6.5 All-Optical Traffic Grooming

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6.5.1 Introduction

Next-generation optical communication networks are expected to exceed aggregate capacities of hundreds of terabits per second to support the recent growth in commercial broadband access fueled by applications such as Video-on-Demand (VoD) and Voice-over-IP (VoIP), and to meet the high-performance demands of grid-computing networks for research consortiums and military applications [1-4]. The continuous increase in need for higher bandwidth has also necessitated in parallel a continuous reduction in cost per bit, which has paved the way for the all-optical revolution. As higher bandwidth with smaller footprint and lower power consumption scales better with lower cost *optics*, the past 30 years has seen *electronics* get gradually pushed out of the core communication network to the lower bandwidth edge user interfaces. The advantage of transitioning to all-optical communication is most evident first with the introduction of the erbium-doped fiber amplifier (EDFA) in the early 1990's. The EDFA not only increased the all-optical reach of bandwidth independent signals by eliminating costly optical-electrical-optical (OEO) repeaters, but it also revolutionized point-to-point communication system capacity by allowing widespread implementation of dense wavelength division multiplexing (DWDM). The second confirmation of the benefit of all-optical communication is the introduction of optical add-drop multiplexers (OADM) at metro and backbone network nodes in the early 2000's. Similarly to the EDFA, the OADM allowed the removal of costly in-line OEO transponders by providing all-optical bypass of express traffic. Furthermore, in realizing the concept of the all-optical core ring network, the OADM provides significant *optics* savings by driving the grooming *electronics* switch to the edge of the network for sub-wavelength processing of the local add-drop traffic.

While the EDFA and OADM have allowed for the realization of today's all-optical point-to-point systems and core ring networks, the current shift to higher data rates of 40 Gb/s SONET, 100 Gigabit Ethernet and beyond opens up the possibility for further cost-saving all-optical innovations in high-capacity edge and core networks. This chapter reviews the next-generation all-optical traffic grooming technologies for both the core and edge networks. Section 2 reviews the state-of-the-art smart optical switching technologies for all-optical wavelength grooming in the core network as these networks evolve to interconnected rings and mesh architectures. Section 3 reviews all-optical circuit grooming, or optical time division multiplexing (OTDM), for aggregating low-speed sub-wavelength circuits into wavelengths between the core and edge networks. Finally, section 4 reviews all-optical edge grooming techniques such as optical packet switching (OPS) and optical burst switching (OBS) for reducing costly *electronics* in edge grooming switches and IP routers.

6.5.2 All-Optical Wavelength Grooming

The aggregate bandwidth capacity increase in next-generation metro and long haul core optical networks requires a considerable increase in DWDM fiber link capacity, which is achieved by increasing both the number of wavelengths and the data rate per wavelength using spectrally efficient modulation formats as recently demonstrated with a 25.6 Tb/s transmission experiment [5]. These high-capacity DWDM links are interconnected into dynamically reconfigurable all-optical mesh networks with efficient wavelength provisioning and optimized use of network elements for both capital and operational cost savings. This agile photonic network is enabled by the next-generation of remotely reconfigurable OADM (ROADM) with express traffic switching and local add-drop wavelength grooming capabilities. The ROADM should support multiple degree nodes, which is defined as the number of DWDM fiber network ports terminating at the node. It should also allow each add-drop port to have fully flexible access to the network to ensure efficient network utility of each access transponder. The latter is of high significance in a multi-degree ROADM design as transponders and regenerators dominate the overall core network cost and should be minimized to the lowest possible required by the network [2,6]. The key enablers for all-optical wavelength grooming of core network traffic are the dramatic savings in (1) cost per express wavelength switching in the optical domain by removing in-line

OEO transponders and electronic switches, and (ii) cost per access wavelength switching by removing redundant edge OEO transponders through flexible optical add-drop.

Traditional degree-two nodes in ring networks have relied upon static OADM's that can transit and add-drop only fixed wavelengths without reconfigurability. These OADM's are either based on a three-port WDM filter approach (Fig.1a) or a pair of concatenated optical demultiplexers (DMUX) and multiplexers (MUX) for splitting and recombining all DWDM wavelengths (Fig. 1b). Next-generation degree-two ROADM's are based on wavelength blockers (WB) using liquid crystals (LC), or one-dimensional micro-electro-mechanical-system (1-D MEMS) switches, or integrated planar lightwave circuits (PLC), where all techniques process and power balance express traffic at a per wavelength basis [7,8]. Add-drop access for both 1-D MEMS and LC-based ROADM's is achieved by tapping the aggregate DWDM signal before and after the WB and separating the channels using fixed wavelength D/MUX's (Fig. 1c). The PLC-based ROADM has the advantage of utilizing the already integrated express D/MUX's for fixed wavelength add-drop access by further integrating per channel 2×2 switches onto the PLC device (Fig. 1d). While degree-two ROADM's provide reconfigurable all-optical wavelength grooming, fully flexible add-drop access requires the use of additional tunable filters and optical switches, the cost of which can be prohibitive for high add-drop ratios.

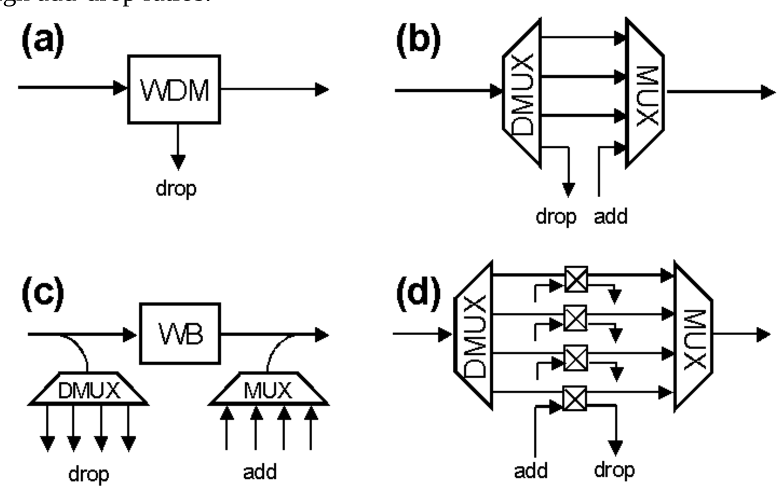

Fig. 1 Schematics of degree-two static OADM's based on **(a)** a WDM filter, **(b)** concatenated DMUX and MUX; and ROADM's based on **(c)** WB's, and **(d)** concatenated DMUX and MUX with 2×2 switches for add-drop access.

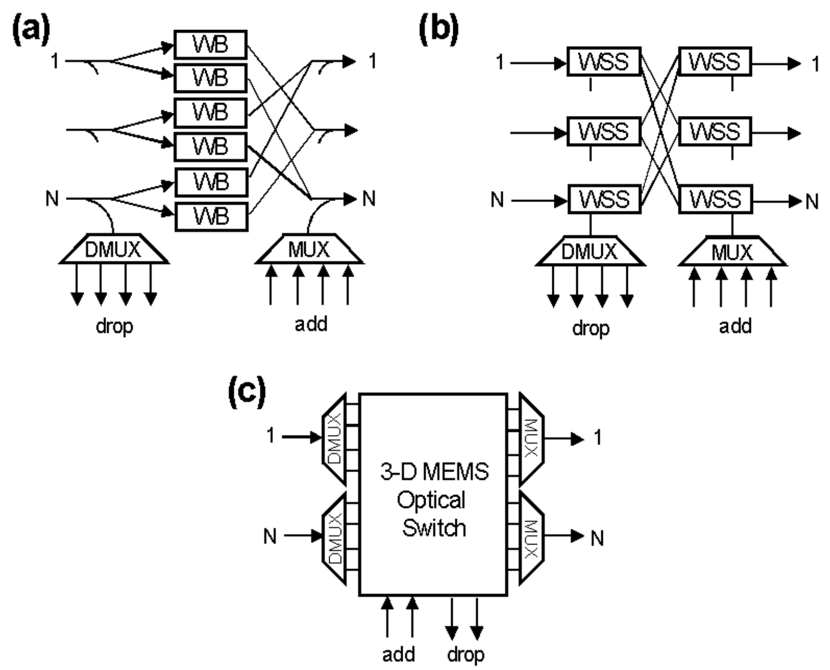

Fig. 2 Schematics of multi-degree ROADM architectures **(a)** broadcast-and-select select using WB's, **(b)** optical cross-connect using WSS's, **(c)** WSXC using 3-D MEMS optical switch.

As next-generation networks evolve into interconnected rings and mesh architectures, multi-degree ROADM nodes with flexible add-drop capability gain high significance. The add-drop flexibility criteria that eliminate additionally redundant and expensive *electronics* with cheap *optics* are summarized as follows [9]:

1. *directionless access* with any add-drop port to any DWDM network port connectivity,
2. *colorless access* with any wavelength-transparent add-drop port to any DWDM network port connectivity, and
3. *contentionless access* between all same-wavelength add-drop ports.

Multi-degree ROADM's can be realized using three distinct technologies as summarized in Fig. 2: (a) a broadcast-and-select architecture using WB's, (b) an optical cross-connect (or broadcast-and-select) architecture using wavelength selective switches (WSS), and (c) a wavelength-selective cross-connect (WSXC) architecture using a large-scale 3-D MEMS optical switch.

The broadcast-and-select architecture shown in Fig. 2a is based on the same 1-D MEMS or LC WB technologies as discussed for degree-two ROADM's [10]. While passive optical splitters are used to broadcast and combine each incoming and outgoing DWDM network port, the WB's select the desired wavelengths to be transmitted. An inherent disadvantage of this architecture is that as the degree of the node (N) increases, the required number of WB's increases quadratically to N(N-1) while the ROADM express through loss increases significantly as well. This multi-degree ROADM also physically separates the express wavelength switching from the add-drop switching by tapping the DWDM signals before and after the core express switch. While the degree based modularity of this ROADM is attractive from a network restoration perspective, this also severely complicates the ability to provide flexible add-drop access with the aforementioned flexibility criteria.

A more attractive alternative to WB's is to use 1-D MEMS or LC based 1:K WSS devices (with typical K<10), which distribute an incoming DWDM signal into any of the desired K outputs [11,12]. A multi-degree ROADM node can be achieved by cascading two WSS devices per network port and inter-connecting N-1 WSS ports from one network port to the others as shown in Fig. 2b [13]. While any of the remaining K-N+1 WSS ports can be used for colorless local add-drop access of a single transponder, the limited number of available WSS ports requires optical aggregation (using D/MUX, splitters, and EDFA's) of the transponders before accessing the WSS. Furthermore, directionless and wavelength contentionless add-drop access requires further optical processing at the edge, which becomes undesirable for high-degree nodes with high add-drop ratios [14]. While the preceding described the optical cross-connect architecture using 2N WSS devices with a fixed through loss, typical ROADM implementations use the broadcast-and-select architecture by cascading an input splitter with a single WSS device per network port [13]. This architecture has the advantage that the number of required WSS devices per node is reduced to N; however, the challenges with flexible add-drop access remain with an additional express insertion loss drawback.

A multi-degree ROADM can also be implemented with a WSXC architecture using a large-scale 3-D MEMS optical switch combined with a set of D/MUX's (Fig. 2c) [15]. While non-blocking 3-D MEMS switches with low optical insertion losses are commercially available with 320 ports, these matrix switches have also been shown to scale beyond 1,000 ports [16,17]. Wavelength switching between DWDM network ports is achieved by directing each wavelength separately to a MEMS port through the use of modular or integrated D/MUX at the DWDM network ports. Furthermore, fully agile add-drop access is realized due to the colorless and non-blocking nature of each MEMS port. A transponder or regenerator can connect to the entire core network at any wavelength using a single MEMS port. Since the add-drop ports use the already existing express filtering devices, no additional elements are required for the add-drops, reducing cost compared to the preceding WSS architectures.

The three multi-degree ROADM technologies are compared in Fig. 3 in terms of WSS functionality and evolution. The first generation WSS is the WB with a single input and output. The limited number of ports on this 1:1 WSS not only results in a quadratic need of these devices in implementing a multi-degree ROADM, but also the absence of local access ports requires additional components with limited add-drop flexibility. The next-generation device is the 1:K WSS, which has a single input port and several output ports. The number of devices required to implement a multi-degree ROADM scales linearly with the number of network ports. While a limited number of the K ports can be used for colorless local access, full add-drop flexibility and high add-drop ratios requires additional components and complicated access architectures. Finally, the integrated WSXC realizes the multi-degree ROADM through a N:N WSS device with additional ports available for fully flexible add and drop access at wavelength granularity with simple operational management. While the latter approach provides the most flexible multi-degree ROADM due to the non-blocking switching nature of each wavelength port, the former two architectures provide a modular growth possibility with less add-drop flexibility. While modular growth of 3-D MEMS switches has been proposed, it can be concluded that network port modularity and local add-drop flexibility of a multi-degree ROADM are competing design criteria [14].

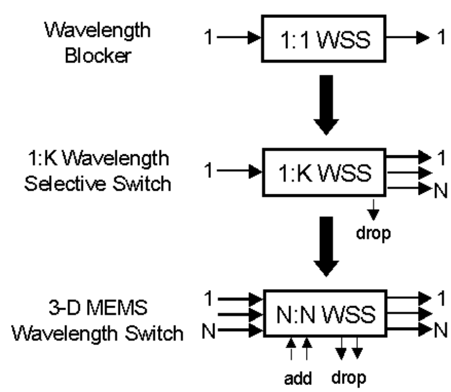

Fig. 3 Comparison of multi-degree ROADM technologies in terms of WSS functionality and evolution.

6.5.3 All-Optical Circuit Grooming

While DWDM is widely utilized to upgrade fiber bandwidth capacity, the cost, provisioning, and management of a huge number of wavelength channels can be highly problematic when considering dynamic mesh networks as opposed to point-to-point systems. Increasing the bit rate of each wavelength channel using traditional serial TDM circuit grooming while keeping the number of DWDM wavelengths to a cost effective and reasonably manageable number is therefore required to satisfy the bandwidth requirements of next-generation high-capacity networks. While TDM based on electronic grooming is currently being deployed at 40 Gb/s in commercial networks and demonstrated at 100 Gb/s in lab trials [18,19], the speed and cost limitations of electronics will mostly likely require all-optical circuit grooming or OTDM techniques for achieving higher data rates of 160 Gb/s and beyond per wavelength [20]. As sub-wavelength multiplexing and demultiplexing are performed in the optical domain, OTDM systems have the advantage of needing opto-electronic component bandwidths only at the lower speed tributary rate. For example, a 160 Gb/s data rate can be achieved with commercially available low-cost 10 GHz devices [21]. Optical grooming or aggregation capability between the edge and core networks also allows for efficient utilization of resources for dynamic sub-wavelength traffic. Furthermore, as lower speed circuits within a given wavelength may have different destinations, the ability to drop the desired circuits and insert new circuits in the available slots, or add-drop multiplexing, becomes a desirable functionality [22]. While traditional TDM requires electronic processing of all sub-wavelength traffic within a given wavelength, optical add-drop multiplexing using OTDM techniques can provide complete optical transparency to express sub-wavelength traffic from source to destination.

The basic principle of OTDM is illustrated in a point-to-point system in Fig. 4a. A typical OTDM transmitter consists of an optical pulse source that emits short pulses at the desired wavelength with a repetition rate of T, which is determined by the bit rate (B) at which electronics can follow. A passive 1:M splitter broadcasts these pulses into separate paths, where each pulse stream is independently data modulated and time delayed. All M pulse streams are then bit interleaved into a single serial data stream with an aggregate data rate of B*M. The number of serial channels that can be packed into a single wavelength depends on the width of the optical pulses. On the OTDM receiver side, a 1:M splitter broadcasts the aggregate data stream to each of the M tributary detectors. A phase-locked optical gating device (DMUX) is utilized prior to the detector for extracting the desired sub-wavelength channel. The concept of add-drop multiplexing using the aforementioned OTDM techniques is shown in Fig. 4b. An optical gate extracts the desired channel to be dropped at the node while the rest of the channels are transmitted transparently. A new channel is then inserted in the available time slot.

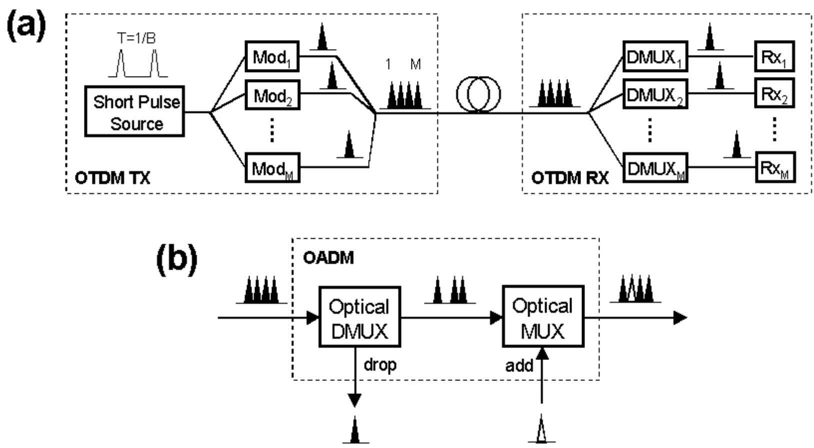

Fig. 4 (a) Basic schematic of an OTDM transmitter and receiver in a point-to-point system, **(b)** concept of OTDM optical add-drop multiplexing.

While various OTDM technologies have been demonstrated in lab trials based on all-optical fiber techniques for ultra-high-speed single wavelength data rates [20,23], the high number of devices required in OTDM sub-systems makes photonic integration essential for commercial viability. Compact optical short pulse sources using a tandem of integrated electro-absorption modulators [24] and further integration with semiconductor optical amplifiers (SOA) for compensating losses have been demonstrated [25]. Further chip level integration of splitters, arrays of modulators and amplifiers on PLC platforms also show promise for commercially viability [26]. An OTDM demultiplexing receiver with an integrated electro-absorption modulator for optical gating followed by a detector has been demonstrated at 40 Gb/s [27]. Further integration of optical amplification has also been achieved for better receiver sensitivity performance [28]. Monolithically integrated SOA devices have been used for add-drop applications [29] while a single electro-absorption modulator has also been shown to simultaneously demultiplex and detect a single channel while transparently transmitting the express channels [30]. Using this capability, an alternative OTDM receiver architecture that imitates high-speed electrical receiver sub-systems with the benefit of operating at the tributary base rate has also been proposed [31]. The compact OTDM receiver eliminates the 1:M splitter and requires a single input fiber into a series of integrated and cascaded modulators to achieve high-speed serial-optical to direct tributary-speed parallel-electrical conversion. Apart from photonic integration, there are several other challenges that need to be considered for OTDM to have commercial penetration. The generation, multiplexing, and gating of such short pulses imposes very strict and challenging polarization, crosstalk, extinction ratio and timing with active signal processing requirements. Finally, further challenges of optical transmission of ultra-high data rates in dynamic networks will require thoughtful consideration.

6.5.4 All-Optical Edge Grooming

Present day networks are based on optical circuit switching with dedicated traffic paths carrying traffic from source to destination. As network bandwidth demands increase, DWDM systems with higher count channels and faster data rates are utilized to provide the required bandwidth capacity. While DWDM is a very effective means of using the bandwidth of the installed fiber base, such switching paradigms exhibit poor performance when sub-wavelength traffic is considered. As described in the preceding section, all-optical circuit grooming using OTDM techniques can help in aggregating several optical channels onto one wavelength. However, the limited granularity and static nature of OTDM switching does not render this as an efficient solution in edge networks. Therefore, traffic grooming at the edge of a network, which presently makes use of the fine granularity electronics can offer, is becoming increasingly important to improve the usage of the available optical resources and to increase the overall network utilization. In SONET and SDH networks, this is mainly accomplished by statistical multiplexing, where data from a large number of logical channels are carried on a single wavelength in the physical medium. The available bandwidth is dynamically allocated only towards active channels, which enables more devices to be connected than other multiplexing techniques. However, as services such as VoD and VoIP are being introduced, the requirements for low latency and high granularity are increasing. Due to the high cost and power consumption of high bit-rate electronics and with progressively more emphasis on transparency, all-optical edge grooming using OPS and OBS are becoming more and more interesting [32].

From a traffic utilization point of view, the highest gains are currently envisaged by using OPS since it can provide both the granularity and latency required for multi-media services [33,34]. Instead of encapsulating each IP packet into larger SONET frames that are transmitted in a synchronous bit stream, with OPS each IP packet is transmitted by itself with an additional small header. Thus, IP packets arrive at the end destination asynchronously as they are not electronically processed and synchronized at each node in the network. While OPS provides highly efficient and granular switching, it also requires new technology at the edge that also permeates into the whole core network. The current lack of switches with nanosecond switching times and optical buffers are prohibitive factors for OPS networks with substantial development time required.

A hybrid between optical circuit and packet switching is OBS [35]. In contrast to OPS where packets are sent out one by one, OBS networks aggregate packets with the same end destination into larger packets, which are denoted as bursts. With significantly larger packets, the speed requirements of the switching elements in the core network are a lot less strict at the expense of decreased network utilization. The minimum length of a burst is determined by the switching technology used and has an upper limit for the time allowed in which a burst can be assembled. As a burst cannot arbitrarily wait long enough for IP packets to arrive in assembling the burst, many burst are likely to be timed out and transmitted without the minimum number of IP packets, in which case the network utilization is decreased. While OBS alleviates the issue of fast switching, it still shares the issue of optical buffers as in OPS.

The complexity of the various technologies discussed in this chapter for all-optical traffic grooming is summarized in Fig. 5 with respect to switching granularity.

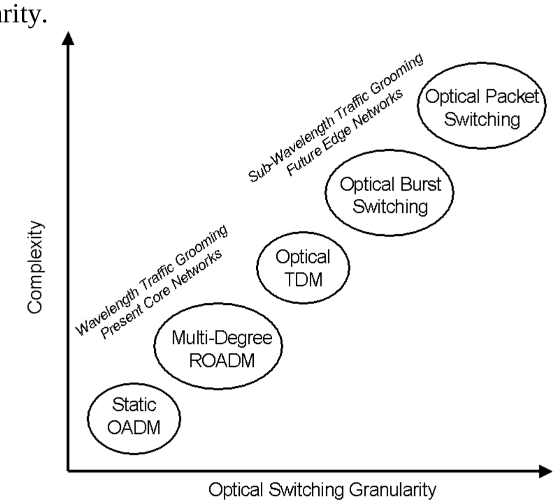

Fig. 5 Complexity of the various all-optical traffic grooming technologies.

6.5.5 Conclusions

In the quest for high-capacity and low-cost optical networks, traditional electronic traffic grooming is being replaced by more efficient all-optical technologies. Multi-degree ROADM's with wavelength grooming capabilities are already being deployed in commercial core networks while active research in OTDM, OPS and OBS is underway for all-optical sub-wavelength grooming of edge traffic.

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