Transparent Optical Packet Switching: The European ACTS KEOPS Project Approach

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***Abstract*—This paper reviews the work carried out under the European ACTS KEOPS (KEys to Optical Packet Switching) project, centering on the definition, development and assessment of optical packet switching and routing networks capable of providing transparency to the payload bit rate. The adopted approach uses optical packets of fixed duration with low bit rate headers to facilitate processing at the network/node interfaces. The paper concentrates on the networking concepts developed in the KEOPS project through a description of the implementation issues pertinent to optical packet switching nodes and network/node interfacing blocks, and consideration of the network functionalities provided within the optical packet layer. The implementation, from necessity, relies on advanced optoelectronic components specifically developed within the project, which are also briefly described.**

I. Introduction

WAVELENGTH division multiplexing (WDM) optical network concepts provide a platform for significant improvement in network bandwidth capacity and are poised to dominate the backbone infrastructure supporting the next-generation high-speed networks (ATM, IP). The rapid increase in traffic levels necessitates networks with fast packet switching, supported by native optical transmission. While current applications of WDM focus on the static usage of individual WDM channels, optical switching technologies enable the fast allocation of WDM channels in an on-demand fashion with fine granularities (microsecond time scales). The challenge now is to combine the advantages of the relatively coarse-grained WDM techniques with emerging all-optical switching capabilities to yield a high-throughput optical platform directly underpinning next generation data networks.

In this context, the ACTS KEOPS Project (KEys to Optical Packet Switching) addresses the analysis and demonstration of optical (bit rate) transparent packet (OTP) switching within all-optical network architectures by means of network and system studies, and laboratory demonstrators based on components developed in the project. Partners contributing to the KEOPS project are Alcatel Alsthom Recherche (F), France Telecom-CNET (F), CSELT (I), Technical University of Denmark (DK), Alcatel CIT (F), Alcatel SEL (D), University of Bologna (I), ETH-Zürich (CH) and the University of Strathclyde (UK). Progress achieved since the start of the project in September 1995, on network and system issues, system demonstrators and components, is reported in this paper, that is structured as follows:

In Section II, the main issues with respect to supporting next-generation high-speed networks are discussed, highlighting the benefits afforded by optical packet networking combined with WDM techniques. Although the focus is here put on interworking with IP networks because of the booming deployment experienced by the Internet, the approach applies also to other high speed networks such as ATM. The required functionalities for interfacing with WDM cross-connected networks are reviewed as well. Section III addresses the optical node architectures, starting with the identification of the subblocks necessary for interfacing the switching fabric with WDM transmission links. Several architectural options are examined with the aim of overcoming the limitations imposed on performance by optical buffering. Section IV summarizes the development of key technologies and functionalities required not only for the KEOPS demonstrator activities but more significantly, representing a common technology base

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for all WDM optical networks. Finally, an examination of the achievements of the project coupled with a detailed evaluation of the potential of optical packet switching enables a critical comparison of the advantages of optical packet networks with respect to electronic systems (Section V).

II. Optical Packet Networks: Linking WDM and High-Speed Data Networks

A. High Bit Rate Networking

1) Issues: The convergence of telecommunications and computer communications has been anticipated for some time since both rely on the underlying digital technology. In the early 1980's, the scenario appeared relatively clear cut: traditional telecommunications traffic was dominant and achieving the integration meant upgrading the connection oriented, circuit-switched telecommunications infrastructure to enable the support of data traffic. Entering the new millenium, the networking environment has completely changed.

- The current trend for data traffic transmission worldwide, in particular of Internet traffic, shows that, in the midterm, it will reach and even exceed traffic due to telephony service, making data communications the dominant traffic type [1].
- The development of WDM techniques on point-to-point links utilizes the optical bandwidth of installed fibers efficiently and incrementally (with respect to the number of wavelength channels as well as the bit rate per channel).
- The future development of optical cross-connected WDM transport networks, dynamically managing optically transparent lightpaths, will potentially render redundant the network functionalities provided by the SDH layer.
- From the client perspective, IP has become the dominant protocol for data communications; it thus represents a very strong candidate for the integration of data communications with telecommunications. Even if present versions of IP cannot support differentiation of the client flows on quality-of-service (QoS) criteria, ongoing development within the Internet Engineering Task Force (IETF) should soon result in advances capable of guaranteeing a sufficient QoS across a spectrum of traffic types.

Thus, within the last two decades, the accepted vision of the Broadband Integrated Service Digital Network architecture (BISDN) has widened and now encompasses IP/WDM in addition to ATM/SDH or IP/SDH/WDM.

The main concern with the IP/WDM approach is the mismatch between the transmission capacities offered by the WDM optical layer and the processing power of current routers [2]. IP routers perform three main tasks:

1) *routing:* supporting various protocols so as to maintain the network connectivity information contained in the routing tables;
2) *forwarding:* referring to the routing table for each incoming packet to determine the output interface to which the packet should be written;
3) *switching:* directing each packet to the proper output interface, as defined by the forwarding process.

With respect to routing, the main issues stem from the size of the routing tables and the frequency of their updates. Such problems are currently addressed and managed by well-known means (route aggregation, routing protocol updating to avoid redundant or obsolete information exchanges). The main performance bottleneck arises at the forwarding level. The time needed for a routing table look-up sets a hard limit to the router throughput (expressed in packet/s). Two different solutions have been proposed to alleviate this bottleneck [3], [4]: 1) parallelization of the forwarding operation, as this is performed independently on packet-by-packet basis and 2) optimization of the routing table encoding and of the look-up algorithm, resulting in impressive improvements. Considering a conservative estimate of the average packet size of 200 bytes with a pessimistic evaluation of 2.10^6 look-ups per second, demonstrated on 200 MHz Pentium Pro platform, the limit on the maximum bit rate set by the forwarding process is about 3 Gb/s.

The adoption of current ATM switching technology or switching technologies inherited from the supercomputer industry provide access to large and fast switching matrices, which might alleviate the switching bottleneck. Advances in technology and architectures have lead to a new generation of IP gigabit routers, a prime example being the Neo Networks 512 Gb/s nonblocking switching matrix for its stream Processor 2400 [5].

Despite these impressive upgrades, it should nevertheless be noted that electronic switching systems lack flexibility regarding their throughput upgrade capability. Given that WDM allows cheap incremental increases of the transmission bandwidth, much more frequent upgrades of the transport layer capacity can be envisaged to match increasing demand. Such frequent increases will place heavy demands on the switching process, which in turn will require frequent, costly upgrades to keep up with the transmission rate.

2) Optical Packet Networking: Given the above trends, KEOPS seeks to combine packet switching with WDM transmission techniques to yield WDM optical packet switching. The goal is to shift most of the switching burden into the optical domain, permitting the successful scaling of the switching capability of IP routers, compatible with the capacity of WDM transmission. In so doing, an effective decoupling between the bandwidth and routing/forwarding is also achieved. The former, involving both transmission and switching, is addressed in the optical domain, accessing the huge fiber bandwidth; the latter is carried out in the electronic domain, where the relatively complex packet routing/forwarding process occurs at the packet header level whatever the size of the attached data entity.

In addition, the optical packet layer provides some basic link layer functions mandatory for efficient interfacing of IP with the WDM layer by transporting IP packets in optical packet payloads. It also provides a further multiplexing level in the time domain, necessary to allow the IP routers to aggregate client flows prior to transmitting information onto the optical WDM pipe. This generally removes the need for SDH as an adaptation layer for IP traffic on point-to-point WDM wavelength channels. This trend is reinforced

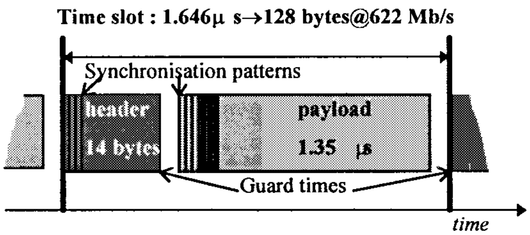


Fig. 1. Packet format used within KEOPS project.

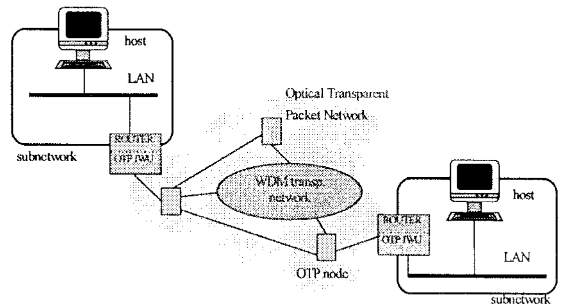


Fig. 2. Connection of IP networks by means of the OTP-N.

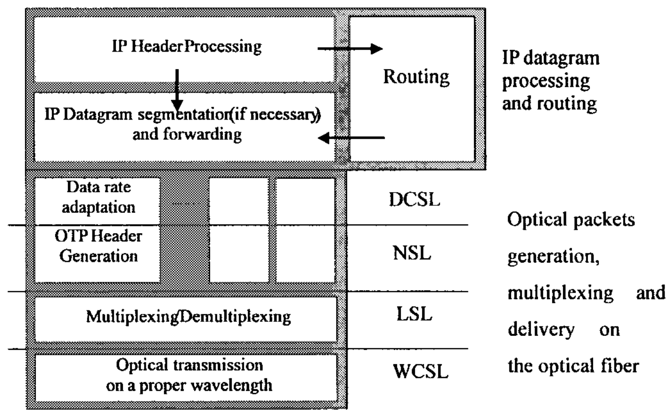


Fig. 3. OTP-N network reference structure.

by recent initiatives which aim to overlay switching and routing technologies directly onto optical networks [6]. Such initiatives imply the realization of a clear-channel 2.5 Gb/s interface between IP gigabit routers and long-haul WDM system, eliminating the need for SDH terminal multiplexers or other intermediate network elements. Such an interface would allow the entire 2.5 Gb/s bandwidth of an STM-16 connection to be treated as a single, dark fiber pipe.

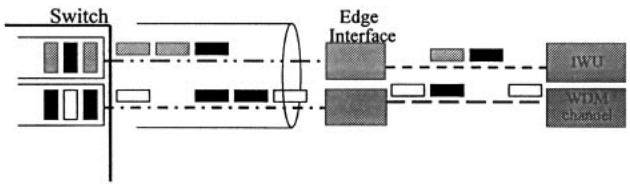
Furthermore, the decoupling of the transmission and switching requirements from the routing/forwarding functionalities, highlights optical packet networking as a promising candidate able to support any dedicated electronic routing/forwarding networking protocols while exploiting the bandwidth of optical fibers. Considering that core routers experience heavy traffic conditions in IP backbones, alleviating the load placed on the forwarding processors remains a crucial goal. Solutions based on label switching are currently being considered within the multiprotocol label switching (MPLS) framework [7] to bypass the forwarding bottleneck. The emergence, therefore, of a solution providing connection-oriented networking capacities, flexible in term of bandwidth management and future proof with regard to bandwidth growth, is much sought after. KEOPS also provides interconnection facilities through the optical packet networking.

A number of approaches exist for realising optical transparent packet networks (OTP-N) [8]. In the case of the KEOPS optical transparent packet network, fixed duration packets are utilized where both the header and its attached payload are encoded on the same wavelength carrier. Routing information is derived from the packet header after opto-electronic conversion; the header is encoded at a low fixed bit rate, e.g., 622 Mb/s, to allow the utilization of standard electronic processing. In order to realize a network insensitive to the load bit rate, the payload duration is fixed whatever its content; the data volume is proportional to the user-defined bit rate which may vary from a few hundred Mb/s to 10 Gb/s, with easy upgrade capability [9]. The packet format is depicted in Fig. 1.

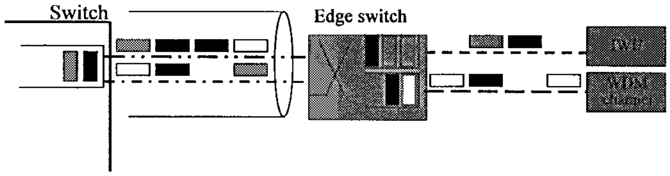
B. Optical Transparent Packet Network Architecture

1) Interworking with Electronic Networks and WDM Transport Networks: In this section, the architecture for the OTP-N architecture is described when, consistent with the scenario outlined in the previous section, the traffic is predominately IP. The OTP-N is seen as a very high-capacity transport facility, able to switch and transport traffic flows made of aggregated IP datagram streams. Access to the OTP-N is provided by high-speed IP routers, with optical packet interfaces, subsequently referred to as edge routers (Fig. 2). The purpose here is to highlight the functions required in the edge routers as well as the architecture and protocol layering of the access interfaces to the OTP-N (OTP interworking unit or IWU). The OTP access interface has been subdivided into four sublayers (Fig. 3).

- The data convergence sublayer (DCSL) is responsible for data rate adaptation, encapsulating incoming IP datagrams into optical packets. Given variable length datagrams, it is assumed that no fragmentation or reassembly is performed in the OTP layer; the maximum length of IP datagrams that can be carried in the OTP-N is set by the OTP length and by the link bit rate. Longer IP datagrams will be segmented by the router according to the IP protocol specification (adding the proper IP header). At the same time short IP datagrams, addressed to the same subnetwork, can be multiplexed on the same OTP, in order to achieve maximum payload usage, but again without any processing of the IP header.
- The network sublayer (NSL), below the DCSL, is responsible for generation of the OTP routing label/address, inserted in the OTP header. Presently, it is assumed that a unique OTP label/address is assigned to each DCSL. Therefore the conventional part of the router is responsible for forwarding the IP datagrams to the proper DCSL according to their final subnetwork destination.
- OTP's from/to different DCSL/NSL pairs are mutliplexed/demultiplexed in the link sublayer (LSL), for instance by means of a simple FIFO queue, and then



(a)



(b)

Fig. 4. Example of packet delivery at the edges of the OTP-N according to the (a) wavelength circuit and (b) wavelength packet option. Packets of different colors belong to different connections. Different line-styles are different wavelengths.

transmitted as a unique packet stream. Note that optical idle packets may be inserted by the LSL to keep the transmitted optical power constant. Empty packets can be discarded at any time in the network and can therefore be neglected as far as teletraffic performance is concerned.

- Proper wavelength encoding for transmission in the optical fiber—taking into consideration the use of the wavelength resource (see Wavelength Management below)—is provided by the wavelength convergence sublayer (WCSL).

2) Wavelength Management: The wavelength resource can be exploited both within the network nodes and in the network links. In the switching fabric, the wavelength dimension is used for routing and internal contention resolution, in conjunction with the space dimension. This use of wavelength is strictly internal to each switch and does not impinge on network issues, assuming the switch outputs conform to the transmission requirements of the links (output wavelength conversion interfaces will be provided if needed).

With respect to the links between nodes, two options have been considered up to now within the KEOPS project for the use of the wavelength domain.

- The wavelengths are taken as circuits and the elementary paths within the network are designated by the wavelength and not the fiber. Thus, packets belonging to a given connection cannot be spread over more than one wavelength per hop. This will be called *wavelength circuit* (WC).
- The wavelengths of a fiber can be used as a shared resource. Traffic load is spread over the wavelength set and packets belonging to the same connection can be transmitted on different wavelengths in the same hop. Paths within the network are associated with fibers and wavelengths. This will be called *wavelength packet* (WP).

Fig. 4(a) shows how each connection makes use of one wavelength only (one logical buffer per wavelength), an example of WC operation. Packets of a given connection remain strictly in sequence and are transmitted on one single wavelength. Interfacing with the WDM transport layer is relatively straightforward, although wavelength reallocation might be necessary depending on the set of wavelengths used (not necessarily in accordance with the set used in the transport layer). In general, this reallocation is required since the wavelength allocation for the provision of end-to-end lightpaths is purely a WDM transport layer concern.

If packets are statistically multiplexed over the wavelength set, bursts of packets can be served more easily as they contend only for their output fiber with a significant reduction in the buffering requirement in switches [Fig. 4(b)]. The drawback, however, is the necessity to properly demultiplex the packet flows carried by a given fiber in the wavelength domain, at OTP-N edges. This operation involves packet queuing and is dealt with by the edge switches comprising full optical packet switches, with as many outgoing ports as wavelength channels utilized in carrying the fiber packet stream. Edge switches are a strict requirement at the IWU's for interfacing with electronic IP subnetworks. They might also be needed at interfaces with the underlying WDM transport network if the transmission capacities allocated by the WDM layer are treated as independent wavelength channels. In case of interconnection capacities scaled over several wavelengths, blind striping of the traffic by IP routers on lightpaths with different delays would result in massive disordering of packets and poor end-to-end performance. With respect to transporting packetized data, WDM transport networks should take into account such delay requirements in their wavelength path management (also true for lightpath allocation in case of failure) as soon as the client network (IP or future OTP-Ns) asks for a bandwidth capacity exeeding that of a wavelength channel.

Both options have advantages and drawbacks and the selection of the best approach is a tradeoff between complexity and performance, highly dependent on the application environment. However, the two solutions are not mutually exclusive and can coexist with the correct interfacing blocks.

III. Optical Packet Switching Nodes

The KEOPS project has generated several new approaches to realising optical packet nodes. The node, which fulfills the most important function in a network, i.e., the distribution of information to the right destinations, has to incorporate a number of functionalities, some of them executed in the electronic domain while others resort to optical signal processing. The relationships between these functionalities are outlined for a generic node structure consisting of the following subblocks:

- the input interface, incorporating a synchronization function;
- the switching fabric;
- the output interface incorporating regeneration and header rewriting.

In this section, the focus is on the core of the node, the switching fabric. The two main architectural options considered within the KEOPS project for the implementation of the basic switching blocks are examined in details. Implementa-

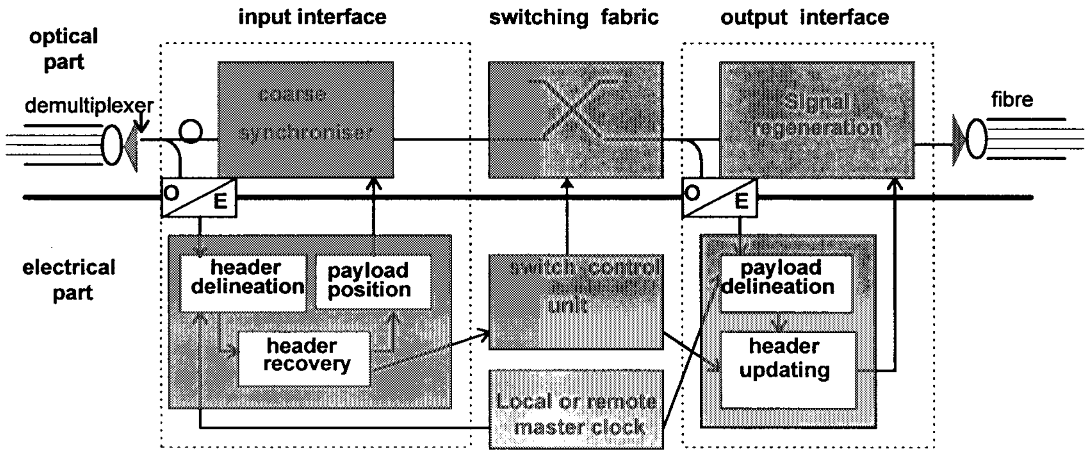


Fig. 5. Generic node structure.

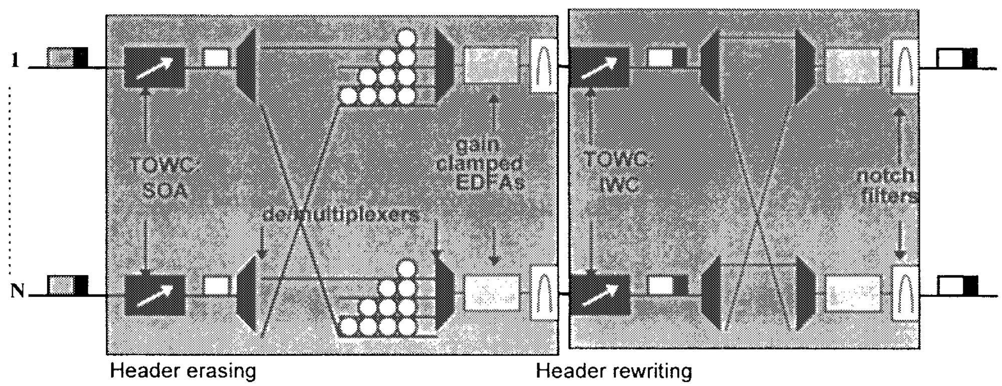


Fig. 6. Schematic of the wavelength routing switch. TOWC stands for tuneable optical wavelength converter, SOA for semiconductor optical amplifier (cross gain wavelength conversion) and IWC for interferometric wavelength converter (cross gain/phase wavelength conversion).

tion requirements for the input and output interfaces will be presented in the next section.

Attaining the buffer depths required in practice for contention resolution is a fundamental difficulty with all optical packet switch designs. Therefore, several realizations of high-performance switch architectures, derived from basic building blocks while minimizing the complexity of the optical buffering function, have been developed.

A. Node Architecture

1) Generic Node Structure: The generic structure of an optical packet switching node is depicted in Fig. 5. In WDM networks, nodes are flanked by passive de/multiplexers, the switching process being carried out at the packet level per wavelength and per time slot. As a result, the number of ports is scaled according to the number of interconnected fibers times the number of multiplexed wavelengths, leading to large switching matrices.

As in electronics, interfaces are necessary for reliable information exchange and are just as crucial in optical systems. The input interface aligns the incoming cell streams relative to the switch master clock, creating synchronous packet flows while properly recovering the header content. The output interface ensures that physical transmission constraints are met, including power levels, wavelength allocation, signal shaping and reinsertion of updated headers.

In any end-to-end connection, the payloads are never electronically recovered, necessitating the use of optical synchronizers to align the payload time position while maintaining transparency. Implementing the required payload delineation blocks after the fiber delay line set takes into account the time jitter undergone by packets within the switching fabric. A pointer field in each header flags the position of the payload relative to its header. Rewriting headers synchronously at the start of each time slot ensures some framing on wavelength pipes.

2) Switching Matrices:

a) Wavelength routing switch (WRS): The first architectural option investigated within KEOPS relies on the wavelength dimension to execute switching by means of tuneable optical wavelength converters (TOWC's) (Fig. 6). Delay lines, used for contention resolution, are grouped in several sets and constitute the first stage of the optical switch. Each input port has access to, at least, one line in each set of the first stage and each set of delay lines has also access to each output port, which means that each delay line is thus shared by every output port. A packet arriving on a given input port and directed to a given output port is routed on one of the available delay lines, given that a delay line of duration d is considered available if:

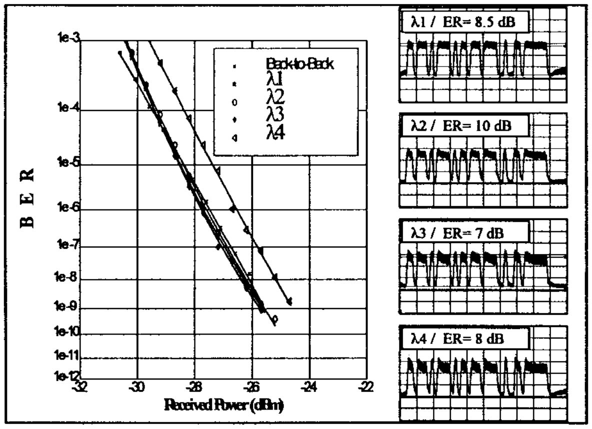


Fig. 7. BER penalty and signal waveforms at the WRS output. Conversion from $\lambda_3 = 1542$ nm to $\lambda_1 = 1534$ nm at the first stage and from λ_1 to λ_i at the second stage (Mach–Zehnder IWC). Payload bit rate: 2.5 Gb/s.

1) no packet is scheduled in d time slots on the appropriate output port;
2) no packet is scheduled in d time slots on any of the delay lines leading to the same second stage TOWC;
3) no packet issued from the same input port and targetting the same output port is scheduled in d' time slots with $d' \geq d$.

Of the available delay lines, the shortest delay is chosen.

This scheduling process is greatly improved by proper distribution of the fiber line lengths. For each input port, nearly optimum output queueing performance is achievable by using only a restricted set of fiber lines with non consecutive delays [10]. As an example, under regular and balanced input traffic conditions, the packet loss rate is kept in the 10^{-9} range for a traffic load below 0.8 for a 16 × 16 switch, although each input port is given access to only 16 delay lines [11], [12] (note that, under similar conditions, the packet loss rate is about 10^{-4} for output buffers built with 16 fiber lines with consecutive delays).

When using dynamic (on a packet-by-packet basis) wavelength conversion to route packets, the signal extinction ratio degradation is critical with respect to the number of nodes a signal can cross while allowing successful recovery of the data. Therefore, interferometric wavelength converters are implemented at the second stage of the switch to achieve signal regeneration prior to transmission to the next node (Fig. 7). A fully equipped 4 × 4 WRS demonstrator has been realized. Wavelength conversion over 12 nm and between four channels $(\lambda_1 = 1534, \lambda_2 = 1538 \lambda_3 = 1542 \lambda_4 = 1546$ nm) has been demonstrated. Each input has a real time header recovery facility operating at 622 Mb/s [13] while a control unit manages the fiber delay line allocation according to the scheduling process. Finally, dummy packets within the incoming streams are erased by the first stage wavelength converters to relax the unnecessary occupancy demands on the delay line buffer. New dummy packets are generated at the second stage (both payloads and headers are encoded at 622 Mb/s) to keep the optical power constant on the outgoing links.

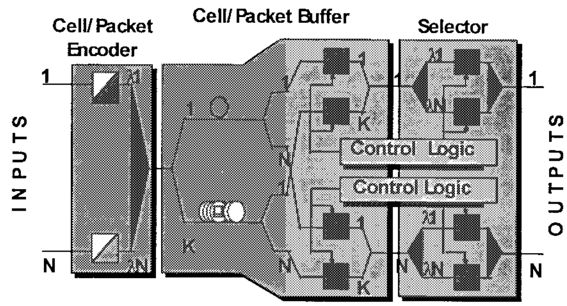


Fig. 8. Schematic of broadcast and select switch.

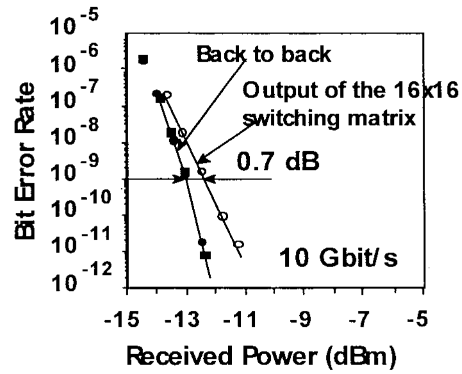


Fig. 9. Physical performance of the 16 × 16 broadcast and select switching matrice at 10 Gb/s.

b) Broadcast and select switch (BSS): The second architectural option exploits WDM to upgrade the internal throughput of the switch, thus easily achieving pure output queuing and hence optimal delay/throughput performance. The $N \times N$ switch consists of three sections: the *wavelength encoder*, the *buffer* and *broadcast section*, and the *wavelength selector block* (Fig. 8). The *wavelength encoding block* consists of N wavelength converters, one per input. Each one encodes its packets on a fixed wavelength. The *cell buffer block* comprises K fiber delay lines followed by a space switch stage, realized using clamped-gain semiconductor optical amplifiers (CG-SOA's) operating as fast gates. The CG-SOA's select packets from the correct delay lines and send them to the correct outputs under electronic control. The last block, the *wavelength selector block,* consists of N demultiplexers which forward the different outputs to SOA gates before the signals are recombined, thus selecting packets from the correct inputs.

The broadcasting principle makes a copy of each packet at any delay, enabling the flexible management of the buffered packets flows. A copy is also available at each output, so that this architecture easily supports multicasting, an attractive capability for future applications.

BER results are reported on Fig. 9 for a test bed consisting of a 16 × 16 BSS matrix operating at 10 Gb/s. The sensitivity penalty is below 1 dB with respect to the back-to-back configuration.

B. Contention Resolution

Given the basic switching blocks depicted above, several ways to improve the queuing process have been investigated,

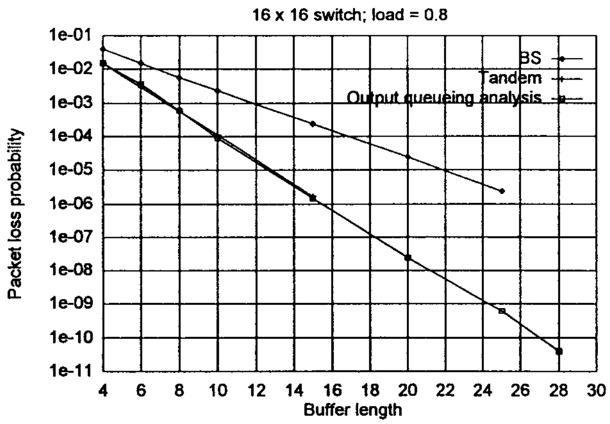


Fig. 10. Cell loss performance of the tandem solution as a function of the buffer length, obtained by analysis and simulation compared with the single broadcast and select switching element with threshold at 85% of the buffer capacity.

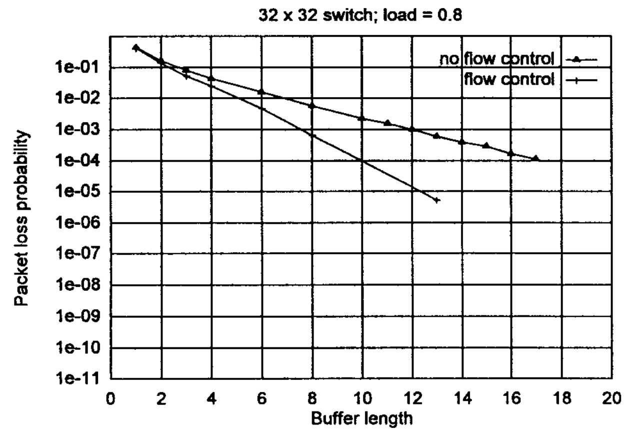


Fig. 11. Cell loss performance of a three-stage Clos configuration as a function of the buffer length, obtained by simulation with and without flow control.

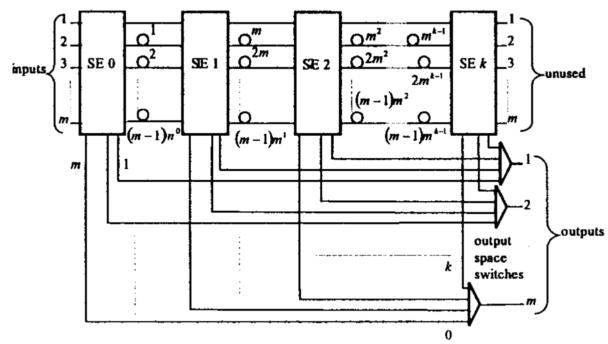


Fig. 12. SLOB architecture; each stage is a modified broadcast and select switch (SE or switch element).

keeping the number of delay lines accessed by input ports unchanged (low) because of technological constraints. In this respect, whether or not contentions are resolved with the help of differentiated wavelength encoding is a key consideration.

1) Collision Avoidance in the Time Domain: The following architectures are intended either for edge switches (controlling the demultiplexing of packet streams carried on a WDM multiplex) or for core switches interconnected through a WDM transport network over geographical distances (in that case, it is assumed that the traffic is smooth enough to be considered Bernoulli-like due to traffic smoothing at the borders and/or to a high level of aggregation).

a) Flow control algorithms for improved traffic performance: Buffer limitations can partly be overcome by cascading two BSS switching elements in tandem with a suitable control procedure [14]. During normal operation the first switch stores packets using a round robin mechanism, while the second switch stores packets according to their addresses. When a buffer of the second stage exceeds a certain threshold, a buffer in the first stage is dedicated to that destination to increase the total buffer capacity. Thus, the two buffers behave like a single, longer buffer with a capacity approximately given by the sum of the two. The cell loss performance enhancement in the case of random traffic is presented in Fig. 10.

The well-known approach of using several stages of smaller switches to implement larger fabrics is attractive given the limited monolithic switch matrix sizes possible with present technology [15]. Therefore, multistage switches, realized by adopting a three-stage Clos architecture, have been studied. For these architectures, especially, interstage flow control techniques effectively reduce packet loss. Due to the discrete-time nature of the switch, a full buffer in a switching stage can only accept one packet from the previous stage. With flow control a signal is sent back to the previous stage to stop all but one incoming packets being directed to the full buffer: to minimize the overall packet loss, the selection of this packet is made on a first-come-first-served principle [16]. The benefit of the flow control policy is shown in Fig. 11. A packet loss probability of 10^{-10} is reached with only 23 packet positions per optical buffer, well within technological limits (32).

b) The SLOB architecture: An alternative to realising a switch with a greater buffer depth through cascading many small switches is the switch with large optical buffers (SLOB's) [17] (Fig. 12). Choosing the BSS as the basic element, although other switches could be used, SLOB has m inputs and outputs. The delay line lengths increase exponentially from left to right along the structure, and each buffer has a depth of $m^k - 1$ packets, where k is the number of stages in the architecture; hence the number of stages increases with the logarithm of the buffer depth and emulates an output-buffered switch.

c) Switch with recirculating ports: The ability of optical switches to resolve contentions can also be improved by adding recycling ports to standard architectures, i.e., additional output ports are looped back to the corresponding input ports. This architectural option enables packets to be launched several times through the switching fabric, thus giving rise to queuing delays larger than the longest delay line. Note, however, that the recirculating scheme does not allow for infinite queuing delays, the number of queuing packets being bounded by the number of packets that can be simultaneously managed within the switch. Although the standard WRS architecture performs well under Bernoulli traffic conditions [11], the packet loss rate cannot be kept low under bursty traffic (Fig. 13). With 16 additional recycling ports, available queuing delays extend one order of magnitude beyond the

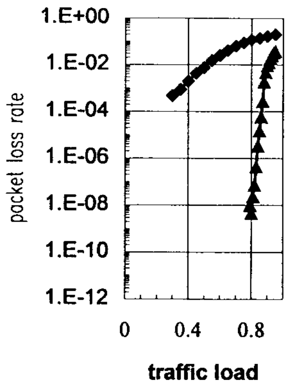


Fig. 13. Packet loss rate versus on/off traffic load (source burstiness: 10): standard 16 × 16 WRS (squares), 16 × 16 WRS equipped with 16 recirculation ports (triangles).

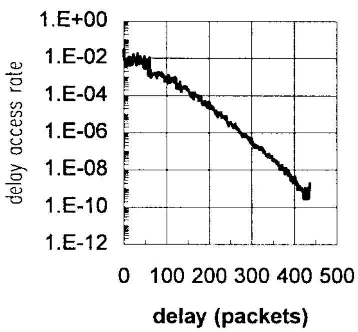


Fig. 14. Delay access rate (16 recirculation ports, ON–OFF traffic load: 0.7, source burstiness: 10).

longest fiber line (∼50 packets long) while the switching fabric size is only twice the standard one (Fig. 14). The packet loss rate is lowered accordingly (Fig. 13).

The drawback with the recirculation scheme is scaling; switch enlargement is proportional to the number of additional recirculation ports. While the issue of the switching fabric size is particularly important if WDM links are to be interconnected, this scheme is compatible with edge switches implementation.

2) Collision Avoidance in the Time × Wavelength Domain: In the network core, packet distribution among the wavelength channels can be used by switches interconnected by WDM links to take advantage of statistical multiplexing at the fiber bandwidth level. Packet switching node architectures have been designed to take advantage of this feature, peculiar to WDM networking.

a) Wavelength routing switch version: The switch design relies on a connection network sorting packets along three dimensions: space, time and wavelength. In the case of n_f interconnected fibers carrying n_λ channels, the whole interconnection network lying in between the input demultiplexers and the output couplers (Fig. 15) is organized as n_f parallel planes. Each plane consists of the $n_\lambda \times n_\lambda$ standard WRS fabric. The input demultiplexers route the wavelength channels so that each input fiber packet stream is distributed over all planes. The statistical allocation of wavelengths within the switch precludes the use of multiplexers at the switch outputs to rebuild the WDM packet multiplexes. However, the optical power loss introduced by the output combiners is the only drawback of this architecture as compared to the basic WRS architecture. Packet routing and packet queuing are again carried out for each packet through two wavelength conversions. The switch control rules the n_f parallel planes to ensure a consistent building of the WDM multiplexes on outgoing links, without any need for wavelength reallocation at the output. The packet loss rate performance reported in Fig. 16 indicates that these switches are able to resolve contentions in a highly bursty traffic environment, obviating optical hardware issues.

b) Broadcast and select switch version: The proposed architecture (Fig. 17) combines WDM and tuneable optical wavelength converters (TOWC's) to exploit the wavelength dimension for storing packets. At each of the M fiber inlets packets arrive on N different wavelengths that are unique to each inlet and at each of the M outputs of the switch the packets are converted to N fixed wavelengths that are unique to respective output ports. Apart from having unique wavelengths on each input/output fiber to enable WDM operation, the switch operates as the regular broadcast and select switch except for the fact that up to N packets can be selected at each output in each time slot.

The combined use of converters and WDM packet switches greatly enhances the traffic performance [18], [19]. When dealing with bursty traffic, where the required buffer depths are large, this enhancement is especially important. To illustrate the important role of using a WDM architecture with TOWC's compared to a WDM architecture without TOWC's, Fig. 18 gives the maximum tolerated load per wavelength channel as function of the burstiness for a packet loss probability of 10^{-10}. Results are given for WDM switches with and without converters for two and four wavelength channels per in- and outlet. The buffer capacity B is 7 and the switch size is 4 × 4 $(M = 4)$. The figure shows that the use of TOWC's effectively provides deeper buffers able to support bursty traffic: For a moderate burstiness of two and with four wavelength channels per fiber, the allowed load per channel increases from virtually "0" without TOWC's to 0.4 with TOWC's. Furthermore, for a fixed throughput per fiber of, for example, 0.8, and with four wavelength channels ($N = 4$ and a channel load of 0.2 gives a load per fiber of 0.8), the tolerated burstiness is increased from ∼1.1 to ∼3.2.

IV. Key Functionalities for WDM Packet Networks

A. Wavelength Processing

A generic WDM optical switching or routing node consists of multiple input and output ports, each of which may carry multiple wavelength channels. A fully reconfigurable WDM switch or routing node must be able to direct individual wavelength channels from any input port to any output port, while reassigning wavelengths as desired or required. In general, three elementary functions are sufficient to ensure full reconfigurability: 1) space switching of WDM traffic, 2) selection (filtering) of individual wavelengths in a WDM traffic stream, and 3) wavelength conversion of individual

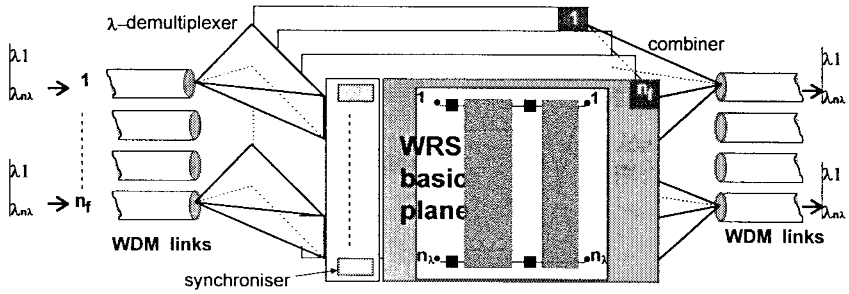


Fig. 15. WDM architecture version of the WRS.

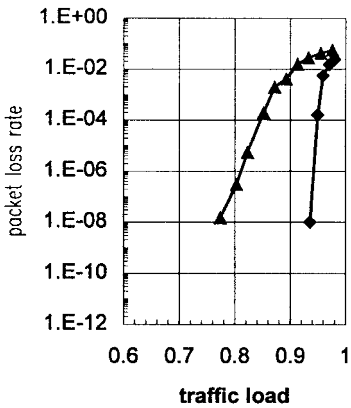


Fig. 16. Packet loss rate for a WDM WRS interconnecting four fibers carrying 16 channels; Bemoulli traffic: squares; ON–OFF traffic (source burstiness: 10): triangles.

data channels. These functions represent a shared requirement (and hence potentially a common technology base) for optical cross-connected networks and packet switching applications, although the required time scale for reconfigurability is obviously much smaller in the case of packet switching. Note that the buffering operation required for packet switching does not introduce any additional elementary functions, as the optical packet switch architectures described in the previous section use space switching among fiber delay lines to achieve contention resolution.

1) WDM Space Switching: Many types of optical switches (e.g., optomechanical) can be used for WDM space switching. However, the nanosecond reconfiguration times required for optical packet switching mandate the use of optoelectronic devices, which of course have the further advantages of small size and integration potential. These latter considerations become increasingly important, from practical and economical viewpoints, as larger node dimensions are considered. This is true for routing as well as packet switching applications.

In the broadcast and select switch architectures studied within KEOPS, space switching is achieved by means of tree-type (perfect shuffle) gated network structures, which allow any connection in a strictly nonblocking mode. Given the requirement for fast reconfigurability, semiconductor optical amplifiers (SOA's) are perhaps the best available optical gates for use in such architectures. They can achieve high ON–OFF ratios (in excess of 45dB with moderate bias current modulation), which are essential to prevent the build-up of interferometric crosstalk products, and offer optical gain to at least partially offset the splitting losses inherent in tree architectures. The primary disadvantage of SOA's is the fast saturation response of the gain medium to varying optical powers, which makes amplitude-modulated signals subject to distortion at high SOA input power levels. This limits the useful power dynamic range of the SOA, and introduces cross-channel modulation distortion products when gating WDM signals. An effective response to this problem is the introduction of wavelength-selective optical feedback in the SOA cavity, which introduces a gain-clamping laser oscillation above a certain bias current threshold. As long as the total injected optical signal power is insufficient to extinguish the laser oscillation through carrier depletion, amplification of arbitrary numbers of wavelength channels can be achieved without introducing interchannel crosstalk. Polarization-insensitive clamped-gain SOA's (CG-SOA's) based on bulk-tensile InGaAsP/InP structures with DBR reflectors (oscillation at 1510 nm) have been fabricated within the KEOPS project for application as gates; see Fig. 19(a). Experiments on these devices verified a total power dynamic range (for 1 dB sensitivity penalty) of 6 dB in 16 WDM channel, 10 Gb/s per channel operation [20]. To demonstrate the integration potential of the technology, fully packaged arrays of four such devices have been realized which exhibited constant fiber-to-fiber gains in excess of 10 dB to input powers of over 0 dBm, with good uniformity (0.6 dB gain variation) between devices; see Fig. 19(b). Subnanosecond gating times were demonstrated on such CG-SOA array modules using dedicated high-speed InP HBT driver circuits developed within the project [21].

Electrooptic switches are a possible alternative to CG-SOA gates for WDM switching applications, and are also pursued within the KEOPS project. Electrooptic switches are potentially fast (sub-ns reconfiguration possible), and unlike SOA gates, they pass or switch signals essentially without distortion over a large power range, and furthermore add no optical noise. They therefore offer a very large effective power dynamic range and are virtually free of interchannel modulation distortion effects. However, very high ON–OFF ratios (40 dB or more) are difficult to achieve. Nevertheless, substantial progress on electro-optic switches has been achieved within the project. Polarization-independent InGaAsP/InP switch matrices with four 2×2 Mach–Zehnder electrooptic switches were fabricated which exhibited fiber-to-fiber insertion losses as low as 5 dB, switching times below 200 ps and ON–OFF ratios of 30 dB in dilated (cascaded switch) configurations [22].

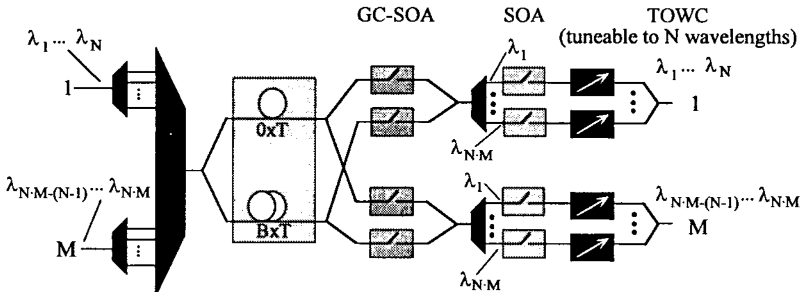


Fig. 17. WDM architecture version of the BSS. The switch has M fiber in- and outlets with N wavelengths on each. The buffer has a capacity of B fiber delay-lines. The length of each fiber delay-line corresponds to a multiple of packet periods, T.

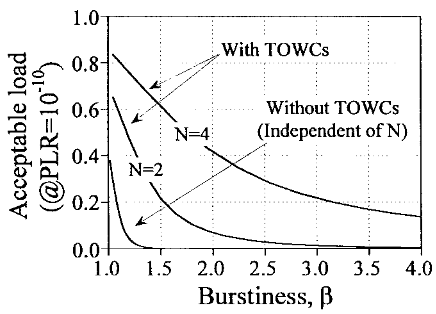


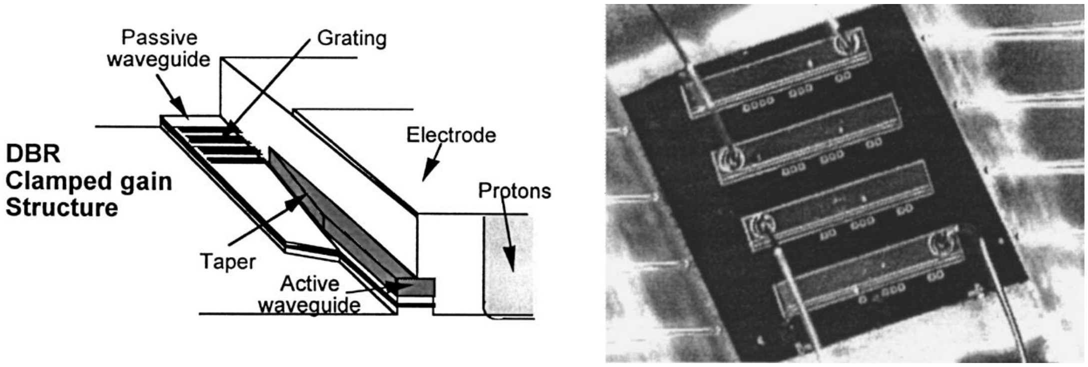
Fig. 18. Highest acceptable channel load (@ PLR $=10^{-10}$) versus burstiness for WDM switch architectures with and without tuneable optical wavelength converters (TOWC). The switch size is 4 × 4 and the buffer capacity is seven fiber delay lines.

2) Wavelength Selection: The wavelength selection function, as implemented within the KEOPS packet switch architectures, operates with respect to a fixed wavelength comb, and can therefore be realized in a straightforward manner by combining wavelength demultiplexers and optical gates (SOA's). This approach allows for convenient digital control, while retaining the advantages of SOA gates, especially their fast reconfiguration times and high ON–OFF ratios. As the WDM signals are demultiplexed before entering the SOA's, interchannel crosstalk is not an issue and conventional SOA's can be used, provided that the resulting power dynamic range is sufficient to allow low sensitivities at high bit rates. We have used self-aligned flip-chip mounting on silicon submounts to produce four-SOA gate arrays suitable for use in hybrid wavelength selectors [23]. Wavelength demultiplexers have been realized on both SiO_2 and InP, the latter offering potential for future monolithic integration. Extremely compact polarization-insensitive demultiplexers have been fabricated on InP with adjacent-channel crosstalk levels as low as −28 dB for four-channel devices and −20 dB for 16-channel components [24].

3) Wavelength Conversion: The particular strength of optical packet switching is that it offers the prospect of direct packet mode access to the WDM optical layer, and hence of handling packets at very high individual line data rates in optical form directly suitable for transmission. Therefore, wavelength converters for application in optical packet switches must, above all, be capable of very high-speed operation: 10 Gb/s today, and higher bit rates in the future. They must also output a high-quality optical signal, in terms of power, Q-factor, optical signal-to-noise ratio, jitter and chirp, and ideally should have some regenerative capacity. Finally, given the large possible dimensions of real switching nodes, they should be physically small and power-efficient. Interferometric wavelength converters have been designed and fabricated within the project, and impressive results have been achieved. Mach–Zehnder interferometric (MZI) devices based on cross-phase modulation in SOA's, which allow counterpropagation of the input and output signals and hence optical filter-free operation and same-wavelength conversion, have been realized using polarization-independent bulk-tensile SOA's in an all-active configuration. Virtually penalty-free wavelength conversion has been obtained with such devices at 10 Gb/s [25], with high output optical powers and a total current consumption below 400 mA; see Fig. 20. Operability at 40 Gb/s has been demonstrated using MQW-based Michelson interferometers [26]; these devices do not allow filter-free operation, but the results obtained nevertheless demonstrate the very high speed potential of interferometric wavelength converters. It should be noted that interferometric converters offer some signal regeneration capability in the amplitude domain (typically 3–4 dB of extinction ratio enhancement for dynamic conversion, plus in-band noise redistribution), and produce low-chirped or even negatively chirped converted signals with high optical signal-to-noise ratios (typically 35 dB in 0.1 nm). Mach–Zehnder converter modules have been fabricated to equip the project's packet switch testbeds, and have also been applied to routing applications in the fully reconfigurable wavelength-translating optical crossconnect constructed within the ACTS project OPEN (Optical Pan-European Network). Five interferometric wavelength converter modules operating at 2.5 Gb/s are included in this crossconnect, which recently completed a four-month field trial experiment [27].

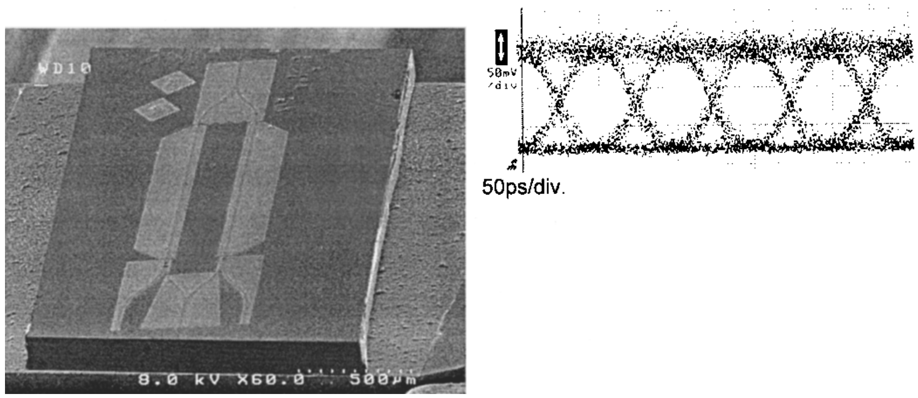
B. All-Optical Regeneration

The proper operation of any telecommunication network requires signal degradation to be bounded. This is achieved, in practice, through signal regeneration. The regeneration requirements are highly dependent on the type of network. In the case of transmission links, the environment is known and well-controlled (distance, terminations, etc., as well as the constituent equipment: lasers, EDFAs/EDFFA's, photodiodes, filters, etc.). In this case, regeneration means optimization of the relevant physical parameters in order to provide a specified quality of signal. On the contrary, with meshed networks, interconnected equipment may be provided by dif-



(a) (b)

Fig. 19. (a) Clamped-gain SOA structure and (b) photograph of a packaged four CG-SOA gate array.



(a) (b)

Fig. 20. (a) Photograph of all-active Mach–Zehnder interferometric wavelength converter and (b) output eye diagram obtained with same device to 10 Gb/s counterpropagative conversion from 1550 to 1560 nm. The input signal rejection at the output exceeds 25 dB, while the total bias currents are less than 400 mA.

ferent manufacturers and networks are continually subject to connectivity expansion. With optical networks, the problem is exacerbated by the unavailibility of a suitable means of storing digital information. Therefore, regeneration of optical signals is mandatory for reliable information exchange and is crucial for optical system viability.

Optoelectronic regenerators can provide full signal regeneration (3R: reamplification, reshaping and retiming), or at least 2R (reamplifying and reshaping) regeneration in the case of bit rate-independent regenerators, but they may impose limitations, for bit rates of 10 Gb/s and beyond, in terms of availability, physical size, power consumption, and cost. All-optical regenerators are thus a crucial enabling technology in terms of economical and practical viability (including integration potential) at these high bit rates. The KEOPS project was the first to identify the regeneration properties of wavelength converters based on SOA's in interferometric structures [28], providing a firm basis for further investigations.

The required level of regeneration is a fundamental consideration; is full 3R mandatory or is 2R practical? 2R regenerative structures based on two wavelength converters in tandem have already been proposed and tested. These regenerators function with acceptable performance irrespective of the input wavelength and their operation has been assessed in a comprehensive system environment up to 2.5 Gb/s [29], [30].

An obvious drawback of 2R regeneration is that it does not address the temporal aspects of the signal: jitter, or more precisely, pattern-dependent effects which can accumulate after several nodes. In fact, it seems that 2R optical regeneration schemes would require devices with very short transition times compared to the bit duration, in order to avoid the accumulation of pattern-dependent transition edge jitter. Full network scalibility in terms of size, bit rate or signal quality, calls for investigations on 3R optical regeneration. A 3R-type regenerator [31], proposed within the KEOPS project, has been shown to enable the cascade of 10 Gb/s optical bit streams through 50 optical switching nodes [32].

1) 2R-Type All-Optical Regenerator: Fig. 21 shows the structure of the 2R regenerator. It consists of two blocks: a two-stage polarization-insensitive cross gain modulation (XGM) wavelength converter, described in [33], using SOA's, which converts input data at wavelength λ_{in} on a dummy wavelength λ_i with a concomitant improvement of extinction ratio. A copropagative configuration was chosen for better signal shape and improved signal-to-noise ratio. The filtered converted data is then coupled to the "data" input port of the second block, comprising an active-passive MZI wavelength converter with a passive phase tuning section which considerably improves device operation [34]. The MZI converts data to the desired output wavelength λ_{out} with partial noise suppression and signal reshaping features owing to the MZI

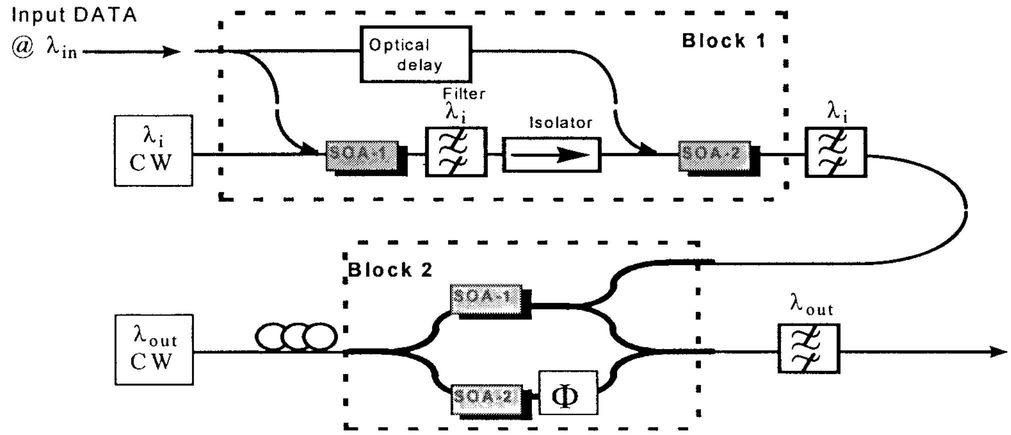


Fig. 21. Structure of the 2R-type all-optical regenerator.

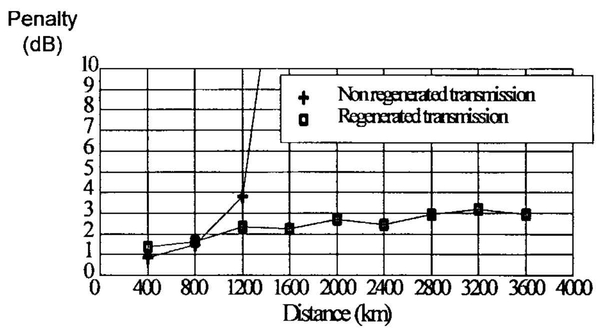


Fig. 22. A 2.5 Gb/s receiver sensitivity penalty versus transmission distance in two cases: with or without the 2R all-optical regenerator inserted in a 400-km long transmission loop.

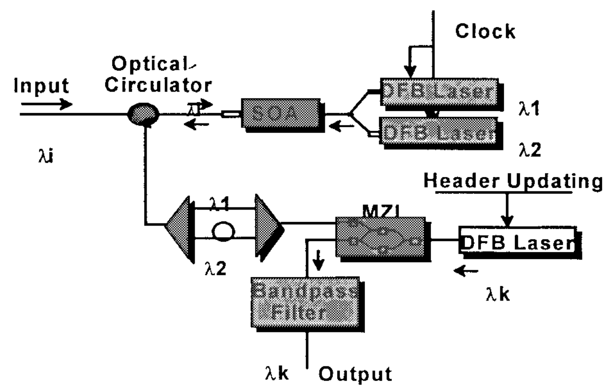


Fig. 23. Structure of the 3R-type all-optical regenerator.

nonlinear power transfer function. This structure is compatible with the WRS architecture (Fig. 6); the first block can be an upgrading of the first stage wavelength converter while the second block is the second stage WRS wavelength converter.

Experiments have been carried out at 2.5 Gb/s over a 400-km recirculation loop incorporating the optical regenerator. The optical transmission path consisted of 5 EDFA's and 4 $\times$ 100 km spools of standard single-mode fiber (G.652); such a span (400 km) is compatible with use in switching nodes separated by geographical distances. The chromatic dispersion was not compensated for along the path while the average span loss was 22.5 dB. Fig. 22 shows the receiver sensitivity penalty versus propagation distance in two cases: without optical regeneration (with the regenerator bypassed), there is an error floor at BER $= 10^{-7}$ after 1600 km, whereas with the 2R all-optical regenerator, there is no error rate floor after 3600 km and the sensitivity penalty is only 3 dB at BER $= 10^{-10}$. The penalty stabilizes at about 3 dB after about 3000 km.

2) 3R-Type All-Optical Regenerator: The 3R-type SOA-based regenerative interface consists of two wavelength converters in tandem, the first one based on cross-gain modulation in a SOA and the second one using cross-phase modulation in an SOA-based MZI structure (Fig. 23).

The incoming signal is simultaneously sampled and shifted onto two distinct wavelengths by crossgain modulation in the first SOA. These two wavelengths are derived from distributed feedback (DFB) lasers modulated at twice the payload bit rate. The phase of the DFB outputs is such that sampling is achieved at the eye diagramme centre of the input signal. Thus, the input nonreturn-to-zero (NRZ) format is converted to an return-to-zero (RZ) format. This operation requires payload delineation at the payload bit rate against a local clock or a distributed clock, whose frequency sets the maximum bit rate used for payload encoding. This first wavelength converter converts fast power fluctuations between consecutive packets into extinction ratio variations, and outputs a fixed optical power at a known and constant wavelength.

One of the two output signals from the first stage of conversion is delayed by half the bit duration (λ_2 in Fig. 23) with respect to the other. This process restores the NRZ format when the two wavelengths are considered together. Finally, the combined wavelengths signal are launched into an interferometric wavelength converter, which provides signal reshaping in the amplitude domain as well as wavelength reallocation. This device has been successfully tested at 10 Gb/s as the output regenerative interface of the BSS input synchronizer. The proper operation of this output interface requires that its input power dynamic range be increased by an additional stage designed for this purpose. This regenerator enables regeneration of the data stream in both the amplitude and time domains, allowing for large network sizes while ensuring bit rate transparency over a hierarchical bit rate grid. These characteristics are obtained as shown in Table I.

TABLE I

Characteristics	Input Signal	Output signal
Power	about 0 dBm	about 0 dBm
Power variations	<2 dB	<0.5 dB
Wavelengths	variable from 1530 to 1560 nm	fixed from 1530 to 1560 nm
OSNR	>23 dB/0.1 nm/>27 dB after a cascade	>35 dB/0.1 nm
Extinction ratio	>9 dB	>10 dB
Jitter	$<1/2$ of the bit time	$<1/4$ of the bit time

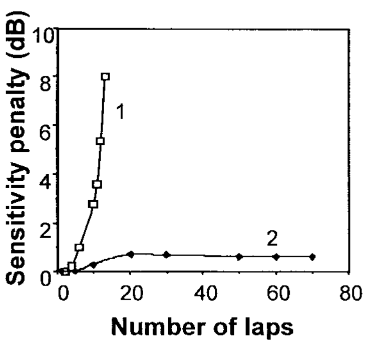


Fig. 24. Cascade at 2.5 Gb/s of 50 km DSF (spans) with 2R regeneration (1) and with 3R regeneration (2). The 2R regenerator is based in this case on the cascade of single SOA and an MZI wavelength converter.

Experiments carried out at 2.5 Gb/s with the 3R regenerator (Fig. 24) highlight the full regenerative capabilities of this structure over a large number of cascaded interfaces. More than seventy 3R interfaces (including transmission over 3850 km) can be cascaded with a constant sensitivity penalty lower than 1 dB.

The regenerator has been tested under different conditions, varying the types of input signal eye diagrams. The regenerator accomodates eye diagram distortions (cross points not in the center of the eye) with no degradation of the output diagram. Thus, this regenerator can be used to reshape the signal coming from a no ideal source such as directly modulated DFB lasers. A minimum signal-to-noise ratio (SNR) of 27 dB/0.1 nm (at 10 Gb/s) is required at the input of the regenerator in order to maintain the sensitivity penalty below 1 dB in cascaded transmission. The structure behaves essentially as a decision gate: the launching of additional optical noise power after each recirculation results in a noise power close to the initial one after crossing several optical nodes.

C. Synchronization

1) Packet Delineation: Packet delineation has to be carried out at each packet switching node and at the Inter Working Units (IWU's), i.e., at the packet network boundaries, in order to identify the header and/or payload start position, and to be able to read the packet data content [35]. Inside packet nodes, packet delineation is a key function for header reading, packet synchronization, and, if required, for header rewriting. At the packet network boundaries, packet delineation applies not only to header detection but also to payload recovery. The packet format proposed in KEOPS takes into account these requirements, providing appropriate fields to facilitate these functions.

In the KEOPS project different solutions for packet delineation have been studied and tested. As a part of the wavelength routing switch demonstrator, a complete real-time header recovery circuit [13], [36] has been developed (phase-locked loop (PLL)-based solutions are too slow to perform clock recovery on a packet-by-packet basis). It includes a specially developed GaAs Gate Array ASIC operating at the header bit-rate of 622 Mb/s. This system performs bit and byte phase alignment by means of an oversampling technique, and is tolerant with respect to packet timing misalignment and errored bits.

The other solution studied for packet delineation is based on "pattern recognition," i.e., the comparison of the incoming data sequence with a fixed Key Word (KW) included in the packet header. To reduce the probability of false synchronization, a reliable technique has been tested, based on the alternate Key Word concept [37]. In this case, subsequent packets use two different Key Words (KW1 and KW2). If KW1 is detected, KW2 is expected to be received in the subsequent packet. If a "KW1-KW2-KW1..." sequence is detected with the expected rate, we can be confident to have found the correct packet position. To ease this operation, KW1 and KW2 can be chosen so that one is the binary complement of the other.

2) Packet Synchronization: The operation of packet switching nodes is synchronous: this implies that packets coming from different links have to be aligned to the node time reference, at least on a coarse basis (much less than the time gap between packets).

In principle all fiber spans interconnecting nodes could be arranged to be equal to a multiple of the packet length (duration). In practice this may not be a very realistic situation, especially in a public network environment. This type of impairment and fiber chromatic dispersion contribute to static misalignments of packets that have to be considered together with long time scale path variations induced by temperature. Furthermore, packets traveling inside the node are processed and routed to the output links following different optical paths, causing a packet-by-packet time jitter in the output flow, due to both the residual misalignment of each input synchronizer and uncertainties in the node path lengths. Coarse input synchronizers are thus necessary at each node input to keep the misalignment of packet payloads well-bounded with respect to the node timing reference (Fig. 25).

At the OTP-N boundaries, the mandatory recovery of high bit rate payload data is likely to be better accommodated if a synchronous data stream is delivered to the end receivers. Fine synchronizers are thus needed at each IWU to rebuild the correct payload cadence prior to the data recovery.

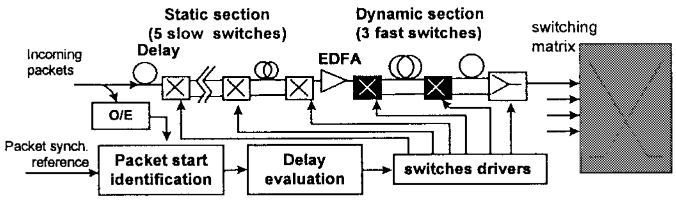


Fig. 25. Schematic of input synchronizer.

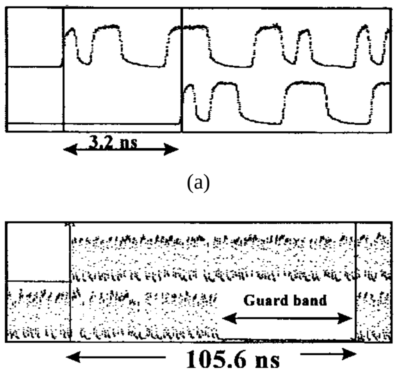


Fig. 26. Oscilloscope traces at the output of the coarse synchronizer for 2.5 Gb/s packets. (a) The upper trace experiences no delay (direct path), while the lower one is delayed of 3.2 ns (minimum step of the device). (b) Same as (a) but in this case the lower trace experienced the maximum delay in the coarse synchronizer. Due to the large time scale, the bit patterns are not distinguishable and the guard band in between consecutive packets identifies the packet boundaries.

In order to preserve the end-to-end optical transparency with respect to the data rate and coding, coarse and fine synchronization have to be performed in the optical domain. The techniques exploited in the KEOPS project for optical packet synchronization rely on tuneable wavelength conversion followed by a high dispersion fiber for fine synchronization [39] and on switchable optical fiber delay lines for coarse synchronization [38], [39]. The minimum and the maximum settable delays in the coarse synchronizer are highlighted in Fig. 26. Taking into account the time jitter experienced by packets through optical switches ($j \leq 20$ ns), the resolution of the synchronization process at node inputs (minimum settable delay $d_m = 3.2$ ns) is high enough to hold packet misalignments at the switch outputs within the guard band $(d_m + j < G)$.

The node reference control signals are normally to be derived from a clock distribution network, which could be dedicated or derived from an existing one (e.g., SDH). In the case of a plesiochronous network, the difference of clock frequencies between the nodes could cause failures in the synchronization process and thus packet loss. In any case, this could be avoided by using the empty packets to recover the right phase.

V. Optical Packet Switching Versus Electrical Packet Switching

The forces driving the deployment of optical packet switching/networking have been discussed assuming a rapid growth of the Internet, supported by a WDM optical transmission infrastructure. However, in order to assess the advantages that will potentially be gained from optical packet switching—and, in particular, from the concept proposed in KEOPS—it is worth determining how long the switching systems based on conventional electronic technology will be able to meet the demand.

Electronic based switching systems (ATM, IP switches, SDH cross-connects) have thus far met the demands of increasing throughput and functionality, attributed directly to the evolution of electronics technology, that still has the capacity for significant margins of improvement. Integrated circuit technology is still increasing the level of integration while reducing the design costs. Devices with several millions of transistors and memories of tens of Mbits with low access time have facilitated the "system-on-chip" design concept. Input–output (I/O) functions can take advantage of new emerging high-speed (tens of GHz bandwidth) and low cost SiGe technology that can be easily integrated with CMOS. New design methodologies based on the Intellectual Property concept allows design reuse and reduced time to market, key considerations in the dynamic telecommunication world dominated by economics and fast responses to new system and service requests. A fundamental bottleneck in these high performances switching systems is the wiring complexity, constraining layout and introducing speed limitations; this will potentially be overcome by the introduction of advanced high density packaging (e.g., multichip modules, MCM) and new technologies, e.g., optical interconnections arrays.

Based on this progress in electronic to date, packet switching systems in the range of 100 Gb/s capacity are available not only as laboratory prototypes but also as products. 60 Gb/s aggregate capacity with 2.5 Gb/s I/O ports (Cisco System, IP level 3 switch), 16×16 10 Gb/s I/O port (Sierra, Fast Packet Switch) and 64 2.5 Gb/s ATM ports (Stream Processor, Neo Networks) are three examples that represent the current state of art for electronic packet switches.

Even if it is fair to conclude that the expected evolution in electronics will probably satisfy the packet switch requirements for some time, research has started to investigate the potential advantages derived from the exploitation of optical technologies to face the longer term needs of the network. The motivation arises from the mismatch between the available 1.5 per year increase of available electronic TDM technology (the Moore law summarizing the expected technological progress) and the acceleration to a factor of eight per year experienced in user demand for bandwidth during the 1990's. This growth rate is mainly due to increased PC usage of the worldwide web [40] and is even more striking considering that most users accept response times within the minute range. The discrepancy between the two trends is expected to surface in the near future and optical fiber appears to be the only candidate able to meet the demand for bandwidth on a sustained basis.

The KEOPS project has already made a significant step into this future by proposing a new "all-optical" transport and switching platform that is "open and future proof" with respect to service and technology evolution. The combination of the high bandwidth of optical WDM technology is used in harness with the "packet optical transparency" concept, which in principle applies to both bit rates and services. Bit rate transparency is obtained by fixing the duration of the optical packet payload, transported and switched as a whole entity without consideration of the formats or the amount of information (number of bits) carried. The performance aspects at the OTP-N layer are thus only governed by the traffic of the optical packets, whatever their content, reducing markedly the sensitivity of the network to any growth in link bandwidth. This is a marked difference with respect to fixed content cell switching.

A particularly significant property of the OTP-N is the separation of data transfer capability (fixed duration payload with variable bit-rate) from the control functionality (fixed, low bit rate header). A powerful and flexible switching and transport protocol results, able to cater to growth in the demand for bandwidth, able to keep pace with increases in the optical transmission capacity, while keeping constant the control processing capabilities.

The large optical bandwidth provided for information transfer within the transparent payload provides further advantages in terms of transparency to service parameters. For example in IP networks, if the MTU (Maximum Transfer Unit) length changes, the OTP-N can upgrade the service parameters by simple updating of the payload bit rate, i.e. increasing in proportion to form a complete packet without any fragmentation process. Full transparency to services, i.e., the capability of a network to act as a connection link directly drawn between the end users, is nearly obtained in OTP-N even if based on the packet concept. Delay issues are alleviated because optical packets are processed "on the fly" while traffic smoothing in the wavelength dimension allows for small buffer depths. Furthermore, algorithms are currently under investigation to support different packet loss rates for connections with different QoS requirements.

The full potential advantages of the OTP-N can only be evaluated when critically compared to the actual benefits that systems and network operators can derive from its introduction. This evaluation must take into account the costs, the lack of standards for this new concept and the fact that optical technology, albeit very promising and powerful, is still in its infancy and hence costly. Although its introduction must be viewed in terms of competing electronic systems in which consolidated standards like ATM or SDH are quite difficult to surplant, optical packet switching should be evaluated against the backdrop of the challenging growth in the demand for bandwidth.

VI. Conclusion

The transparent optical packet concept is a futureproof solution, taking into account the growth of IP networking and the requirements that could result consequently. The KEOPS project has gone a significant way, both from the network concepts and developments in technology, toward deriving a platform directly carrying packets on a WDM infrastructure. Optical packet networking has the potential to provide a unified technology widely based on WDM, on which high-throughput backbone switches/routers as well as the interconnection links can be supported. Furthermore, the experimental validation work carried by the KEOPS project has proved the viability of this concept. Relying on advanced high performance optoelectronic components, the operation of fast packet switching demonstrators as well as of synchronization and regeneration interfaces has been assessed, supporting the assertion that optical techniques have the ability to support end-to-end packetized information transfer.

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