lines decreases when the



(a)



(b)

Fig. 10. Required number of fiber delay-lines (a) and normalized complexity, $N \cdot \alpha = N \cdot (B/N + 1)$ (b) versus the load per wavelength channel (@PLR $= 10^{-10}$). The switch size is 4×4, and the parameter N is the number of wavelength channels per inlet and outlet. The burstiness of each channel is two.

number of wavelengths is increased. Very importantly, this reduction ensures that the size of the space switch of, e.g., the configuration in Fig. 7 remains nearly constant (it is pointed out, that this also holds for random traffic). The constant complexity is illustrated in Fig. 10(b) that gives the product $N \cdot \alpha$ versus the load for a 4×4 switch with one, two, and four wavelength channels per inlet and outlet. So, the throughput can be increased by increasing the number of wavelength channels without increasing the number of gates. On the other hand, for a fixed input load per fiber, $N \cdot \rho$, of say 0.8 the use of TOWC's together with WDM fiber delay-line buffers drastically decreases the product, $N \cdot \alpha$, from 87 ($N = 1$ and $\rho = 0.8$) to 20 ($N = 4$ and $\rho = 0.2$) and thereby the number of gates in the space switch of the configuration in Fig. 7 from 1392 to 320. Note, ρ is the traffic load per input channel.

If the burstiness is increased the required number of fiber delay-lines increases. If the number of delay-lines is kept constant, the possible traffic load will decrease when the burstiness is increased. For a 4×4 switch with a fixed and relatively low number of seven fiber delay-lines in the buffer, Fig. 11 clarifies the important role of the TOWC's. The figure gives the maximum tolerated load per wavelength channel as a function of the burstiness when a packet loss probability of 10^{-10} is required. Results are given with and without converters for two and four wavelength channels per in- and out-let.

As expected, the burstiness degrades the obtainable switch throughput significantly. On the other hand, Fig. 11 shows that

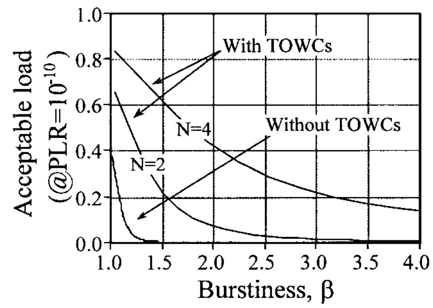


Fig. 11. Highest acceptable channel load (@PLR $= 10^{-10}$) versus burstiness. The switch size is 4×4 and the number of delay-lines is seven ($\alpha = 8$).

tuneable wavelength converters can be used to compensate for the impairment due to bursty traffic; with seven fiber delay-lines and for increasing burstiness a much higher traffic load can be switched when TOWC's are employed. For a moderate burstiness of 2 and with four wavelength channels per in- and out-let, the throughput is only 160 Mb/s without tuneable converters while it is increased to 64 Gb/s with tuneable converters assuming a channel bit rate of 10 Gb/s (the throughput is defined as $N \cdot M \cdot \rho$ times the bit rate in this case).

Another point is, that with wavelength converters and a fixed load per input fiber of 0.8, Fig. 11 shows that with four wavelength channels (i.e., $N = 4$ and $\rho = 0.2$) the tolerated burstiness is increased from ~1.1 to ~3.2.

The results in this section clearly underline the importance of wavelength converters for reducing the switch node complexity. Next, we turn to networks where add–drop functionalities are required in each node.

V. Traffic Performance of Optical Packet Switches with Add–Drop Functionality

As illustrated in Fig. 2, add–drop packet switch nodes can be used to construct network partitions or subnetworks taking the form of, e.g., metropolitan area networks (MAN) and on a large scale even wide area networks (WAN) [41]–[44]. The packet switch architectures described in the previous sections can almost directly be transformed into add–drop switches by dedicating a number of inlets as add-inlets and a number of outlets as a drop-outlets. Nevertheless, some differences in the architectures occur as discussed below.

As an example of a network that uses add–drop switches the Shufflenetwork [41]–[44] is shown in Fig. 12. The figure illustrates a general WDM Shufflenetwork with eight add–drop switch nodes. The network consists of 2×2 nodes (not including add–drop) and has two columns (last column is not counted since it is a replica of the first). It is noted that the generalized Shufflenetworks (that are generalizations of the perfect Shuffle) build with $M \times M$ switches and with k columns consist of $k \cdot M^k$ nodes. This shows that the Shufflenetwork is not very modular, e.g., for $M = 4$ the number of nodes is 32 for $k = 2$ and 192 for $k = 3$. Therefore, a slightly different way of increasing the network size in a modular fashion is used following the principle described

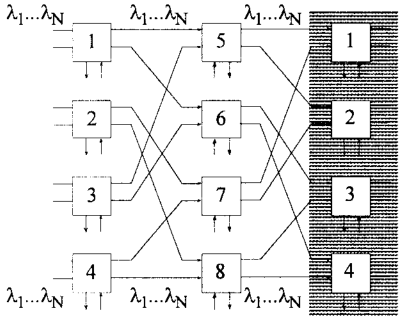


Fig. 12. WDM add–drop Shufflenetwork with N wavelength channels per fiber, 2 × 2 switches ($M = 2$) and two columns ($k = 2$) not counting the last column as it is a replica of the first.

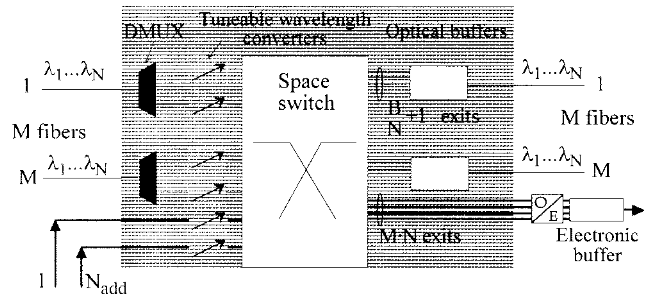


Fig. 13. Optical add–drop switch node with M optical fiber inlets and outlets (network in- and out-lets) and $N_{\rm add}$ add inlets. Each of the network inlets and outlets carries N wavelength channels, $\lambda_1, \cdots, \lambda_N$. Tuneable wavelength converters are used to address free space in the fiber delay-line optical output buffers. The drop buffer is electrical but could optionally be optical.

in [45]. Modularity is obtained by adding columns to the standard Shufflenet meaning that for a given value of k and M the addition of c columns gives a total of $(k+c) \cdot M^k$ nodes. For the network in Fig. 12 this means that by adding one column, a network with 12 nodes is obtained. For such networks the mean number of hops between nodes can be found by expanding the method given in [43].

The cylindrical connectivity pattern of the Shufflenetworks gives a simple addressing scheme, enables self-routing capabilities and alternate routing in response to congestion and network failures [42], [44]. Furthermore, and of great importance for the traffic performance as will be shown latter, these networks ensure a small number of hops between the transmitting and the receiving nodes.

Before carrying on with the description and analysis it is important to consider the network and switch sizes that are of interest. Local and Metropolitan area networks rarely number more than 250 nodes [46]. For reference, the RAINBOW-II network [47], which is a WDM MAN, comprises 32 nodes operating at 800 Mb/s while the STARNET network [48], which is a LAN, supports up to ~200 nodes at a bit rate of 1 Gb/s or 80 nodes at a bit rate of 2.5 Gb/s. Although these examples are very specific they indicate the network sizes of interest.

Concerning the size of the optical add–drop packet switches it is important that it be kept relatively low, i.e., $2 \times 2\ (M = 2), 4 \times 4\ (M = 4)$ or $8 \times 8\ (M = 8)$, to ensure that, e.g., the number of required wavelengths is practical and also to ensure a low complexity of the entire network.

A general architecture of optical add–drop packet switches is shown in Fig. 13. At each of the M inlets (network inlets) packets are received from other network nodes while the remaining inlets (add-inlets) $N_{\rm add}$ are used for adding local traffic. At the network inlets demultiplexers select the packets arriving at N fixed wavelengths $\lambda_1, \cdots \lambda_N$ while $N_{\rm add}$ channels carrying packets are added locally. Next, tuneable wavelength converters are used to address free space in the fiber delay-line output buffers (see Fig. 8). A space switch is used to access the optical fiber delay-lines and to route packets to the appropriate outlets. A packet that has to be dropped is routed to the drop outlet with subsequent optical to electrical conversion and electrical buffering (other outlets are referenced as network outlets). Note, that in principle the buffer at the drop outlet could be optical and be realized as a WDM buffer.

A. Traffic Theory for WDM Add–Drop Packet Switched Networks

Having identified the architectures we next develop a traffic model that accounts for wavelength converters, WDM and importantly the number of hops between nodes.

The analytical traffic model is based on the WDM packet switch model in [37] and on the ideas from [45] and [49]. It must be pointed out that although we consider Shufflenetworks, the model applies to any add–drop packet network provided that the following assumptions hold: 1) all add-inlets generate the same traffic load $\rho_{\rm add}$ and the traffic is assumed randomly distributed, 2) a routing algorithm exists, so that the traffic on each channel has the same distribution and carries the same mean load $\rho_{\rm net}$, and 3) each generated packet has the same probability of being destined for any node in the network, i.e., $1/(N_{\rm nodes} - 1)$ if the number of nodes in the network is $N_{\rm nodes}$.

It is recognized that the assumption of randomly distributed traffic made here as well as in [49] is a simplification. Yet, the traffic burstiness in the optical packet layer compared to the electrically switched ATM layer is generally low thereby justifying the assumption. As far as 2) is concerned, it is shown in [50] that this is a good assumption if an adaptive routing algorithm is employed for the Shufflenetwork.

The traffic flow out of, e.g., the electrical drop buffer is denoted $\rho_{\rm drop}$ and thereby the initial traffic variables are defined as shown in Fig. 14. With $\rho_{\rm add}$ signifying the load per add-inlet, the total network packet loss will be $1 - \rho_{\rm drop}/(N_{\rm add} \cdot \rho_{\rm add})$, thus the task is to derive equations to find $\rho_{\rm drop}$ for a given value of $\rho_{\rm add}$.

The throughput of the network queues (all other queues than the drop queue) is $N - \rho_{o\lambda}$ where $\rho_{o\lambda}$ is the mean number of unused wavelengths. With the above assumptions, the mean load on each of the $N \cdot M$ output channels is $(N - \rho_{o\lambda})/N$. This load is also the load of each channel at the network inlets of the switch $\rho_{\rm net}$ (see Fig. 14), since equal load on each channel in the network is assumed.

To use the queuing model described in [37], which applies for an optical WDM output queue, the arrival process to

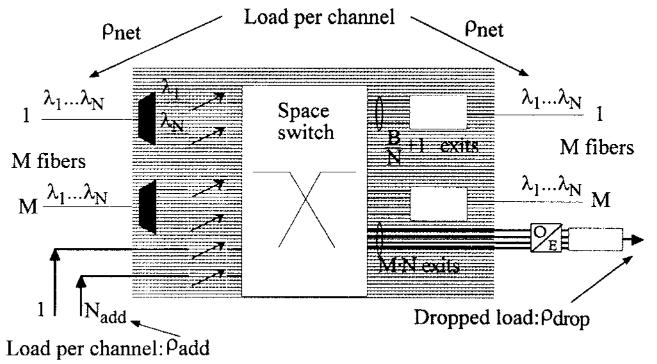


Fig. 14. Optical add–drop switch node with traffic parameters. When reaching stationary conditions, the load in the network channels is $\rho_{\rm net}$ while $\rho_{\rm drop}$ for the dropping outlet. The load offered to the network is $\rho_{\rm add}$ per adding inlet.

each of the network queues must be found. There are two contributions: 1) packets from the $N \cdot M$ channels originating from the network inlets and 2) packets from N_{add} channels originating from the adding inlets.

If the mean number of hops between nodes is denoted E then the probability of a packet from the network inlet going to the network outlets is given as, $1 - 1/E$. Looking specifically at one of these outlets, the probability of a packet choosing the given outlet is then $\rho_{\text{net}} \cdot (1 - 1/E)/M$, assuming that packets are equally likely to go to any of the M outputs. Thereby, the probability $c_{\text{net},j}$, of j packets arriving to a given network queue from the network inlets can be written as

$$
\begin{aligned}
c_{\text{net},j} &= \binom{N \cdot M}{j} \left(\frac{\rho_{\text{net}}\left(1 - \dfrac{1}{E}\right)}{M} \right)^{j} \\
&\quad \cdot \left(1 - \frac{\rho_{\text{net}}\left(1 - \dfrac{1}{E}\right)}{M} \right)^{N \cdot M - j} \\
\langle c_{\text{net}} \rangle &= \sum_{j=0}^{N \cdot M} j \cdot c_{\text{net},j} = N \cdot \rho_{\text{net}} \cdot \left(1 - \frac{1}{E}\right) \qquad (1)
\end{aligned}
$$

where the last term is the mean number of arriving packets. Likewise, the arrivals from the N_{add} adding inlets to the network output queue has a load of ρ_{add}/M and the probability $c_{\text{add},i}$ of i arriving packets from these inlets is

$$
\begin{aligned}
c_{\text{add},i} &= \binom{N_{\text{add}}}{i} \left(\frac{\rho_{\text{add}}}{M}\right)^{i} \left(1 - \frac{\rho_{\text{add}}}{M}\right)^{N_{\text{add}} - i} \\
\langle c_{\text{add}} \rangle &= \sum_{i=0}^{N_{\text{add}}} i \cdot c_{\text{add},i} = N_{\text{add}} \cdot \frac{\rho_{\text{add}}}{M}. \qquad (2)
\end{aligned}
$$

Combining the above equations, the probability, c_l, of a total of l packets arriving to the network queues can be written as

$$
\begin{aligned}
c_l &= \sum_{i=\max(0, l-N_{\text{add}})}^{\min(l, N \cdot M)} c_{\text{add},j} - c_{\text{net},l-i} \\
\langle c \rangle &= N_{\text{add}} \cdot \frac{\rho_{\text{add}}}{M} + N \cdot \rho_{\text{net}} \cdot \left(1 - \frac{1}{E}\right) \qquad (3)
\end{aligned}
$$

where summations account for boundary conditions and the latter formula gives the mean number of arriving packets to a given buffer of a network outlet.

The arrival of packets to the drop queue is similar to that described by (1) except that the probability $(1 - 1/E)/M$ is changed to $1/E$ and thus the probability $c_{\text{drop},p}$ of dropping p packets is

$$
\begin{aligned}
c_{\text{drop},p} &= \binom{N \cdot M}{p} \left(\frac{\rho_{\text{net}}}{E}\right)^{p} \left(1 - \frac{\rho_{\text{net}}}{E}\right)^{N \cdot M - p} \\
\langle c_{\text{drop}} \rangle &= \sum_{p=0}^{N \cdot M} p \cdot c_{\text{drop},p} = N \cdot M \cdot \rho_{\text{net}} \cdot \frac{1}{E}. \qquad (4)
\end{aligned}
$$

With the arrival probabilities given by the above equations, the transition probabilities for the number of packets in the optical queues can be found according to the method described in [37] and the PLR can be calculated. For the single channel electrical drop buffer, the method from [23] is used.

With one of these methods it is possible to calculate ρ_{drop} and hence the PLR for the total network. However, it is necessary first to find the steady state value of ρ_{net}. This is done by iteratively solving the queuing problem: In each step, a new value for the throughput of the network queues is found by calculating the PLR for these queues. When the throughput (equal to $N - \rho_{o\lambda}$) equals $N \cdot \rho_{\text{net}}$, the stationary value for ρ_{net} is obtained. This in turn will solve the packet loss probability for the drop queue through the arrival process described in (4). Consequently, the packet loss probability of the total network can be determined.

B. Routing Algorithms and Model Verification

The accuracy of the analytical model has been tested for two different sizes of the Shufflenetwork. However, before describing the results it is necessary to comment on the routing algorithms used. As described in [51] the routing algorithm must connect nodes such that the network resources are best utilized and so that the end-to-end delay is minimized. To keep the delay low, only shortest paths are used here, i.e., paths that use a minimum number of hops. It is noted, that in some cases the use of longer paths can improve the traffic performance [52].

In the simulations two routing algorithms are considered. The algorithms utilize that there can be more than one shortest path between two nodes. The first algorithm cyclically chooses between the paths. The second algorithm is more sophisticated and closely related to the one described in [50]. Based on the given traffic situation, packets are routed along the path where the maximum queuing delay in one of the nodes belonging to the path is smallest (see Fig. 15). This method is referred to as the min-max routing algorithm.

In the first simulation only the advanced routing algorithm is used. The results are shown in Fig. 16(a) that gives the PLR versus offered load, ρ_{add}. The network is an 8 node Shufflenetwork build from 2 $\times$ 2 switches with one wavelength channel per fiber $N = 1$ and where one channel is added per node, $N_{\text{add}} = 1$. Both the total network packet loss as well as the packet loss in the optical network queues for a single switch are considered (node loss). As in the related

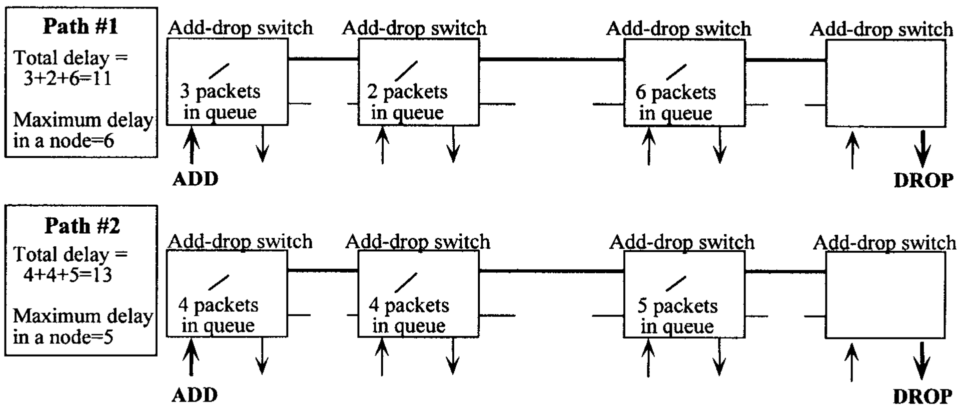


Fig. 15. Min-max adaptive routing algorithm that chooses the path with the smallest maximum queuing delay. There are two paths between the transmitting and receiving node. Path #2 is chosen even if the total delay is higher than for path #1 because the maximum delay in a single node is smallest for path #2.

analyzes for Shufflenetworks in [45], [49], [53], [54], excellent agreement with theoretical results is obtained.

Note, that the buffer size in the optical network queues is three while the electrical buffer for the drop queue can store 128 packets. This buffer size is chosen because a drop queue larger than ~100 ensures a packet loss probability (PLR) for the drop queue well below 10^{-10} even for a high drop load of 0.9. The realization of such an electrical queue size is not facing the same difficulties as an optical buffer and is used in the rest of the section.

To test the model on a larger network and compare the routing algorithms, Fig. 16(b) shows the results for a 24-node Shufflenetwork for both the advanced and the cyclic routing scheme. Again good agreement with theory is obtained. Furthermore, it is seen that with the advanced routing scheme superior performance is obtained. Additional simulations have revealed that the main reasons for this is, that the load is better balanced with the min–max path assignment scheme.

The conclusion from the simulations is that the theoretical model describes the traffic performance of packet switched add–drop networks correctly and will be used in the following analysis where we focus on the advantage of WDM together with the use of wavelength converters (see also [55]). For this analysis three basic scenarios for 2 × 2 add–drop packet switch architectures with two wavelength channels per fiber are considered as shown if Fig. 17. It is assumed that the total added load is 0.8: In Fig. 17(a), the architecture has wavelength converters on all switch inlets. In this case only one adding channel is needed to carry the full load. In Fig. 17(b), there are not wavelength converters on any switch inlet. This requires two adding channels, $N_{\rm add} = 2$, each carrying half of the load. Finally, Fig. 17(c) shows a wavelength converter only on the adding inlet. In this case as well, only one adding inlet, $N_{\rm add} = 1$, is required to carry the load of 0.8.

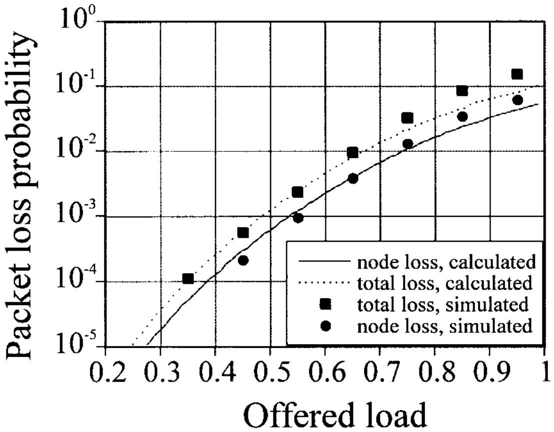
C. Comparison of WDM Add–Drop Switch Nodes with and Without Converters

We start with the configuration where tuneable converters are used on all inlets. To reduce the optical buffer size the number of wavelength channels can be increased as also indicated by Fig. 9. This is also the case for add–drop nodes as illustrated in Fig. 18 that gives the required number of wavelength channels per fiber to keep the PLR of the network below 10^{-10} when there are no optical buffers in the nodes, $B/N = 0$. The results are given as a function of the number of nodes in the network and a total added load of 0.8 is assumed with $N_{\rm add} = 1$. Results are not shown for situations without wavelength converters because more than 20 wavelength channels are then required. Comparison with architectures that only use converters in the add inlets is carried out later.

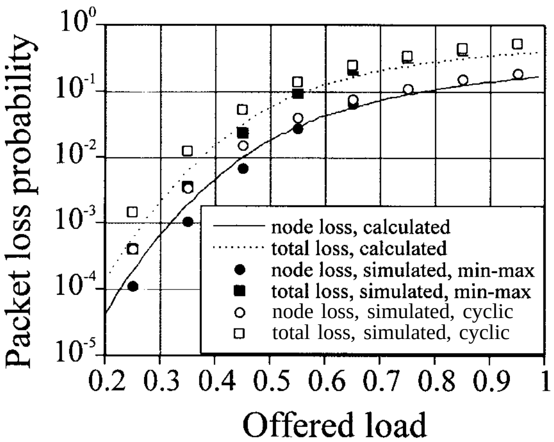
It is seen that with a realistic set of 16 wavelength channels per fiber and with wavelength converters, more than 1000 nodes in the network is possible with 8 × 8 add–drop switch nodes without optical buffering. Decreasing the size of the switch nodes, reduces their complexity, but leads to an increase in the mean number of hops in the Shufflenetwork due to the lower connectivity. The lower connectivity is caused by the fact that fewer nodes can be reached in each hop. As a result, more wavelength channels are needed and consequently, a choice has to be made, whether the complexity should be in terms of wavelength channels or in terms of switch size.

The geographical area covered by, e.g., a MAN optical packet network is relatively small so the number of nodes is small. Hence, it is interesting to find the obtainable throughput for a fixed network size. For a 32 node Shufflenetwork without optical buffers Fig. 19 gives the required number of wavelength channels (PLR $< 10^{-10}$) versus the offered load per node. Again it is noted, that as the switch size decreases the number of needed wavelength channels increases. Still, with small 4 × 4 add–drop switches an offered load per node of 0.7 can be accepted with only 8 wavelength channels.

To reduce the number of channels a few delay-lines can be used. This is illustrated in Fig. 20 that gives the required number of wavelength channels to ensure a packet loss probability below 10^{-10} versus the number of fiber delay-lines in the optical buffers. The network is a 32 node Shufflenetwork realized with either 2 × 2 switch nodes ($k = 2$ and the number of extra added columns is $c = 6$) or with 4 × 4 switch nodes ($k = 2$ and the number of extra added columns is $c = 0$). The total offered traffic per node, $N_{\rm add} \cdot \rho_{\rm add}$, is 0.8 in all cases. When no wavelength converters are used $N = N_{\rm add}$ is required accord-

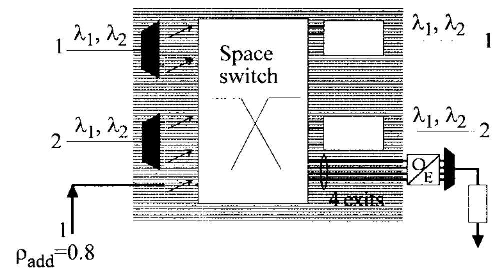


(a)

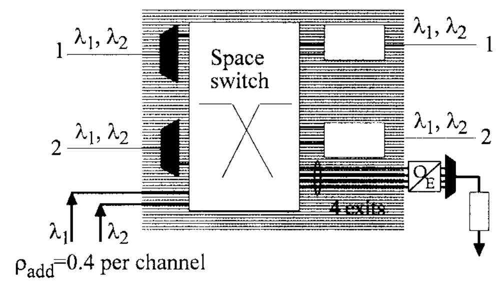


(b)

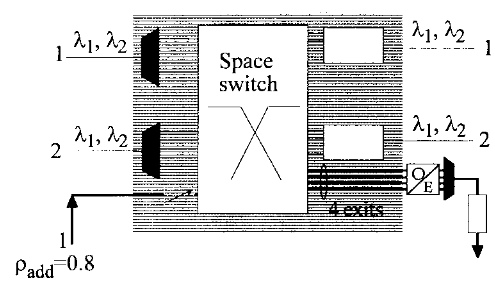
Fig. 16. (a) Packet loss probability in the network queues (node loss) and in the entire network (total loss) versus the offered load per node $\rho_{\rm add}$. Solid lines are calculated for the network queues while the dashed line is calculated for the total loss. Dots and squares are simulated values found by the min-max scheme. The network size is eight with $M = 2$ and $k = 2$ for the Shufflenetwork. One wavelength channel is added per node and one wavelength channel is used per fiber, i.e., $N = N_{\rm add} = 1$. The optical buffer size is 3 delay-lines. (b) Packet loss probability in the network queues (node loss) and in the entire network (total loss) versus the offered load per node, $\rho_{\rm add}$. Solid lines are calculated for the network queues while the dashed line is calculated for the total loss. Closed circles and squares are simulated values found using the min-max scheme; open symbols are for the cyclic path allocation. The network size is 24, $M = 2$ and $k = 3$. One wavelength channel is added per node and one wavelength channel is used per fiber, i.e., $N = N_{\rm add} = 1$. The optical buffer size is three delay-lines.



(a)



(b)



(c)

Fig. 17. Three possible configurations for realizing a 2 × 2 add–drop packet switch architetcure with 2 wavelength channels per fiber. It is assumed that the total added load is 0.8. (a) Wavelength converters on all switch inlets. In this case only one adding channel is needed to carry the full load. (b) No wavelength converters on any switch inlet. This requires two adding channels, $N_{\rm add} = 2$, each carrying half of the load. (c) Wavelength converters only on the adding inlet. In this case as well, only one adding inlet $N_{\rm add} = 1$ is required to carry the load of 0.8.

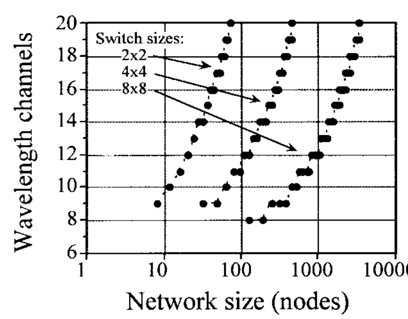


Fig. 18. Required number of wavelength channels N (PLR of the total network $<10^{-10}$) versus the network size when there are no optical buffers. The offered load per node is 0.8 with $N_{\rm add} = 1$. The switch size M is the parameter. Wavelength converters are assumed. $k = 2$ and the network size is increased by increasing c.

ing to Fig. 17 while with converters only one added channel is needed. When a converter is used only for the add inlet there are no converters at the network inlets and $N_{\rm add} = 1$.

For both switch sizes, Fig. 20 shows, that when wavelength converters are used at all inlets, a small optical buffer significantly reduces the required number of wavelengths. With only one fiber delay-line, the number of wavelengths is reduced from 14 to 6 and from 9 to 4 for $M = 2$ and $M = 4$, respectively. This has a significant influence on the number of gates needed in the nodes. The total number of gates in the space switching stage is $N \cdot M \cdot \alpha \cdot M + N \cdot M + N_{\rm add} \cdot \alpha \cdot M$ (see Fig. 13): The first term is the number of gates needed to combine each channel from the network inlets with the network queues, the second term combines the same channels with the drop queue while the third term represents the gates needed to connect the adding inlets with the network queues.

In the case of 2 × 2 switch nodes with converters, the use of one fiber delay-line instead of none reduces the number

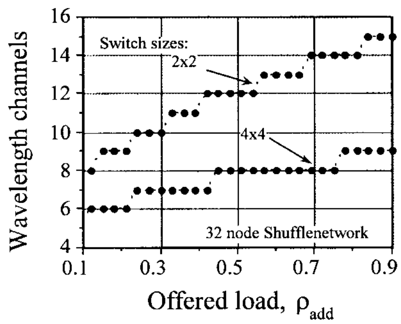


Fig. 19. Required number of wavelength channels N (PLR of the total network $<10^{-10}$) versus the offered load per node when there are no optical buffers. The offered load per node is 0.8 with $N_{\mathrm{add}} = 1$. The switch size M is the parameter. The network size is 32. Wavelength converters are assumed. $k = 2$ and the network size is increased by increasing c, i.e, for 2 × 2 switch nodes c is 6 while c is 0 for 4 × 4 switch nodes.

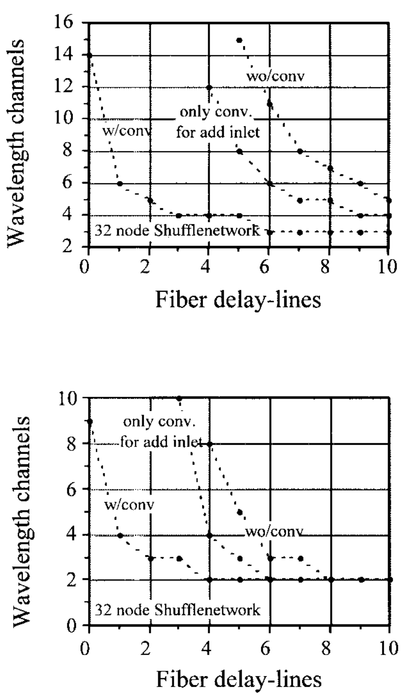


Fig. 20. (a) For a 32 node Shufflenetwork: Required number of wavelength channels (PLR $< 10^{-10}$) versus the number of fiber delay-lines in the optical buffers. When no wavelength converters are used $N = N_{\mathrm{add}}$ is required while with converters $N_{\mathrm{add}} = 1$ (see Fig. 17). When a wavelength converter is used only for the add inlet there are no converters at the network inlets and $N_{\mathrm{add}} = 1$. The total offered traffic per node $N_{\mathrm{add}} \cdot \rho_{\mathrm{add}}$ is 0.8. $M = 2$. (b) For a 32 node Shufflenetwork: Required number of wavelength channels (PLR $< 10^{-10}$) versus the number of fiber delay-lines in the optical buffers. When no wavelength converters are used $N = N_{\mathrm{add}}$ is required while with converters $N_{\mathrm{add}} = 1$ (see Fig. 17). When a wavelength converter is used only for the add inlet there are no converters at the network inlets and $N_{\mathrm{add}} = 1$. The total offered traffic per node $N_{\mathrm{add}} \cdot \rho_{\mathrm{add}}$ is 0.8. $M = 4$.

of gates in the space switch from 86 to 64 and the number of converters from 28 to 12 not including the converter in the add inlet. For both $M = 2$ and $M = 4$ it is noted, that by using more than two fiber delay-lines the required number of channels hardly changes and therefore only adds to the complexity.

Without converters, it is seen in Fig. 20(a) that for $M = 2$, no more than eight wavelength channels are necessary with eight fiber delay-lines. For $M = 4$ the number of hops between the nodes is smaller compared to the case of $M = 2$. This increases the channel efficiency and therefore only four delay-lines are required if no more than 8 wavelength channels are desired as seen in Fig. 20(b).

With wavelength converters only at the add inlet, larger buffers are needed compared to the case with converters at all inlets. Still, the approach with converters only at the add inlets is superior to the solution that does not use converters at any inlet. If 8 fiber delay-lines are feasible for $M = 4$, though, it must be recognized that there is no advantage in terms of fewer wavelength channels by using converters.

VI. Optical Packet Switching Without Packet Alignment

So far, the approaches to optical packet switching have relied on synchronous operation of switch blocks with packet alignment at the input in analogy with an electronic packet switch. The packet alignment is, however, difficult to implement in the optical domain since signal processing at bit level is not readily available. Therefore, it is of big interest to assess switch block performance in the case where the packets are routed without alignment.

In the following, it is shown that asynchronous (unaligned) operation leads to an increased packet loss ratio. However, use of the wavelength domain for contention resolution can counteract this. Thereby, a good traffic performance is attained while the use of complicated packet alignment units is avoided.

An example of an optical packet switch block without packet alignment is shown in Fig. 21 [34]. It is an expanded WDM version of the broadcast and select switch that is proposed in the KEOPS project (see Fig. 4) and relies on header detection and alignment of incoming packets. Regarding the optical parts of such a switch block nothing is generically synchronous: the gates and the converters can be controlled with a variable offset to an internal clock, the buffering by fiber delay-lines is passive and so are the remaining multiplexers, splitters and waveguides. So, the complex optical packet alignment can be eliminated if instead each packet is time tagged relative to a local clock.

A. *Traffic Simulation Model*

To assess the traffic performance of an asynchronous switch two models have been implemented. The first is an analytical model for a synchronously operated switch and is identical to [23] while the second is a computer simulation model for an asynchronous packet switch for which analytical expressions are not available. The numerical model uses a subdivision of each time slot into subtime slots (see Fig. 21) enabling the emulation of randomly arriving packets. Furthermore, the model accounts for the use of WDM buffers constructed from fiber delay-lines in combination with wavelength converters. The buffer is efficiently controlled to minimize the time delay of the packet. It is noted that this can violate the packet sequence integrity, however, the probability for this is very low and therefore it has only negligible influence on the overall traffic performance [37].

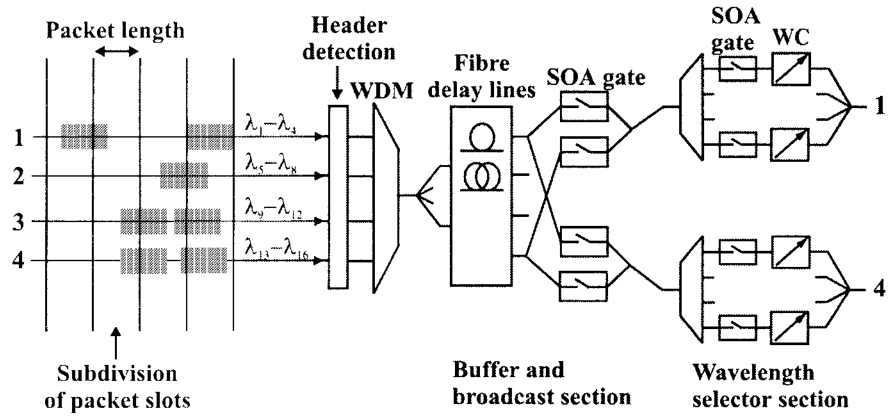


Fig. 21. Optical broadcast and select 4 × 4 WDM packet switch which can be operated without packet alignment units. The subdivision of the time slots used in the traffic analysis is shown to the left together with the packets arriving unaligned.

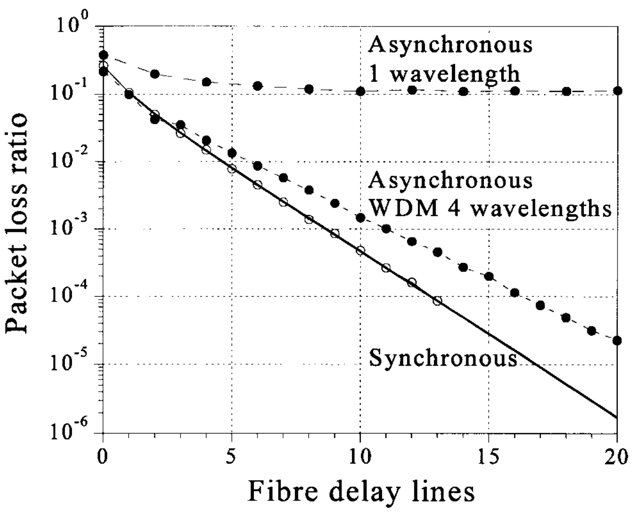


Fig. 22. Packet loss ratio for a 4 × 4 switch block with a load of 0.8 per wavelength as a function of the number of fiber delay-lines for both synchronous and asynchronous operation. A large reduction in packet loss ratio is observed using WDM. For synchronous open circles are simulations (open circles) while solid lines give predictions of the analytical model. All results for the asynchronous case are obtained from computer simulations.

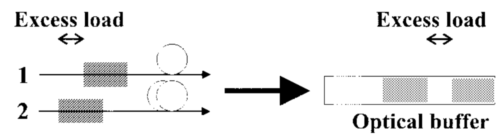


Fig. 23. Excess load arises when packets enter the optical buffer with random arrival time, i.e., unaligned with packets from other inlets.

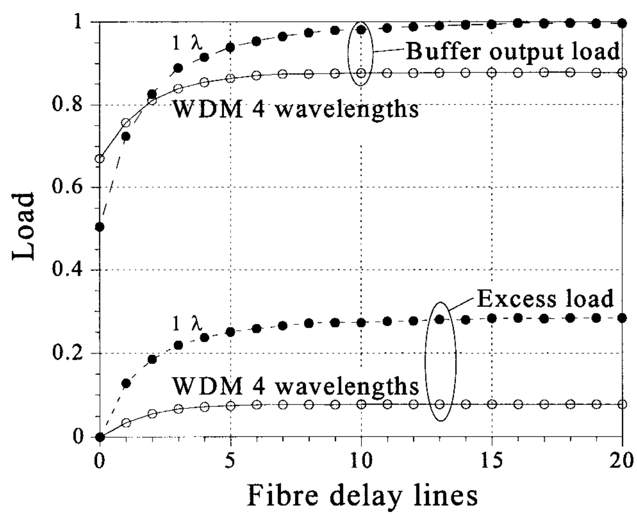


Fig. 24. Simulated buffer output load (top) and the load of the empty data stored (bottom) as a function of the number of fiber delay-lines for a 4 × 4 switch block with a input load of 0.8 with one and four wavelengths, respectively. Asynchronous operation is considered.

Essential aspects of an asynchronously operating packet switched network are illustrated in Fig. 22. The PLR for a 4 × 4 switch block with a load of 0.8 per wavelength as a function of the number of fiber delay-lines shows a significant increase in the PLR when an asynchronous operation scheme is used and a floor of $\sim 10^{-1}$ is noticed. However, if four wavelengths are used on each in- and outlet the buffer becomes more flexible and the throughput is increased to a total of 4 × 0.8 per fiber. Hereby, the impairment of the asynchronous operation is almost eliminated so that, e.g., for 12 fiber delay-lines the PLR is only increased from 2×10^{-4} to 7×10^{-4} going from aligned to nonaligned operation.

The poorer performance of nonaligned operation originates from the efficiency in the use of buffer space. If the packets arrive in a synchronous manner the buffer capacity will be used optimally and with no wasted buffer space. On the contrary, packets with random arrival time will result in generation of an excess load as depicted in Fig. 23. For multiple wavelengths per inlet, the packets can be assigned the wavelength that will result in the smallest amount of excess load thereby yielding a more efficient buffer.

In Fig. 24 both the excess load and the total load out of the buffer, i.e., data plus unused buffer space, are shown as a function of the number of fiber delay-lines for a 4 × 4 switch block with an input load of 0.8 per wavelength. The excess load increases to ∼0.3, which together with the input load of 0.8 result in the total load of >1. This means that packets are lost and that the total output load saturates at ∼1 resulting in a PLR floor as seen in Fig. 22.

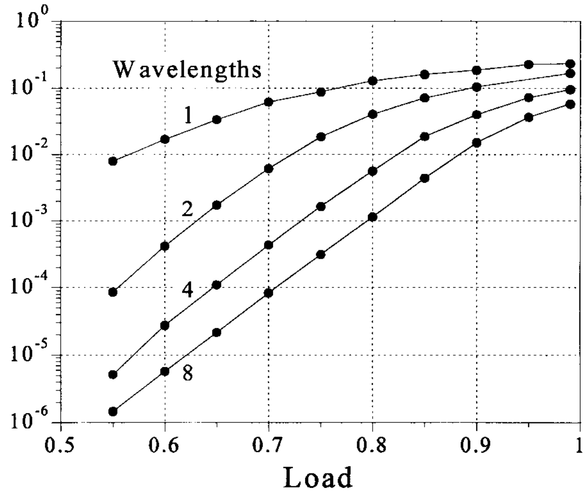


Fig. 25. Simulated packet loss ratio as a function of the load for a 4×4 switch block with eight fiber delay-lines and the number of wavelengths as a parameter. Asynchronous operation is considered.

It is essential to note that the generation of an excess load can not be counteracted by increasing the number of fiber delay-lines but only by altering the buffering process. The excess load will, therefore, be reduced when using multiple wavelengths. This is observed in Fig. 24 where the excess load is reduced to only ~0.1 and the total output load consequently saturates at ~0.9. In turn, this explains the improved performance shown in Fig. 22.

The improvement from using WDM depends on the input load as showed in Fig. 25. Here, the PLR for unaligned packet operation is shown as a function of the load per wavelength for eight fiber delay-lines and with the number of wavelengths as the parameter. The PLR increases with the load while more WDM channels lead to a significant improvement. Already for two wavelengths the added flexibility in the buffer is evident from the reduction in the PLR.

VII. Conclusion and Summary

This paper has described investigations of important issues for optical packet switched networks. The emphasis has been on ways to reduce the switch complexity related to optical buffering and optical synchronization. Moreover, use of the wavelength domain for contention resolution by using wavelength converters has been examined. The results clearly show that converters greatly improve the traffic performance of WDM packet networks. These improvements are manifested by reduced switch complexity, switch size, number of optical gates and number of wavelength channels. These are trends that not only hold for randomly distributed traffic patterns but also for bursty traffic, showing that photonic networks transporting bursty data are both realistic and practical. Furthermore, it is noted, that the flexibility rendered by the converters even allows for optical packet switches without any fiber delay-lines for buffering.

The scenarios considered in the traffic studies include both simple interconnection networks as well as networks where the switch nodes require add–drop functionality like in, e.g., Shufflenetworks. The importance of minimizing the number of hops between origin and destination in the latter type of networks has been addressed. It has been shown that by using a few fiber delay-lines in the optical buffers (less than eight) while keeping the node sizes low (less than eight fiber input/outputs), the required number of wavelength channels can be kept at realistic levels of 4–16. This indicates that such high-performance bit rate scalable networks can be deployed within a foreseeable future.

Finally, it is shown that the optical packet alignment at switch inlets may be avoided. The asynchronously operated optical packet switch blocks suffer a high packet loss ratio, but use of wavelength converters together with WDM reduces the impairment significantly. So, complex optical packet alignment units may be avoided.

In conclusion, the time for deployment of a transparent optical packet layer is coming still closer due to the rapid evolution of all-optical functional devices such as semiconductor gates and wavelength converters as pointed out through the traffic analysis in this paper.

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