Trends in Optical Switching Techniques: A Short Survey

Martin Maier, Institut National de la Recherche Scientifique (INRS)
Martin Reisslein, Arizona State University

Abstract

We are currently witnessing a strong worldwide push toward bringing fiber closer to individual homes and businesses. The emerging FTTX access networks will move the bandwidth bottleneck from the first/last mile toward metropolitan and wide area networks, creating a need for efficient optical-switching mechanisms. In this article, we review the current trends in optical switching that help to improve the bandwidth efficiency, as well as to decrease the cost and power consumption of next-generation optical networks. Our review provides an overview of the optical switching domain and facilitates the understanding of newly emerging switching techniques and their interpretation as derivatives of the presented main optical switching trends.

Wide area networks (WANs) were one of the first network segments that experienced the widespread deployment of optical technologies to provide sufficient capacity in support of heavy long-haul traffic. Currently, by means of wavelength division multiplexing (WDM), optical WANs offer large bandwidth pipes where a single fiber can carry tens or even hundreds of wavelength channels, each operating at a bit rate of 10 Gb/s or higher. Given these vast amounts of available bandwidth, one of the major design criteria of current backbone networks has been not to maximize the utilization of bandwidth resources but to simplify network operation and reduce capital and operational expenditures. Toward these goals, a few optical network technologies were commercially adopted, for example, Erbium-doped fiber amplifier (EDFA), reconfigurable optical add-drop multiplexer (ROADM), wavelength cross-connect (WXC), and tunable laser, whereas others still must demonstrate their practical importance [1]. Most current operational optical WDM backbone networks deploy circuit switching at the wavelength granularity. The resultant point-to-point wavelength channels are often referred to as *lightpaths* (or *light-trees* in the case of point-to-multipoint wavelength channels). At present, there is a strong worldwide push toward bringing fiber closer to individual homes and businesses. Fiber-to-the-home/business (FTTH/B) or close to it (FTTX) networks are poised to become the next major success story for optical fiber communications [1]. For a survey of recent developments and deployments of FTTX networks, see [2].

Due to ever increasing speeds of access networks, the bandwidth bottleneck will move from the first/last mile toward metropolitan and wide area networks. To provide higher bandwidth efficiency, optical metro and core wavelength-switching networks could be required to resort to more efficient switching techniques at the sub-wavelength granularity in the near- to mid-term. In this article, we explain the current trends in optical switching, covering techniques across the range of switching granularity, ranging from switching entire fibers to switching individual packets on each wavelength channel.

Future optical networks can deploy any of the presented switching techniques or a combination thereof. To support a wide range of devices with different switching granularities, a unified control plane based on generalized multiprotocol label switching (GMPLS) with appropriate extensions is required. GMPLS widens the scope of packet-switching MPLS networks toward the time, optical, and space domains. Note that GMPLS is outside the scope of this article due to space constraints.

The remainder of the article is structured as follows. In the next section, we discuss waveband switching (WBS), followed by a description of photonic slot routing (PSR). Then, optical flow switching (OFS) is explained. The next two sections deal with optical burst switching (OBS) and optical packet switching (OPS), respectively. We then briefly interpret some recent switching techniques as derivatives of the presented switching trends, and the final section concludes the article.

Waveband Switching

Compared to ordinary optical cross connects (OXCs), so-called multi-granularity OXCs (MG-OXCs) hold great promise to reduce significantly the complexity, size, and cost of OXCs by switching fibers and wavebands together without demultiplexing the arriving WDM comb signal into its individual wavelengths, giving rise to WBS. As a result, the size of ordinary cross connects that traditionally switch at the wavelength granularity can be reduced, including the associated control complexity and cost, by using a single input/output port instead of multiple input/output ports, one for each individual wavelength. Figure 1 depicts a typical multi-granularity photonic cross connect, consisting of an MG-OXC at the fiber

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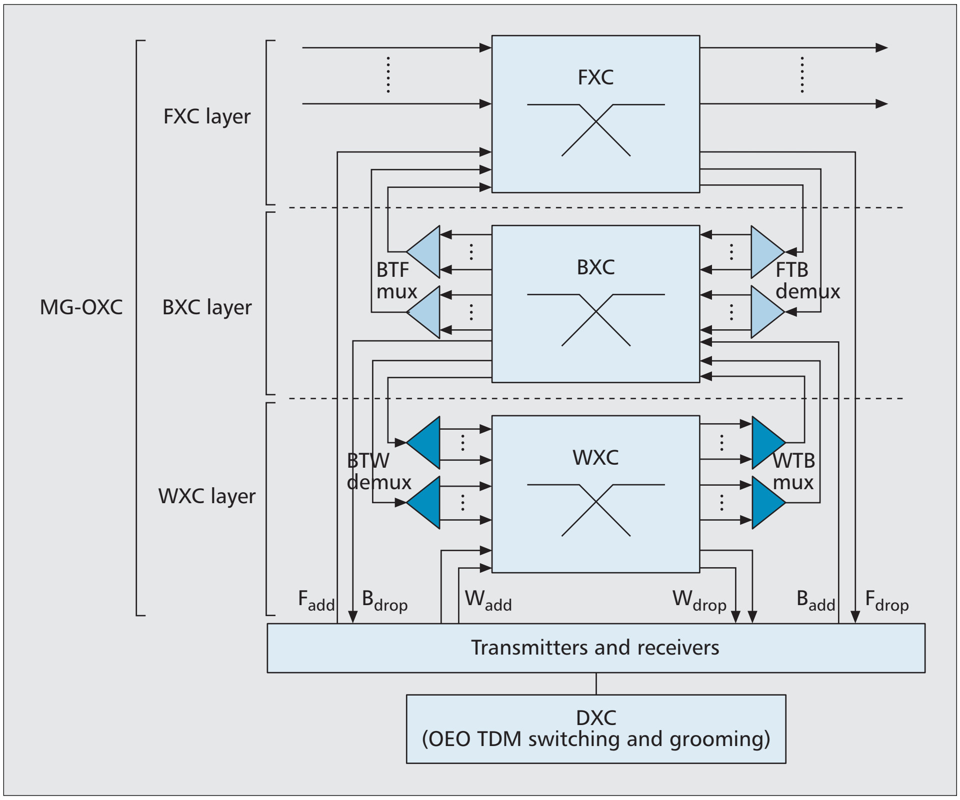


■ Figure 1. *Multigranularity photonic cross-connect consisting of a three-layer multigranularity optical cross-connect (MG-OXC) and a digital cross-connect (DXC) [3].*

(FXC), waveband (BXC), and wavelength (WXC) layers, as well as a digital cross connect (DXC) [3]. The MG-OXC allows to switch, as well as to add and drop traffic at multiple granularities by deploying a bank of transmitters and receivers. Traffic can be shifted from one granularity level to another by using appropriate multiplexers (MUX) and demultiplexers (DEMUX). For sub-wavelength switching the MG-OXC is equipped with an additional DXC that performs optical-electronic-optical (OEO) conversion. By using MG-OXCs, fibers and wavebands that carry in-transit traffic are not required to undergo demultiplexing and multiplexing.

Waveband Grouping

To determine which wavelengths to group together into a single waveband, several waveband grouping strategies exist, which can be categorized into *end-to-end* or *intermediate* approaches. In [4], an end-to-end waveband grouping strategy that groups wavelengths with the same source-destination pair into a waveband was compared with an intermediate waveband grouping strategy that groups wavelengths with the same destination at an intermediate node. The obtained results indicate that intermediate waveband grouping strategies outperform end-to-end grouping strategies in terms of required ports at MG-OXCs.

Routing and Wavelength Assignment

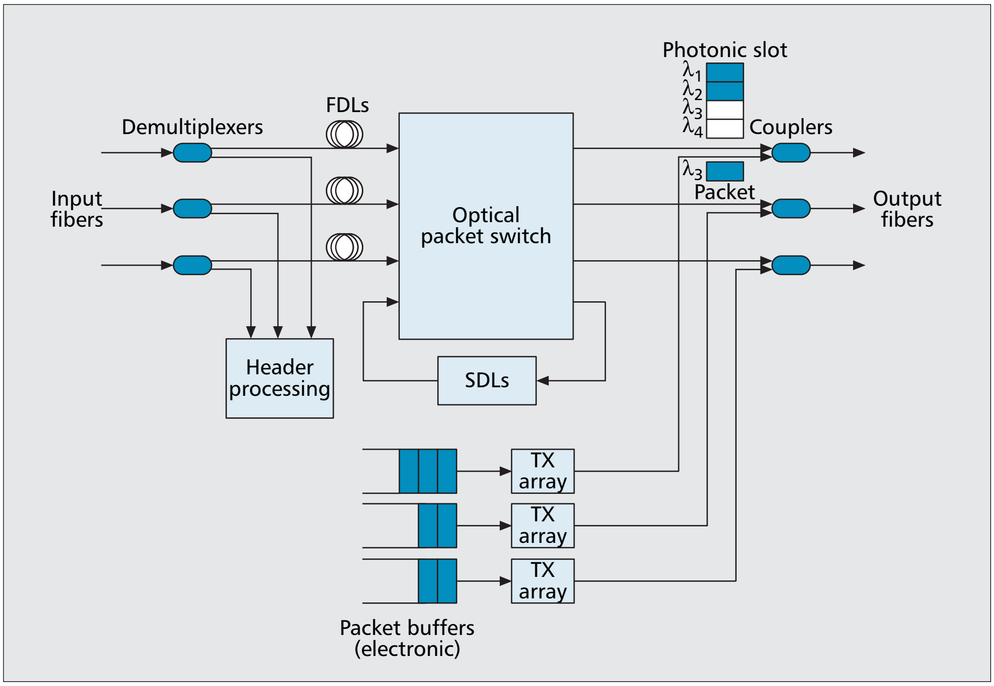
The routing and wavelength assignment (RWA) problem in WBS networks that use MG-OXCs is, in general, more involved than that in conventional wavelength-switching networks due to additional constraints, apart from wavelength continuity. Several new RWA-related problems in WBS networks were identified and solved. The so-called routing and wavelength/tunnel assignment (RWTA) problem deals with the bundling and switching of wavebands and fibers and routing lightpaths through them [5]. The so-called *RWA+* problem is formulated as a combinatorial optimization problem with the objective to minimize the bottleneck link utilization of mesh WBS networks [6]; whereas the so-called routing, wavelength, and waveband assignment (RWWBA) problem aims at maximizing cost savings in terms of required MG-OXC ports and minimizing blocking probability in mesh WBS networks [7]. The benefits of various types of wavelength conversion on solving the RWA problem in WBS networks were examined in [8].

TDM Switching and Grooming

The additional DXC in Fig. 1 is used to perform TDM switching and grooming in the electrical domain by means of OEO conversion of wavelengths and wavebands. Grooming allows for grouping multiple low-volume traffic flows into a wavelength or waveband and thereby improve their bandwidth utilization. In [9], a design study of networks based on a hybrid WBS-OEO grooming switch architecture was performed taking physical transmission impairments into account to study the maximum distance and number of nodes the optical signal can traverse without undergoing OEO conversion.

Photonic Slot Routing

To improve the utilization of lightpaths under bursty traffic without requiring electronic traffic grooming at the source node, a cost-efficient design approach for WDM networks called PSR was proposed in [10]. In PSR networks, time is divided into fixed-size slots, whereby each slot spans all wavelengths, and slot boundaries are aligned across all wavelengths. The resultant multi-wavelength slot is called a *photonic slot*. Each wavelength in the photonic slot may contain a single fixed-size packet. Furthermore, all packets in a given photonic slot must be destined for the same node, but each photonic slot may be destined for a different node. As a consequence, the photonic slot can be routed as a single entity, thereby avoiding the need for demultiplexing the individual



■ Figure 2. *PSR node with multiple input/output ports [13].*

wavelengths and routing them individually. Thus, PSR networks require no wavelength-sensitive components, resulting in lower network costs by using wavelength-insensitive components and reduced complexity of switching nodes.

PSR Functions

PSR nodes perform the following three functions on a per photonic slot basis [11]:

- **Photonic slot routing**: photonic slots arriving on any input port are switched to any output port, possibly invoking contention resolution (see below).
- **Photonic slot copying**: a photonic slot arriving on an input port is duplicated and switched to two or more output ports, giving rise to multicasting.
- **Photonic slot merging**: photonic slots concurrently arriving on multiple input ports are switched to the same output port.

Synchronization

To achieve the aforementioned functions, PSR requires mechanisms to achieve and maintain network wide slot synchronization such that photonic slots arrive synchronized at PSR nodes. One possible solution is the use of fiber delay lines (FDLs) at the input ports of PSR nodes to delay and synchronize arriving photonic slots [11]. Another way to achieve network wide synchronization for a two-layer PSR networks was described in [12].

Contention Resolution

Figure 2 shows a PSR node that deploys switched delay lines (SDLs) to resolve contention [13]. The PSR node consists of a wavelength-insensitive optical packet switch, SDLs to temporarily store photonic slots, and electronic buffers to hold locally generated packets. Each SDL comprises FDLs interconnected by photonic cross-bar switches that are set to delay photonic slots until contentions at the output ports are resolved.

Evolution Toward OPS

By breaking up the photonic slot and switching each wavelength independently, PSR can be transformed into individual wavelength switching (IWS). It was shown in [11] that the network capacity can be increased significantly by carefully replacing a relatively small percentage of conventional PSR switches with IWS switches. IWS enables smooth migration paths from PSR networks to (synchronous) OPS networks, which are discussed in greater detail in the next section.

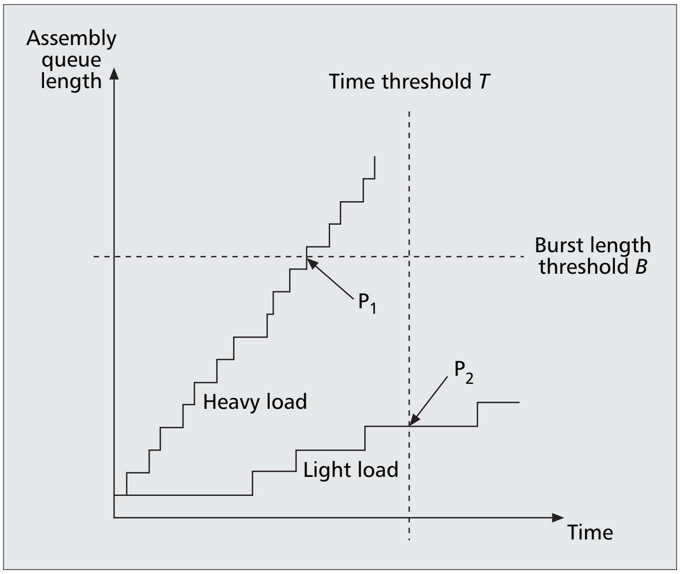
Optical Flow Switching

One of the main bottlenecks in the current optical Internet is electronic routing at the IP layer. To alleviate this electro-optical bottleneck, routers can be offloaded by switching large transactions and/or long-duration flows at the optical layer, leading to so-called OFS [14]. In OFS, a dedicated lightpath is set up for the transfer of large data files or upon detection of long-duration flows, whereby flows with similar characteristics (e.g., same destination IP router) may be aggregated and switched together by means of grooming to improve the utilization of the established lightpath. Because in OFS the set-up of a lightpath takes at least one round-trip time between source and destination IP routers, clearly, the size of a transaction/flow should be in the order of the product of round-trip propagation delay and line rate of the lightpath.

The set-up lightpath enables the optical bypassing of intermediate IP routers and thereby eliminates the need for (electronic) packet processing, for example, buffering, routing, and so on. It is important to note that OFS can be *end-user initiated* or *IP-router initiated* [15]. OFS offers the highest-grade quality of service (QoS) because the established lightpath provides a dedicated connection. However, OFS must determine carefully when to set up a lightpath because wavelengths are typically a scarce network resource.

The dynamic lightpath set-up in OFS requires flow routing, wavelength assignment, and connection set-up through signaling. In [16], the following two integrated OFS approaches were proposed for dynamic lightpath set-up in OFS networks:

- **Tell-and-go (TG) reservation**: TG is a distributed algorithm based on periodic or event-driven link state updates that allow each node to acquire and maintain global network state. TG uses a combined *K*-shortest path routing and first-fit wavelength assignment approach. Connection set-up



■ Figure 3. *Burst length and time thresholds for burst assembly algorithms [19].*

is achieved by one-way reservation, where the control packet precedes the trailing optical flow along the chosen route.
- **Reverse reservation (RR)**: In RR, the initiator of an optical flow sends link state information gathering packets to the destination node on the K shortest paths. Upon arrival at the destination, route selection and first-fit wavelength assignment are performed by the destination node, and a reservation control packet is sent along the chosen path in reverse to establish the connection.

Optical Burst Switching

OBS aims at combining the transparency of optical circuit switching with the statistical multiplexing gain of optical packet switching [17]. In OBS, only preceding control packets carried on one or more control wavelength channels undergo OEO conversion at each intermediate node, whereas data is transmitted and all-optically switched at the burst level on a separate set of data wavelength channels. OBS is best explained by first discussing the functions executed by users at the edge of an OBS network, followed by a description of the functions performed by OBS nodes inside an OBS network [18].

OBS Network Edge

Each edge-OBS user executes the following four functions:

Burst assembly: OBS users collect traffic originating from upper layers, for example, IP, sort it based on destination addresses, and aggregate it into variable-size data bursts by using appropriate burst assembly algorithms. Most burst-assembly algorithms use either burst-assembly time or burst length or both as the criteria to aggregate bursts. Typically, the parameters used are a time threshold T and a burst-length threshold B, which can be fixed or dynamically adjusted. Various time and/or burst length-based assembly algorithms can be designed based on these thresholds [19]. Figure 3 illustrates the impact of B and T on the transmission of a burst under light and heavy loads. Under a light load, a burst length-based assembly algorithm does not provide any constraints on the queuing delay of packets that wait to be aggregated into a burst of size B. A time-based assembly algorithm could solve this problem because it sends out the burst after time T at point P_2 in Fig. 3. Under heavy traffic, however, a burst-length algorithm leads to smaller average queuing delays because it already sends out the burst at point P_1 in Fig. 3. Clearly, it is desirable to use mixed time/burst length-based assembly algorithms.

Signaling: in OBS, there are two types of signaling.
- Distributed signaling with one-way reservation
- Centralized signaling with end-to-end reservation

In the more common one-way reservation scheme, a source OBS user sends a control packet on a separate out-of-band control channel prior to transmitting the corresponding burst. The control packet contains information about the burst, for example, size and offset (defined shortly), and is OEO converted and electronically processed at each intermediate OBS node. Examples of one-way reservation are so-called just-in-time (JIT) and just-enough-time (JET) signaling. In the less frequently used centralized signaling approach, OBS users send their connection set-up requests to a central server that sends ACKs to the requesting edge-OBS users upon connection establishment.

Routing and wavelength assignment: Routing in OBS networks can be done either on a hop-by-hop basis by deploying GMPLS routing protocols to compute explicit or constraint-based routes. Along the selected path, each link must be assigned a wavelength on which bursts are carried.

Offset: After sending the control packet, an OBS user waits for a fixed or variable delay, called offset, until it starts transmitting the corresponding burst. The offset is used to enable the control packet to be processed, reserve the required resources, and configure the optical switching fabric at intermediate OBS nodes, such that the arriving burst can cut through each intermediate OBS node without requiring any buffering or processing. Note that by using different offsets, traffic classes can be isolated and service differentiation can be achieved [20].

OBS Network Core

OBS nodes located in the core of OBS networks perform the following two functions:

Scheduling: Based on the information carried in the control packet, resources inside the optical switching fabric of a core OBS node are reserved and released for either explicitly signaled or estimated start and end times. Available burst scheduling algorithms can be categorized into *non-void-filling* and *void-filling* algorithms [21].

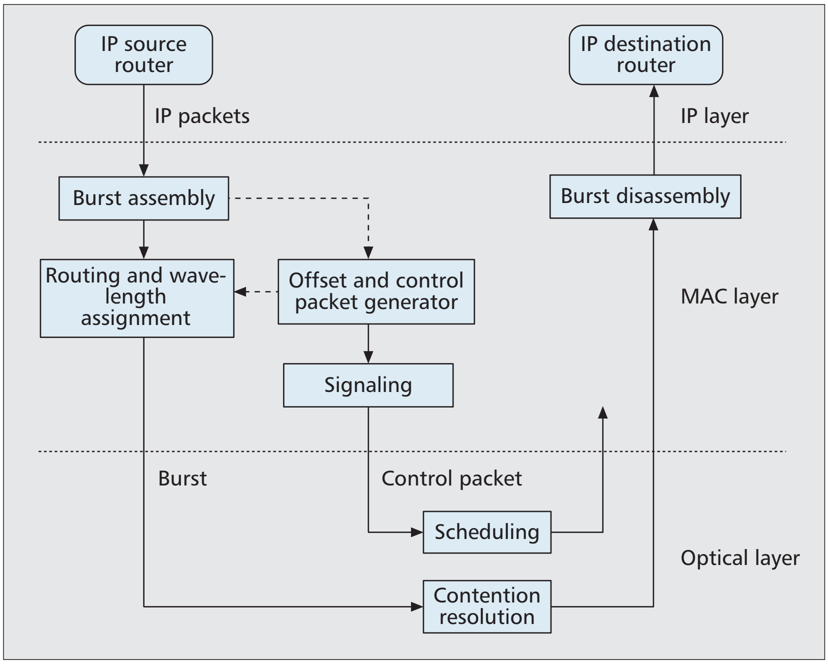
Contention resolution: Contention occurs if two or more simultaneously arriving bursts contend for the same local resources of a given core OBS node. Several techniques for contention resolution in OBS networks have been investigated, for example, optical buffering (FDL, SDL), deflection routing, wavelength conversion, and burst segmentation, or any combination thereof.

OBS MAC Layer

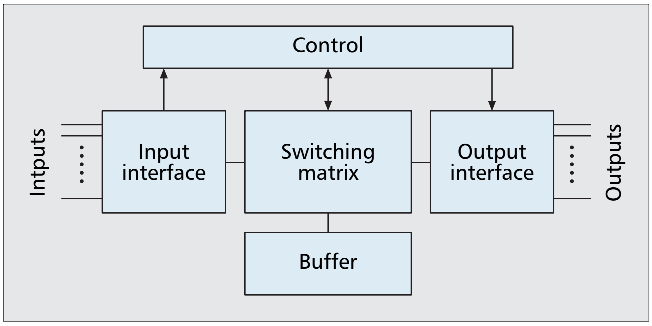
To implement the aforementioned functions, a medium access control (MAC) layer is required between the IP layer and the optical layer [22]. Figure 4 illustrates the functional blocks required at the MAC and optical layers for implementing OBS networks. Note that the functional blocks correspond to the previously described functions executed by edge-OBS users and core-OBS nodes.

Optical Packet Switching

One might argue that economics will ultimately demand that optical network resources are used more efficiently and the switching granularity is decreased to optical packets, resulting in OPS [23]. Unlike OBS, OPS does not require edge routers to perform any burst (dis)assembly algorithms at the network



■ Figure 4. *Block diagram of OBS networks consisting of IP, MAC, and optical layers [22].*



■ Figure 5. *Generic OPS node architecture [25].*

periphery. Moreover, in OPS, the header is generally not sent on a separate control wavelength channel, thus avoiding the issue of properly setting the offset time. OPS can be viewed as an attempt to mimic electronic packet switching, most notably asynchronous transport mode (ATM) and IP, in the optical domain while taking the shortcomings and limitations of the current optics and photonics technology into account, for example, the lack of optical random access memory (RAM) and the limitation of optical logical operations. An interesting approach to realize practical OPS networks in the near term is the so-called optical label switching (OLS) [24]. In OLS, only the packet header, referred to as a label, is processed electronically for routing purposes, whereas the payload is switched in the optical domain.

Optical Packet Switches

OPS networks can be either slotted or unslotted networks that deploy synchronous or asynchronous switches, respectively. Figure 5 depicts a generic OPS node architecture where its building blocks perform different functions [25]:

- **Input interface**: The input interface performs packet delineation. In the case of synchronous switches, synchronization is done for the performing phase alignment of arriving packets. Next, the packet header is extracted, OE converted, decoded, and forwarded to the control unit. The control unit processes the routing information, configures the switch accordingly, updates the header information, and forwards the header to the output interface. If necessary, the external wavelength of an arriving optical packet is converted to an internal wavelength for use in the switching matrix.
- **Switching matrix**: The switching matrix carries out the switching operations of the payload in the optical domain. Additionally, it also resolves contention (see below).
- **Output interface**: The output interface performs reamplification, reshaping, and retiming (3R) regenerative functions. Furthermore, it attaches the updated header to the corresponding optical packet and performs packet delineation. In synchronous switches, the output interface also performs packet resynchronization. When required, it converts internal wavelengths back to external wavelengths.

Based on the switching fabric, OPS nodes can be classified into the following three categories:

- *Space switch*
- *Broadcast-and-select*
- *Wavelength-routing* OPS node architectures [26]

Contention Resolution

Similar to OBS, contention in OPS networks can be resolved by using buffering, wavelength conversion, and deflection routing, or any combination thereof. Deflection routing simplifies the OPS node architecture in that no buffers are required. On the downside, however, deflection-routed packets generally consume more network resources, incur higher delays, and may require packet reordering mechanisms at the destination nodes to achieve in-order packet delivery. Typically, optical buffers are implemented by using an array of FDLs of different lengths or SDLs. According to the position of the optical buffer, OPS nodes can be classified into four major configurations:

- *Output buffering*
- *Shared buffering*
- *Recirculation buffering*
- *Input buffering*

All these optical buffering schemes can be implemented in either *single-stage* or *multiple-stage* OPS nodes in a *feed-forward* or *feed-back* configuration. The advantages and disadvantages of the various buffering schemes are discussed at length in [27]. It is important to note that optical buffers realized by FDLs or SDLs offer only fixed and finite amounts of delay, as opposed to electrical RAM.

Service Differentiation

Service differentiation in OPS networks is closely related to the techniques chosen to resolve contention. Apart from using one or more of the aforementioned dimensions of space, time, and wavelength, service differentiation also can be achieved by means of *preemption* and *packet dropping*. With preemption, a high-priority packet is allowed to preempt an OPS node resource currently occupied by a low-priority packet, which is then discarded. With packet dropping, an OPS node drops low-priority packets with a certain probability before attempting to utilize any resources, resulting in a decreased packet loss of high-priority packets.

Example Hybrids and Extensions

We believe that the presented overview of the current trends in optical switching techniques provides a framework for anticipating and understanding specific optical switching techniques. In most cases, specific unmentioned or newly emerging techniques can be interpreted as extensions or hybrids of the presented switching techniques. To illustrate, we briefly discuss two example derivatives in the following.

Light-Trail

A so-called *light-trail* is a generalization of a conventional point-to-point lightpath in which data can be dropped and added at any node along the path, as opposed to a lightpath where data can be added only by the source and dropped only by the destination node [28]. Light-trails enable optical multicasting and help improve the utilization of wavelength channels.

Fractional Lambda Switching

Another good example for switching derivatives is fractional lambda switching (FλS) [29]. FλS uses the globally available coordinated universal time (UTC) as a common time reference to synchronize all optical switches throughout the FλS network. FλS might be viewed as a sub-wavelength circuit-switching technique where periodically recurring time slots are all-optically switched at intermediate nodes without requiring optical processing and optical buffering due to the network-wide synchronization of optical switches via UTC.

Conclusions

We have presented the current trends in switching techniques for next-generation optical networks and explained their underlying concepts and mechanisms. Each of these trends has its own specific strengths and limitations and may be deployed depending on various criteria, such as costs, capacity requirements, and traffic characteristics. Our comprehensive overview of the current trends of optical switching provides a framework for anticipating new switching techniques, such as hybrid techniques that exploit the different switching granularities offered by the presented switching techniques. The discussed optical switching techniques significantly improve the flexibility of the data plane by providing a wide range of different temporal and spatial switching granularities. For commercial viability, however, further research is required to reduce the complexity introduced to the control and management planes by each of these optical switching techniques.

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Biographies

MARTIN MAIER (maier@ieee.org) was educated at the Technical University of Berlin, Germany, and received Dipl.-Ing. and Dr.-Ing. degrees, both with distinction (summa cum laude), in 1998 and 2003, respectively. In the summer of 2003, he was a post-doc fellow at the Massachusetts Institute of Technology (MIT), Cambridge. He is an associate professor at Institut National de la Recherche Scientifique (INRS), Montreal, Canada. He was a visiting professor at Stanford University, California, October 2006 through March 2007. He is the founder and creative director of the Optical Zeitgeist Laboratory. His research aims at providing insights into technologies, protocols, and algorithms shaping the future of optical networks and their seamless integration with broadband wireless access networks. He is the author of the books *Optical Switching Networks*, Cambridge University Press, 2008 and *Metropolitan Area WDM Networks — An AWG Based Approach*, Kluwer Academic Publisher, 2003.

MARTIN REISSLEIN (reisslein@asu.edu) received his Ph.D. in systems engineering from the University of Pennsylvania, Philadelphia, in 1998. He is an associate professor in the Department of Electrical Engineering at Arizona State University, Tempe. From July 1998 through October 2000, he was a scientist with the German National Research Center for Information Technology (GMD FOKUS), Berlin. He maintains an extensive library of video traces for network performance evaluation, including frame size traces of MPEG-4 and H.264 encoded video; available at http://trace.eas.asu.edu