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Overview of optical packet switching

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Abstract: Optical packet switching has been researched for about two decades, but it has not been deployed in commercial networks yet. Nonetheless, the research on optical packet switching continues as it promises to perform better than electronic hardware. We report on the established results of optical packet switching, and examine the reasons for its current state.

Keywords: optical networks, optical packet switches, optical buffers

1. Introduction

Communication networks are necessary in modern societies. Their role is to relay information quickly and reliably. A communication network is built of nodes that process information, and links between nodes, that transport the information. Communication networks can be broadly divided into radio networks, electrical networks, and optical networks.

The backbone communication networks are usually optical. The volume of data transported by optical networks is growing, the service level agreements (SLA) are getting stricter, while the pressure on lowering costs keeps strong. Therefore the optical networks are constantly being expanded and improved, and new hardware solutions and control protocols are being developed. The current optical networks use only a small fraction of the bandwidth offered by optical fibers, and one of the reasons for it are slow electronic components. So far, the replacement of electronic components with their optical counterparts has been beneficial. An excellent book on optical networks and their evolution is [32], which describes in a clear and practical manner a wide range of topics, starting from optical physical laws to the management of optical networks. Another book on optical communication is [27], which concentrates on the recent research results.

At the beginning of the eighties of the twentieth century, optical fibers were used for short distance communication. At nodes the optical signal was converted to the electrical signal, and then converted back to the optical signal to be sent to the next node. This conversion is called the optical-electrical-optical conversion OEO. If the distance between nodes exceeded the optical reach, then OEO regenerators were deployed. The optical reach increased as the technology advanced. The optical transmission employed one wavelength only.

The introduction of the wavelength division multiplexing (WDM) was ground-breaking, because it enabled the transmission of a number of wavelengths in a single fiber. While WDM resulted in more bandwidth, still the expensive OEO regeneration was required, but now of many wavelengths. The introduction of optical amplifiers was another ground-breaking event, which enabled optical amplification of many wavelengths simultaneously, which in turn reduced of the number of OEO regenerators required.

In regular electric switches a wavelength has to be converted to the electric signal, but in the optical cross connects (OXC) it can be switched optically. Additionally, there are available optical add-drop multiplexers (OADM), which can add or drop a single wavelength from a fiber. The WDM networks are build mainly of OXCs and OADMs, with the support of optical amplifiers, regenerators and wavelength converters. WDM networks are able to establish lightpaths between network nodes, which are trailed to the networks at the higher layer: PDH, SONET/SDH or IP. In [4] the history of optical networks is described, and their evolution towards supporting electronic client networks.

A number of solutions have been proposed that are capable of switching below a wavelength [5]:

- It has been proposed to establish a lightpath between two network nodes, and sharing it with the nodes through which the lightpath transverses. A number of solutions have been proposed for establishing unidirectional connections between a single source node and many destination nodes called super lightpaths [25], between many source nodes and a single destination node called time-domain wavelength interleaved networking [37], and between many source nodes and many destination nodes called optical light-trails or distributed aggregation [16, 6].
- In optical burst switching it was proposed to establish lightpaths for a short period of time, even for a few milliseconds. The lightpath does not have to be entirely established for the sender to start transmission. If at some node the lightpath has not been switched, then the data already received is buffered at the node. When the source node has finished transmitting, it can request the network to tear down the lightpath even if the destination node has not received all the data. An optical burst is longer than an optical packet, and so the required switching times at nodes equal a few milliseconds, and not microseconds as in packet switching. A disadvantage

of burst switching is the necessity of maintaining a low network utilization level in order to guarantee a satisfactory service availability.

- Another proposed solution is optical packet switching (OPS) that we describe in the section that follows.

2. Optical packet switching

In optical packet switching the payload (the user data) is switched optically. OPS can be faster, and also cheaper to purchase and maintain than traditional switching with the OEO conversion [12].

OPS hardware could lower power requirements, dissipate less heat and take less space compared to electronic equipment [31]. However, electronic equipment is getting cheaper and more efficient, which highers the requirements for OPS. Moreover, the well-established SONET/SDH technology is being improved to transport the data traffic better [14].

If the packet header is processed electronically, then this version of OPS is called transparent OPS. If the packet header is processed optically, then this version of OPS is called all-optical packet switching. Another version of OPS is photonic slot routing, whose hallmark is switching many packets on different wavelengths simultaneously [46].

We can expect OPS to eventually replace traditional electronic switching, because optical network equipment is cheaper to maintain, is more reliable and consume less energy [31] in comparison with their electronic counterparts. Even though OPS progressed considerably, still this technology is unlikely to be deployed in a few years time.

A general model of an optical packet-switched network is shown in Fig. 1. Electronic access nodes (AN) are connected to edge nodes (EN), which in turn are connected to core nodes (CN). In an access node clients of the network operator receive service. In an edge node the incoming packets (mainly IP packets, [22] are grouped into optical packets for better utilization of the optical core and for lowering the disadvantageous effects of self-similarity [23]. Next the packets are converted to the optical signal and sent to the core network. Packets are sent between core nodes, or in other words, they make hops between nodes. Core nodes switch packets optically, i.e. without the OEO conversion. In the destination edge node, the packet is converted to the electric signal, and sent to the access node.

The overview of the early works on OPS is discussed in [21]. The overview of hardware techniques needed in OPS is discussed in [3]. The overview of switch architectures is presented in [36, 24, 39, 44]. There has been a number of large projects carried out on OPS, most notably KEOPS [12], DAVID [10], STOLAS [26], projects at the University of California, Davis [45], and others.

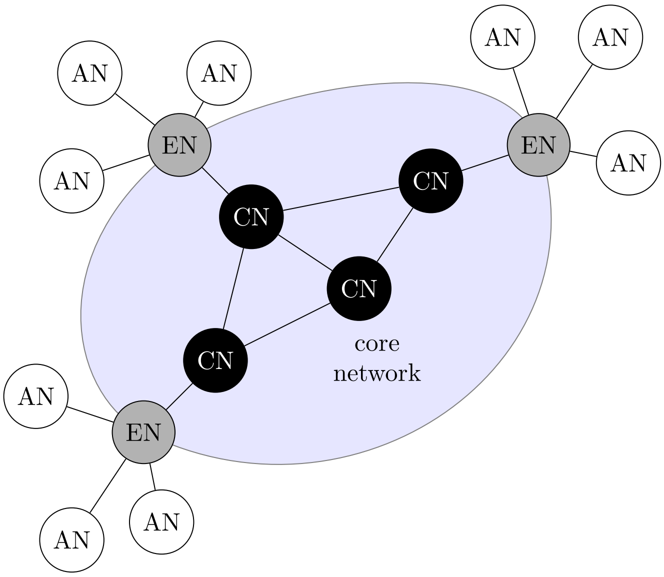

Fig. 1. Optical packet-switched network, where “AN” is an access node, “EN” is an edge node, and “CN” is a core node

A practical perspective on OPS is offered in a number of papers. In [31] this technology is criticized for having failed to meet practical expectations, but that still promises to deliver in the future. In [11] a similar criticism is delivered. Some practically oriented works on optical networks even do not mention optical packet switching [19, 15, 20]. Nonetheless, several works investigated practical applications of the current OPS technologies [13, 35, 22, 28], and how OPS could transport IP traffic [17, 41, 8, 30].

There are companies that offer optical packet switches. The Yokogawa Electric Corporation offers an optical packet switch with two ingress fibers and two egress fibers, where each fiber carries one wavelength [43]. The switching time, i.e. the time it takes to change the switch state from “=” to “x” or from “x” to “=”, equals about two nanoseconds. The switch is used to build rings in the core.

OPS can be either synchronous or asynchronous:

- In synchronous OPS the time domain is divided into slots during which packets are sent and received, and the duration of a packet is not longer than the time slot. The duration of a time slot depends on the technology used in the equipment. The existing optical gates can be switched on and off in about two nanoseconds, which corresponds to the guard time between packets. For instance, in the KEOPS project the time slot lasts 1.64μs [12].
- In asynchronous OPS the time domain is slotted, and so packets can arrive at any time. This technology received less attention than the synchronous technology,

> even though it is easier to build, because no synchronization is needed [11]. It has probably been so, because the asynchronous OPS suffers of larger contention probabilities in comparison with the synchronous technology [10]. The other reason might be the low network utilization needed, so that the network delivers packets with low probability of packet loss.

Access control and routing algorithms play an important role in OPS. An access control algorithm is responsible for managing packets that request admission to the core network from the access network, so that the core network is not overloaded, and so that the clients receive the required quality of service.

A routing algorithm directs packets toward their destination nodes, and tries to optimize the use of the scarce OPS resources (such as buffers and wavelength converters). The routing algorithm is responsible for forwarding packets to the appropriate output fibers on the appropriate wavelength. In a time slot a switch can send to an output fiber up to as many packets, as there are wavelengths available in the output fiber. If there are more packets requesting this output fiber, then the switch needs to resolve the contention among packets. A number of contention resolution algorithms have been proposed, which are usually the DiffServ rules for establishing the order of sending the packets [2].

One of the methods for resolving contention among packets is deflection routing, which copes with the lack or scarcity of optical buffers by sending a packet to an output fiber that is not requested by it. The action of sending a packet to a wrong output fiber is called a deflection. Deflection routing prevents packets from being dropped by using available output fibers as buffers. Deflection routing can improve network performance for light loads [40], but it can also worsen network performance for heavy loads, because then packets can be deflected many times causing a livelock [7].

3. Components

he basic optical components of OPS are a multiplexer, a demultiplexer, a coupler, a splitter, a fixed wavelength converter, a tunable wavelength converter, an optical gate, an optical delay line, an optical amplifier, a 2×2 switch, and an $N \times N$ arrayed waveguide grating (AWG). Fig. 2 shows the symbols of the elements. Light travels through these elements only in one direction.

A multiplexer (Fig. 2a) has several input fibers and a single output fiber. From each input fiber a single wavelength is selected and sent to the output fiber. The output fiber carries several wavelengths, where each of the wavelengths is taken selectively from the input fibers.

A demultiplexer (Fig. 2b) has the opposite function to a multiplexer. A multiplexer has a single input fiber and several output fibers. Wavelengths from the input fiber are sent to the output fibers, one wavelength per each output fiber.

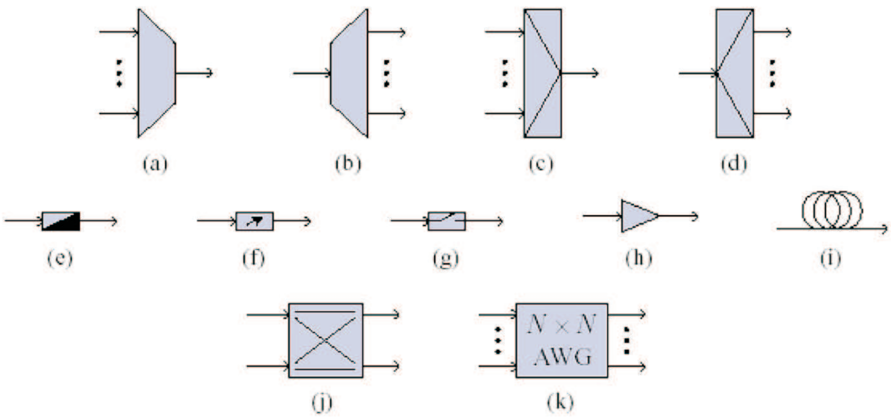

Fig. 2. Optical components: (a) multiplexer, (b) demultiplexer, (c) coupler, (d) splitter, (e) fixed wavelength converter, (f) tunable wavelength converter, (g) optical gate, (h) optical amplifier, (i) optical delay line, (j) 2 × 2 switch, (k) $N \times N$ AWG.

A coupler (Fig. 2c) has several input fibers and a single output fiber. All wavelengths from the input fibers are sent to the output fiber.

A splitter (Fig. 2d) has the opposite function to a coupler. It has a single input fiber and several output fibers. All wavelengths from the input fiber are sent to the output fibers.

A fixed wavelength converter (FWC, Fig. 2e) converts a wavelength from the input fiber to a required wavelength and sends it to the output fiber. In the input fiber there should be only one wavelength from a specific range. The light sent to the output fiber is of a fixed wavelength.

A tunable wavelength converter (TWC, Fig. 2f) is capable of tuning the wavelength at the output fiber.

An optical gate (Fig. 2g) amplifies or damps the incoming optical signal in the given wavelength range. It is controlled by the electric signal in nanoseconds. An optical gate can be implemented with a semiconductor optical amplifier (SOA), which, unfortunately, introduces considerable noise to the optical signal.

An erbium-doped fiber amplifier (EDFA, Fig. 2h) amplifies the incoming optical signal in the given wavelength range. The switching time is in the range of milliseconds. In comparison to the SOA, the EDFA distorts the optical signal less.

An optical delay line (ODL, Fig. 2i) is a piece of an optical fiber, which delays the optical signal.

A 2 × 2 switch (Fig. 2j) can switch all wavelengths with its “x” or “=” state. The switch is controlled electrically in a few nanoseconds.

An arrayed waveguide grating (AWG) element has a number of input fibers and a number of output fibers. Each input fiber can carry up to as many wavelengths as there are output fibers, where each wavelength is sent to a specific output fiber. Each output fiber can carry a single wavelength.

4. Optical packet switches

A general model of an optical packet switch is shown in Fig. 3. The input block of the switch extracts headers and interprets them. Next the controller configures the switching fabric based on the header data, and the current state of the switching fabric. An optical packet switch can have an optical delay line for delaying packets for a number of time slots. The output block adds headers to payloads.

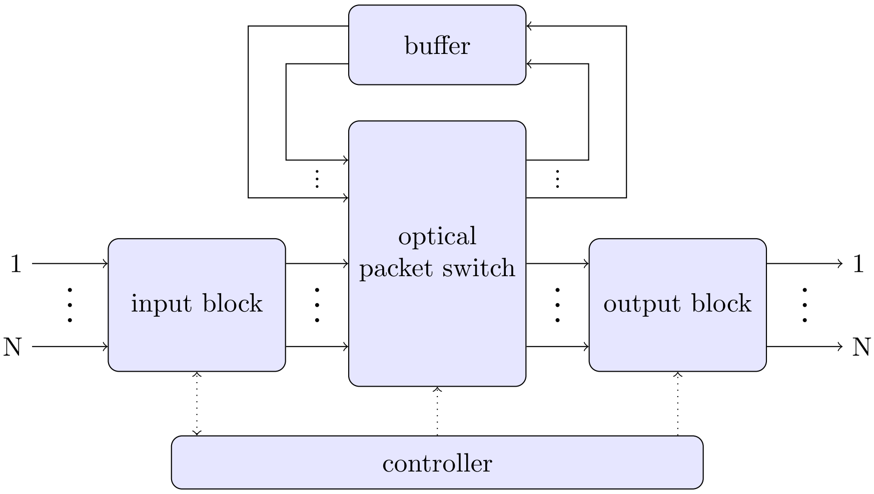

Fig. 3. A general model of an optical packet switch

Among many proposed types of optical packet switches, there are two main ones, that we describe in some detail in the following two subsections. One of them is called the broadcast-and-select switch, the other one is based on the AWG.

4.1. The broadcast-and-select switch

The broadcast-and-select switch (Fig. 4) has N input fibers an N output fibers. The input and output fibers carry one wavelength only. Splitters broadcast the input signals, and then the optical gates select the packets appropriately (they block them or let them through), so that the packets leave the switch after a required number of time slots, and at the right output fiber. A switch can be divided into three interconnected blocks: the wavelength encoder, the space switch and the wavelength selector.

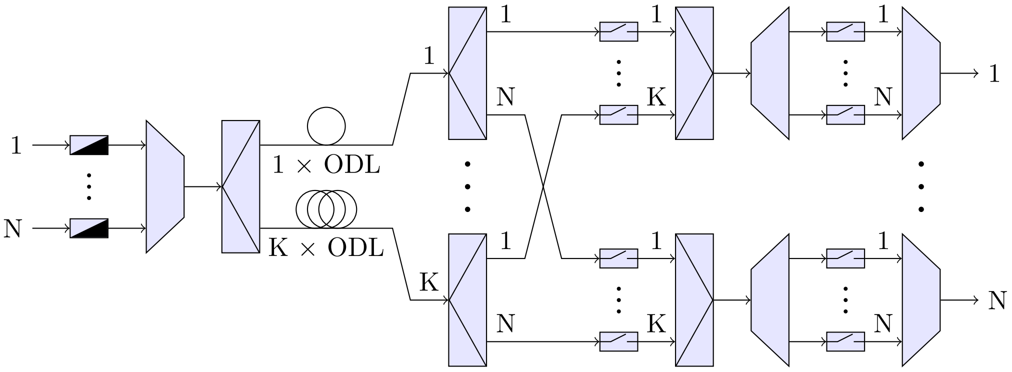

Fig. 4. The broadcast-and-select switch

The wavelength encoder has N input fibers, which are the input fibers of the switch. Each input fiber carries a single wavelength, which is converted by the fixed wavelength converter to a specific wavelength that does not change. The wavelengths are multiplexed into a single fiber which is connected to the space switch.

Packets that arrive at the input fiber of the space switch are broadcast by the splitter to optical delay lines which delay the packets by a number of time slots from 1 to K. The packets from the optical delay lines are broadcast again, but this time to optical gates. By controlling the optical gates, packets can be sent to the required output fibers after the required number of time slots. Packets that were let through the optical gates are then sent to the output fibers through combiners. The controller should not allow more than one packet to be sent through an output fiber in a time slot, even on different wavelengths.

The wavelength selector is built of N blocks: one block for each output fiber. A block is built of a demultiplexer, N optical gates, and a multiplexer. A block selects a packet to leave through the output fiber, depending on the wavelength of the packet.

The advantage of this switch type is the multicast ability: one input packet may leave the switch on multiple output fibers after various delays. The disadvantage of this switch type are large power losses of optical signal and the introduction of noise.

4.2. A switch based on AWG

A switch based on AWG has the AWG element as the switching fabric (Fig. 5). It has N input fibers and N output fibers. Each input fiber and each output fiber carries n wavelengths. The switch has three blocks connected in sequence: the input wavelength converter, the AWG element, and the output wavelength converter.

The input wavelength converter has N demultiplexers and $N \times n$ tunable wavelength converters. Each tunable wavelength converter receives up to one wavelength

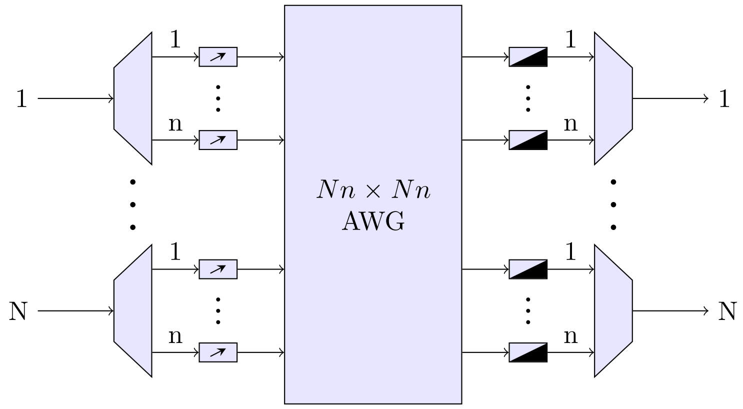

Fig. 5. A switch based on AWG

from a demultiplexer. The wavelength converters are tuned to a specific wavelength for each packet in each time slot, so that the packet is sent to a specific output fiber of the AWG element.

The function of the AWG element is, as mentioned in section 3, sending an optical signal to a specific output fiber based only on the wavelength, and regardless of the input fiber.

The output wavelength converter has $N \times n$ fixed wavelength converters and N multiplexers. After leaving the AWG element, a wavelength is converted by the fixed wavelength converter to one of the n wavelengths, and then multiplexed to an output fiber for the WDM transmission.

5. Buffering

One of the main technical problems of OPS is the lack of optical RAM memories, which hinders the application of the traditional store-and-forward routing, where packets are buffered in large numbers and sent when possible [39]. Optical buffering is limited mostly to optical delay lines (ODL). Unfortunately, ODL buffers are physically large and their capacity expressed in the number of packets is small.

The overview of optical buffers and the ways of using them with optical packet switches is discussed in [18, 9]. Optical buffers are practically and critically reviewed in [35], taking into account also slow light buffers. For optical packet switching there has been even proposed a buffer based on electronic memory [34].

The optical delay lines alone are not buffers; there are switches needed, which will direct packets to optical delay lines. There are a number of types of optical buffers and ways of controlling them [33, 42]. However, two basic and useful buffer types are the circulating buffer, and the cascade buffer:

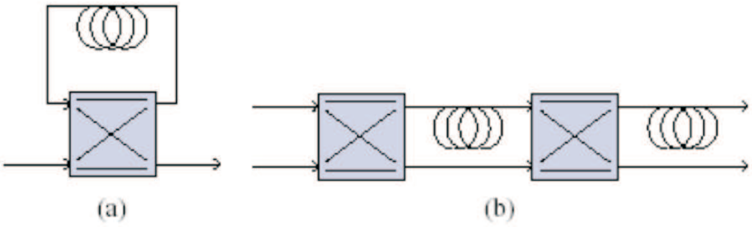

Fig. 6. Optical buffers: (a) circulating; (b) cascade

- The circulating buffer (Fig. 6a) is built of an ODL and a 2 × 2 switch. The switch directs a packet into and out of the ODL. The number of packets that can enter the ODL depends on the length of the ODL and the switching time of the 2 × 2 switch. The ODL usually has a few hundred meters, but a buffer with an ODL of 2 meters has been proposed too [29]. A packet usually cannot circulate more than 20 times because of the optical noise introduced by the 2 × 2 switch.
- The cascade buffer (Fig. 6b) is built of several ODLs and 2 × 2 switches connected in a cascade. The subsequent ODLs can delay packets in the number of time slots equal to the powers of two. Therefore the buffer can delay packets for a given number of time slots with the packet passing through a smaller number of 2 × 2 switches, and distorting the optical signal less in comparison with the circulating buffer. The buffer can delay more than one packet, but can also reorder them, which is usually undesirable.

An electronic switch currently in operation has large electronic memory, and is capable of storing millions of packets. In contrast, an optical packet switch with its optical buffer is capable of storing only a few packets. If the TCP (Transmission Control Protocol) traffic keeps being the predominant data traffic in the optical core networks, then small optical buffers should suffice resulting only in a network performance drop of about 10% [1, 38].

6. Conclusion

Optical packet switching was envisioned to be the technology of the next generation optical network. This vision has not been realized yet, but it still promises to be realized in the future. While optical packet switching offers well-established and functional switch architectures, the main problems still are the lack of RAM memories and the expensive wavelength conversion and regeneration. Optical packet switching should start to be deployed in operational networks when it becomes a commercially-viable alternative to the electronic hardware.

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Przegląd optycznego przełączania pakietów

Streszczenie

Technologia optycznego przełączania pakietów jest tematem prac badawczych od około dwóch dekad, ale mimo tego nie została ona jeszcze zastosowana w sieciach operatorów telekomunikacyjnych. A artykule jest opisany aktualny stan wiedzy z dziedziny optycznego przełączania pakietów z wyszczególnieniem problemów technicznych. We wprowadzeniu omawiane są podstawowe sposoby komunikacji w sieciach optycznych. Na rys. 1 pokazany jest schemat sieci optycznej, której węzły są zbudowane z elementów optycznych symbolicznie przedstawionych na rys. 2. Następnie omówiona jest ogólna budowa przełączników optycznych (rys. 3) i bardziej szczegółowo są omówione przełączniki typu "rozgłaszanie i wybieranie" (rys. 4) i przełączniki oparte na krotnicach falowych AWG (rys. 5). Omówione zostały także problemy techniczne związane z optycznym buforowaniem pakietów (rys. 6). Optyczne przełączanie pakietów ma większy potencjał niż elektroniczne przełączanie pakietów i dlatego nad tą technologią ciągle prowadzone są prace badawcze. Należy jednak pamiętać, że elektroniczne przełączanie pakietów jest ulepszane, co sprawia, że optyczne przełączanie pakietów powinno sprostać jeszcze większym wymaganiom, aby mogło być zastosowane w sieciach operatorów telekomunikacyjnych.