Flexible Architectures for Optical Transport Nodes and Networks

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ABSTRACT

Flexibility to support mesh topologies, dynamic capacity allocation, and automated network control and light path setup are key elements in the design of next-generation optical transport networks. To realize these capabilities, reconfigurable optical add/drop multiplexers with dynamic add/drop structures, embedded control planes, and lightpath characterization are required. This article presents the architectures and various ROADM implementations including colorless, directionless, and contentionless add/drop structures. The effect of scaling bit rates beyond 100 Gb/s on ROADM architectures is reviewed including providing variable channel bandwidth depending on bit rate. Automated provisioning and restoration using the GMPLS control plane and optical measurement approaches for lightpaths are also discussed.

INTRODUCTION

Optical transport network architectures are evolving to allow more flexibility in both wavelength routing and wavelength assignment while also needing to support bit rates of 100 Gb/s and beyond. Channel bandwidth is becoming an important consideration since filtering penalties can be an issue with 40 Gb/s and 100 Gb/s wavelengths. Dense wavelength-division multiplexing (DWDM) nodes started as fixed add/drop linear or ring structures without the ability to dynamically route wavelengths. With the development of wavelength-selective switches, DWDM node architectures that allow mesh configurations and wavelength routing have become commonly deployed. This allows large mesh networks to evolve dynamically since the addition of nodes and degrees can be performed in service [1]. These nodes generally support from four to eight fiber directions for mesh networking, but the wavelength add/drop structure is fixed. In these add/drop structures, generally referred to as *colored*, a specific wavelength must be connected to its port on an add/drop multiplexer, and that multiplexer is only associated with a single fiber direction. These restrictions in the add/drop structure limit wavelength assignment and the ability to dynamically assign wavelengths to particular fiber directions.

This article looks at requirements for truly flexible DWDM networks including removing restrictions on wavelength assignment. Architectures that allow a service to be commissioned on prepositioned resources with dynamic assignment of the wavelength as well as the route through the network are required. These architectures would support not only flexible service creation, but would allow network reconfiguration to optimize network utilization, or provide restoration for link or node failures.

Over time, networks have evolved to support higher bit rates with the expectation that upgrading existing networks would require minimal changes. To improve optical reach, spectral efficiency, and tolerance to impairments, signal processing techniques that were developed for wireless communication are being adapted for optical communications channels. The processing is performed in the receiver after the signal is digitized. Due to the high bit rates, both the analog-to-digital converter and digital signal processing are challenging, and require design of custom application-specific integrated circuits (ASICs). Fiber impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) have been significant concerns, but they can largely be mitigated by newer transceiver implementations with digital signal processing.

In addition to using higher bit rates, fiber capacity has been further increased by reducing channel spacing, and the use of 50 GHz spacing is quite common in new systems. In such systems most of the available channel bandwidth is being utilized, and filtering penalties for 100 Gb/s wavelengths may become an issue with large cascades of nodes such as can be expected in metropolitan systems. Supporting 400 Gb/s wavelengths with 50 GHz channel spacing would require a four-fold increase in spectral efficiency; e.g., by using polarization multiplexed (PM) 256-QAM (Quadrature Amplitude Modulation), over the PM-quadrature phase shift keying (QPSK) format that is commonly utilized at 100 Gb/s. However, an increase in the spectral efficiency of the modulation format also requires a significant increase in the signal-to-noise ratio (SNR) per bit, and thus a decrease in optical reach. To facilitate future system upgrades to 400 Gb/s or even 1 Tb/s wavelengths, it would be advantageous to allow channel bandwidth to be increased with bitrate, and this can be accomplished by using ROADMs with flexible and programmable bandwidth.

EVOLUTION OF TRANSPORT NODE ARCHITECTURES

When DWDM technology was introduced in optical transport networks, its main function was to provide capacity enhancement so that a fiber could carry more synchronous optical network (SONET) or synchronous digital hierarchy (SDH) channels. Although the SONET/SDH network has mainly a ring structure, DWDM was used as a point-to-point topology between nodes so that many SONET/SDH rings could share a fiber. The only function needed was wavelength multiplexing and demultiplexing at each node. Figure 1a shows an example of point-to-point multiplexing and demultiplexing where four nodes are connected by four linear DWDM segments to form a ring.

To add flexibility, DWDM networks evolved into multinode linear and ring configurations. When a wavelength reached a node, it could be designated to either stop at the node or pass through the node. The channels that pass through the node are referred to as express channels. In addition, wavelengths could be added into the DWDM stream at intermediate nodes. This introduced the concept of wavelength add/drop in nodes that are referred to as optical add/drop multiplexers or OADMs. With the wavelength add/drop function, particular wavelengths could now be added and dropped in pre-planned network configurations. The channel add/drop function, however, is static, and generally required manual reconfiguration to modify channel add/drop locations. Figure 1b shows a DWDM ring with fixed add/drop capability.

Adding wavelength switching into the optical transport network allows the wavelength management paradigm to change from static to dynamic. An optical channel can be flexibly added and dropped by a network operator under software control through the switching function built into the transport node. The network planner no longer needs to accurately predict the traffic growth pattern when a network configuration is planned since the network can be reconfigured as required. This gives the network operator huge flexibility for network designs and management. With reconfigurability added, the OADM is now referred to as a reconfigurable optical add/drop multiplexer or ROADM. In its initial implementation, reconfigurability was limited to selecting whether a channel is expressed through, or added or dropped at, a node.

When wavelength flexibility is introduced into the network, the lightpath of a channel is not necessarily limited to linear or ring configurations. Instead, a wavelength is able to reach any adjacent node in the network through the switching function as long as transmission distance is not an issue. Therefore, with this new function, the network is more mesh-like, at least at the wavelength level. With mesh networking in mind, each node in the network behaves more like a junction point rather than a stopping point in the road. In this way the concept of degree is introduced into ROADM networks. Each degree represents a direction in which the node connects to another node. Figure 2a shows the basic architecture of a ROADM with four degrees.

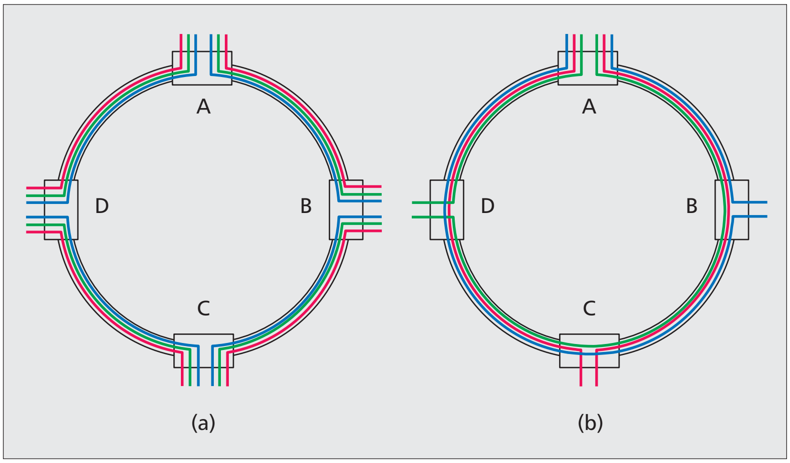

Figure 1. *Basic DWDM functions: a) multiplexing/demultiplexing; b) add/drop.*

After introduction of the basic multi-degree ROADM implementations, technology has continued to evolve to improve wavelength agility and meet challenges in future networks. Wavelength agility for both the color and add/drop direction are important. A service is defined as colorless if a wavelength can be set under software control and is not fixed by the physical add/drop port on the ROADM. Colorless is realized by providing a tunable wavelength source and by implementing an add/drop structure that is not color specific. Wavelength add/drop structures are generally associated with a particular ROADM direction. When a wavelength can be added or dropped from any direction (under software control), the implementation is referred to as directionless. Some implementations restrict wavelength utilization in the add/drop structure. A contentionless architecture allows multiple copies of the same wavelength on a single add/drop structure. In a colorless, directionless, and contentionless ROADM implementation, a service can be assigned its color and direction without any restrictions as long as the wavelength color is available at the network level for that direction. Figure 2b shows the architecture of a colorless, directionless, and contentionless 4-degree ROADM node. In these approaches the wavelength grid and channel bandwidth are generally fixed, but to accommodate even higher bitrates, flexibility in the channel plan may also be required. Detailed implementation examples for various ROADM architectures are shown in the following sections.

IMPLEMENTATION OF ADVANCED TRANSPORT NODE

Several basic elements are used in ROADM functional designs. Even though particular ROADM implementations vary based on the design goals, the basic building blocks are quite similar. Differences between ROADM designs reflect the design philosophy and emphasized functionality. As an example, the number of fiber degrees or the number of add/drop ports supported varies significantly based on the node architecture and component trade-offs. Initial cost and complexity of the design affect longer-term node scalability. Figure 3 shows the common building blocks used in implementing ROADMs.

A 1 × N optical splitter as shown in Fig. 3a distributes the optical power from the input port (on the left side of the diagram) to the output ports on the right. The power splitting ratio along the output ports is device-dependent. The power splitting ratio is generally designed to be wavelength-independent over the operating frequency range of the ROADM. A 1 × 2 fiber coupler is a typical optical splitter, and splitting ratios such as 50/50 or 90/10 are common. When a splitter is used in the opposite direction, it becomes an optical coupler. The power loss between a pair of input ports and output ports remains the same in both the splitter and coupler configurations. An $N \times N$ optical coupler is an expanded version of a 1 × N optical coupler. For an $N \times N$ coupler, the input power at any port on one side of the device is distributed into all ports on the other side of the device with a certain distribution ratio.

A wavelength splitter (also referred to as a wavelength multiplexer/demultiplexer) is a device to separate optical channels with different wavelengths, or different "colors," with minimal loss through the device as shown in Fig. 3b. For example, an arrayed waveguide (AWG) is a device that can separate a group of DWDM channels in one fiber into a set of individual fibers with one channel per fiber. Planar lightwave circuit (PLC) technology is used to build AWG devices [2]. Thin film technology can also be used to build wavelength filters [3], although these devices are generally limited to a small number of ports. A wavelength splitter can operate to combine or separate wavelengths to perform wavelength multiplexing and demultiplexing functions. The channel separation is normally distributed evenly along optical frequency. For example, the channel separation or channel spacing, can be 50 or 100 GHz. Since a wavelength splitter is a passive device, the wavelength or wavelengths assigned to each port are fixed. A tunable filter (shown in Fig. 3c) is a device that allows a wavelength or a range of wavelengths to pass through but blocks all other wavelengths. It is commonly used to select a particular wavelength from a group of wavelengths before the optical receiver. A tunable filter provides flexibility in channel selection without the need for optical switching.

A 1 × N wavelength selective switch (WSS) is a device that is able to switch a selected wavelength or wavelengths from an input port to an output port as shown in Fig. 3d. 1 × 5 or 1 × 9 WSSs are typical devices used in ROADM designs today. Several technologies have been used for building WSS devices including liquid crystal (LC) and micro electro mechanical systems (MEMS). In LC- and MEMS-based 1 × N WSS devices, the input optical beam is separated with a bulk grating with respect to wavelength. The LC pixels [4] or the micro mirrors of the MEMS chip [5] are used to steer each channel to its destination output port. As an alternative to WSSs, PLC multiplexers with integrated Mach-Zehnder interferometric switches have been used to construct 2° ROADMs. These devices cannot support higher-degree designs and have largely been replaced by WSSs in newer ROADM designs. In recent years liquid crystal on silicon (LCoS)

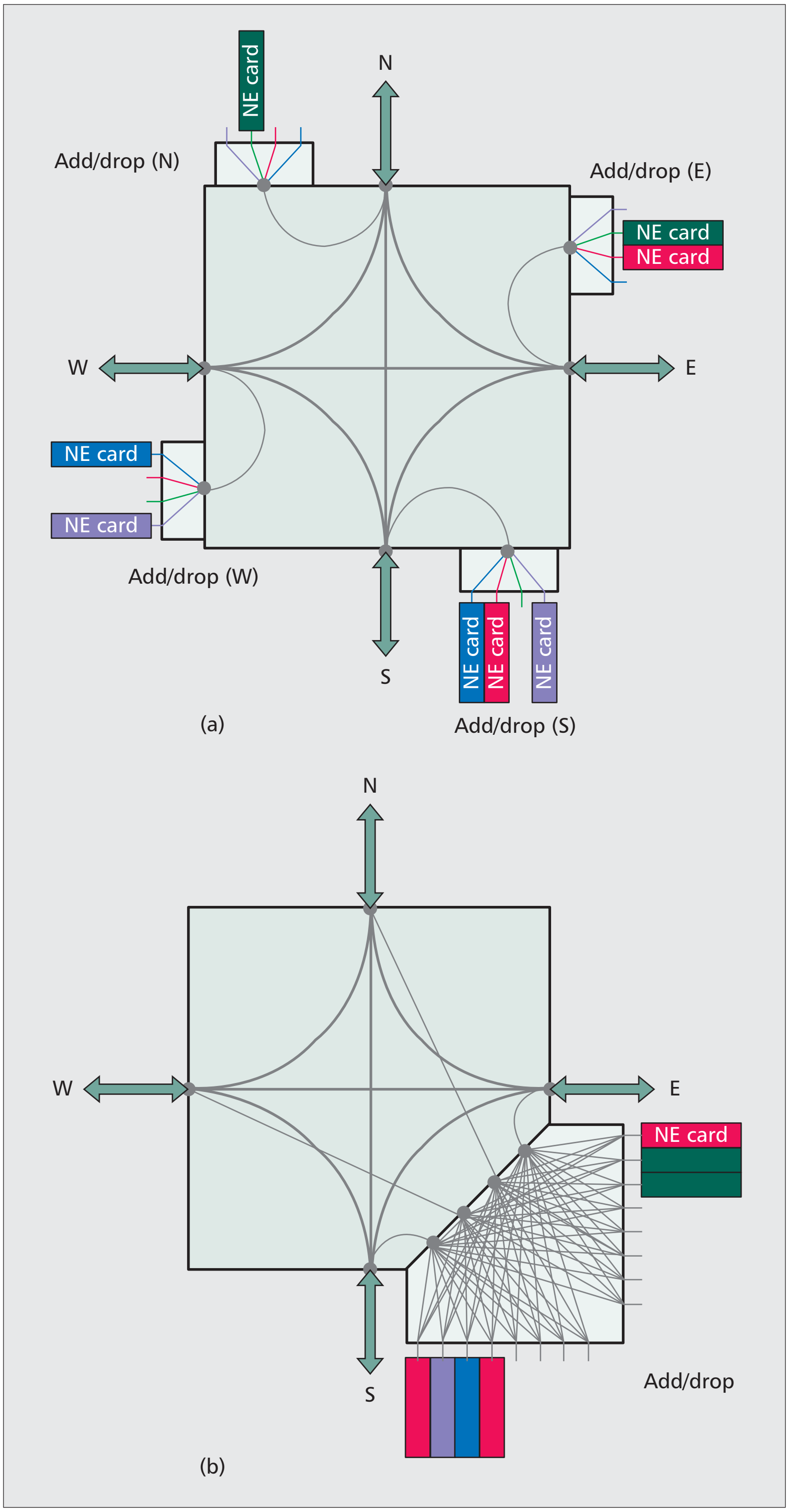

Figure 2. *Architectures of a) basic ROADM design; b) colorless, directionless, and contentionless ROADM design.*

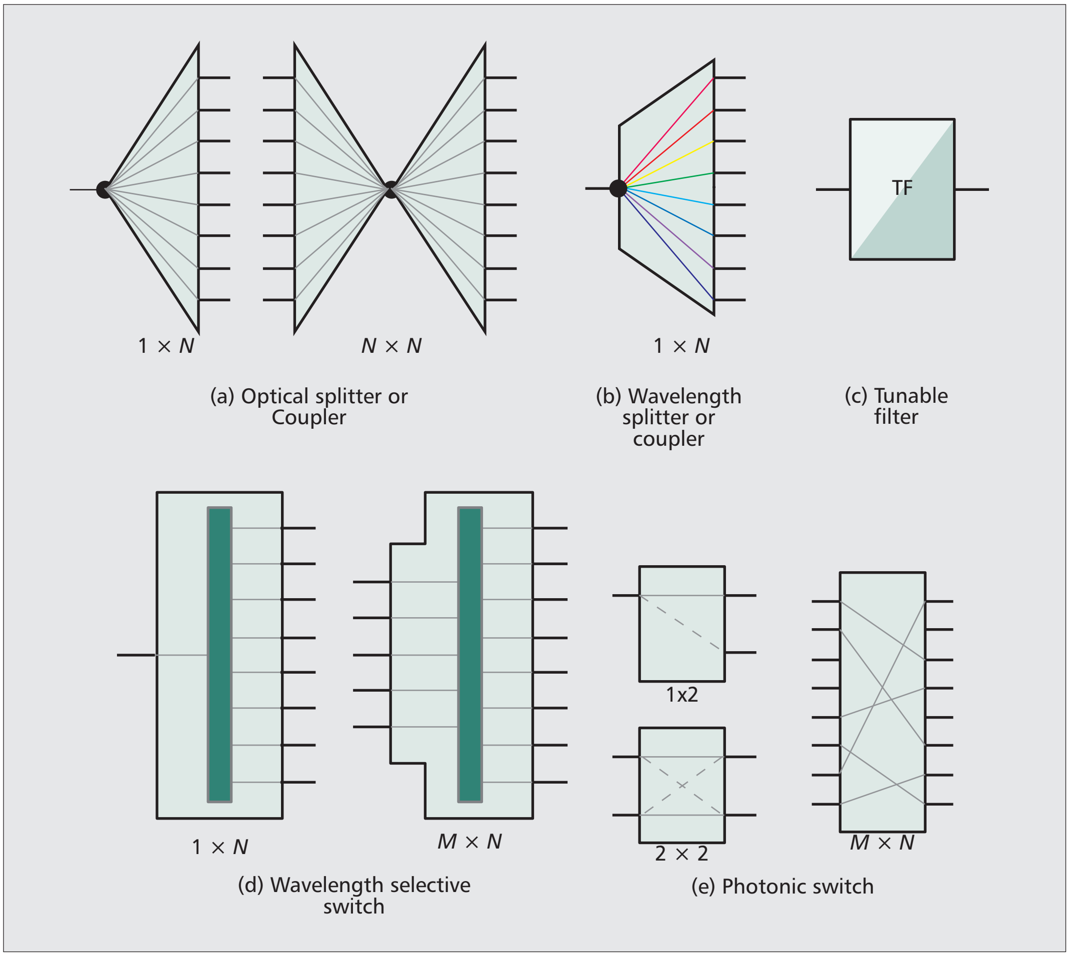

Figure 3. *Common building blocks for ROADMs.*

Most transmitters in optical transport equipment today are equipped with wavelength tunable lasers, and most receivers are equipped with broadband photo detectors. Therefore, the colored add/drop limitation is not due to transmitters or receivers but caused by the add/drop structure.

and digital MEMS [6-8] technologies have been introduced in WSS designs. The major difference between these designs and previous ones is that each optical channel is switched by a small group of micro mirrors or pixels instead of a single mirror or pixel. The advantage of these new designs is that the spectral width of each optical channel can be adjusted according to the required bandwidth, and the device is more fault tolerant since a single pixel (or mirror) failure does not cause a channel failure [7]. An $M \times N$ WSS is a generalization of a $1 \times N$ design and is able to switch a channel or many channels from any input port to any output port, as long as there are no wavelength conflicts (routing multiple copies of the same wavelength to a single output) [9].

A photonic switch is also a useful building block for ROADM designs. The photonic switch provides pure optical signal routing with no conversion of the signal into the electrical domain. A photonic switch may have small port counts, such as 1×2 or 2×2 as shown in Fig. 3e. Various technologies, such as mechanical beam steering, polarization rotation, or interference, can be used to build photonic switches [10]. Photonic switches with large port counts are also useful for ROADM designs. For example, a 320×320 photonic switch with multiple wavelength splitters can provide a flexible add/drop structure for an ROADM node [11].

Basic ROADM Implementation

As optical transport networks move toward more meshed topologies, ROADM designs will be required to support more degrees of interconnection than in simple ring-based networks. A 4° ROADM is shown in Fig. 4a. In a basic ROADM design, channels are routed to a particular degree or to the wavelength add/drop structure. This is accomplished by using an optical splitter, wavelength splitter, and WSS. The optical splitter distributes incoming channels from one degree to the add/drop portion of this degree and to the WSSs of all other degrees. A wavelength splitter separates the channels to the drop ports. To add channels, an optical coupler combines channels and sends the channels to a port on the WSS. In applications where a large number of channels are added, the optical coupler is replaced with a wavelength coupler to reduce loss. In this basic ROADM design the reconfigurability is limited to routing the wavelength, and the add/drop structure is fixed (referred to as a colored design). Most transmitters in optical transport equipment today are equipped with wavelength tunable lasers, and most receivers are equipped with broadband photo detectors. Therefore, the colored add/drop limitation is not due to transmitters or receivers but caused by the add/drop structure.

COLORLESS ROADM IMPLEMENTATION

In a colorless design any wavelength can be assigned to an add/drop port. In the previous design the wavelength splitter limited each drop port to only one particular wavelength. To reconfigure a services wavelength color, the receiver must be moved to the port with the corresponding drop color. To eliminate this constraint, a WSS can be used to replace the wavelength splitter and provide the colorless functionality as shown in Fig. 4b. The WSS is able to direct any wavelength to a particular port in the drop structure. For the transmitter side, the optical coupler does not need to be changed since each transmitter sends out only one wavelength, and the optical coupler is color blind. When combining channels with a coupler, crosstalk between overlapping channels can be an issue. Designs may need to specify the laser side mode suppression ratio or filter the signal to reduce its bandwidth (and filter out noise) before the colorless combining is performed. Also, with this implementation software must protect the system from an incorrect wavelength assignment that interferes with a preexisting channel of the same wavelength. In this design each degree of the node has its own add/drop section. Since the add/drop structure is unique for each degree, moving a wavelength to another degree requires physically

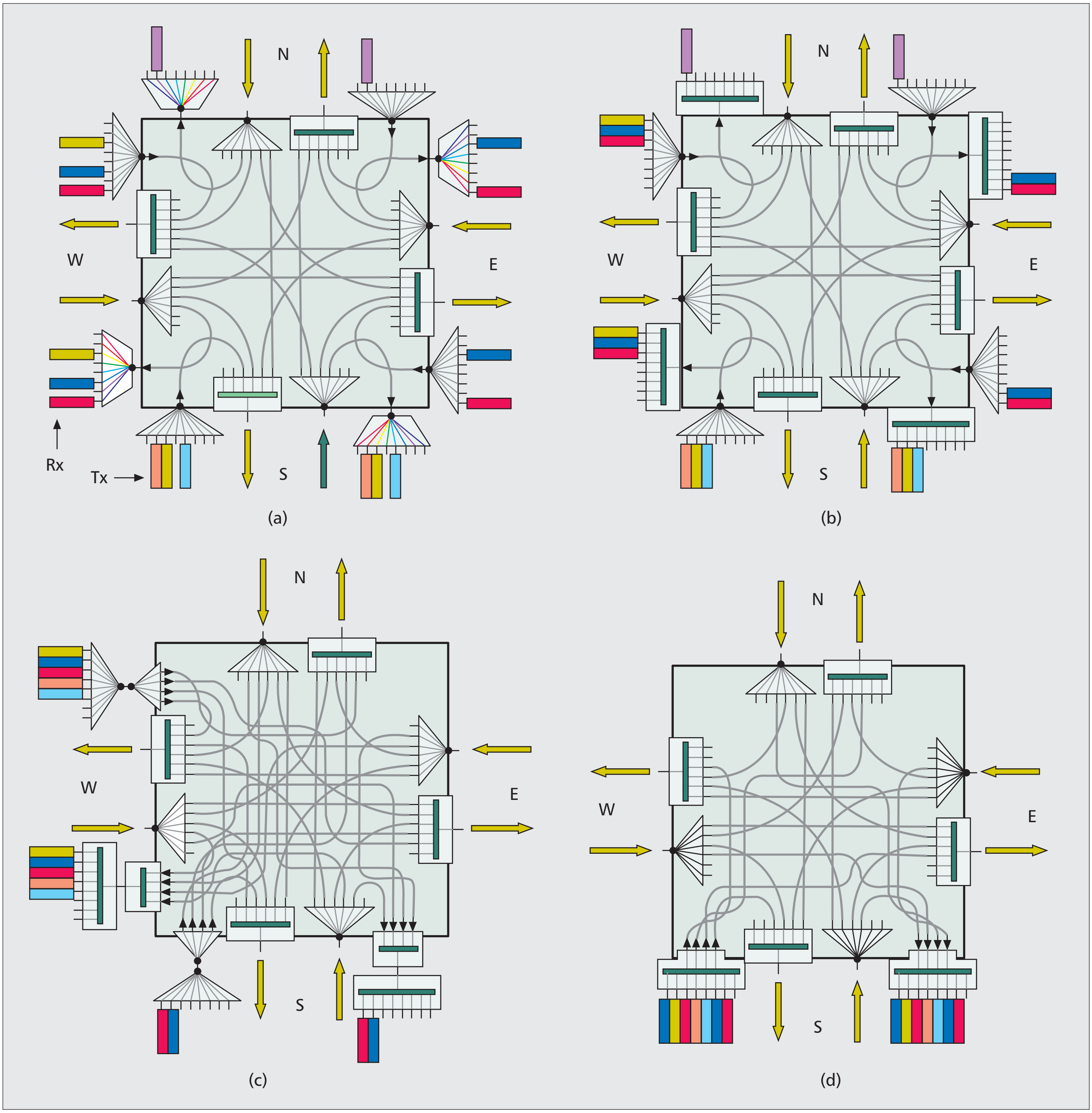

Figure 4. *Examples of ROADM designs with various features.*

moving the service to different ports on the desired degree. This is a significant constraint for wavelength planning at the network level.

Colorless and Directionless ROADM Implementation

A directionless add/drop structure provides the freedom to direct a channel to any degree of the ROADM and is implemented by connecting an add/drop structure to every degree on the ROADM. This can be realized by adding another $1 \times M$ optical coupler to the add structure and another $1 \times M$ WSS to the drop structure as shown in Figure 4c [12]. Note that with this modification, a separate add/drop structure no longer needs to be associated with each degree of the node. As the number of components increases in colorless and directionless designs, optical amplification will be required in the add/drop structure for most practical implementations to overcome component loss. In applications where 100 percent add/drop is not required, the number of add/drop structures can be reduced, although the same channel color can be used only once per add/drop structure. This case is illustrated in Fig. 4c, where the second red and blue colored channels must be placed in the add/drop portion at the right side, since red and blue channels are already in use in the add/drop structure on the left side. To remove this constraint the concept of "contentionless" must be introduced.

Colorless, Directionless, and Contentionless ROADM Implementation

A contentionless ROADM design removes wavelength restrictions from the add/drop portion of the ROADM node so that a transmitter can be assigned to any wavelength as long as the number of channels with the same wavelength is not more than the number of degrees in the node. This architecture guarantees that only one add/drop structure is needed in a node. Network planning is simplified since any add/drop port can support all colors and connect to any degree. There are many ways to implement the contentionless function. Figure 4d shows an example with the add/drop portion equipped with an $M \times N$ WSS. As previously discussed, the $M \times N$ WSS can switch any wavelength from any input port to any output port as long as that wavelength is not already in use on the output port. The $M \times N$ WSS is the perfect fit for this architecture, since reusing a wavelength on a fiber degree is not possible. Today, $M \times N$ WSSs are not yet commercially available, but the function can be built using many smaller switches. Photonic switches and $1 \times N$ WSSs can be used to construct a colorless, directionless, and contentionless ROADM node [13, 14]. For example, a large port count $M \times N$ photonic switch is particularly useful for a node with a high wavelength add/drop ratio [10].

An $M \times N$ WSS may not provide sufficient add/drop ports, especially for nodes that require a high add/drop ratio. An alternative design uses optical couplers, arrays of photonic switches with small port counts, and tunable filters. In this way the number of add/drop ports is scalable, while the full flexibility of contentionlessness is maintained. Figure 5 shows an example of a scalable colorless, directionless, and contentionless ROADM [12]. It should be noted that with a colorless, directionless, and contentionless ROADM node, constraints on wavelength assignment are only removed from the add/drop structure. Wavelength assignment constraints still exist at the network level, since two channels with the same wavelength are not allowed on the same fiber connecting any two nodes [3]. Contentionless design, however, is able to reduce wavelength congestion by optimizing the wavelength assignments dynamically or even automatically. Wavelengths can be reassigned by the network operator under software control to ease wavelength conflicts in the network.

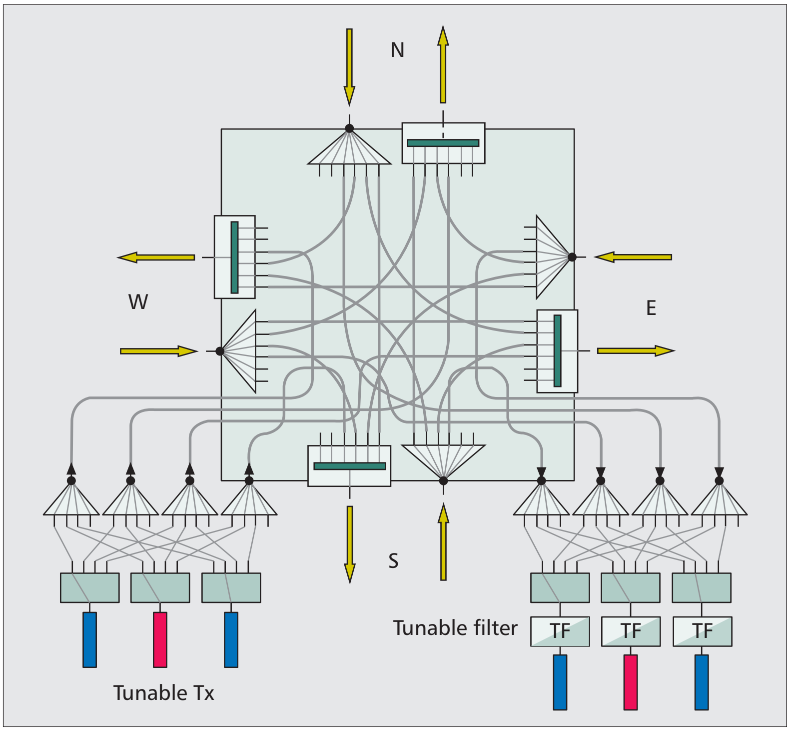

Figure 5. *Example design of scalable colorless, directionless, and contentionless ROADM.*

Impact of Coherent Detection

Coherent detection will be the main transmission technology choice for high-performance 40 and 100 Gb/s applications [15]. With coherent detection, the local oscillator (the local laser) in the receiver can be tuned to select a desired channel from a group of DWDM channels, allowing the filtering in the ROADM drop structure to be simplified [16]. Depending on the design specifications of the coherent receiver, the number of channels that can be selected from may be limited due to penalties. Current designs can discriminate one out of a small group of wavelengths [16], although it is possible to select one wavelength from the entire channel spectrum with an ideally balanced receiver (two receivers with matched specifications that are used differentially to remove common mode noise, eliminating all direct detection terms including the signal-optical noise and noise-noise beat terms) [17, 18]. Figure 6 shows an example ROADM design considering the capabilities of coherent receivers. The incoming channels are divided into smaller groups with a 1 × *N* WSS. The channels in each small group are distributed to several coherent receivers with an optical coupler. Each receiver connects to all degrees of the node via a 1 × *M* photonic switch. The receiver picks the desired channel by tuning the local laser inside the receiver. A ROADM design with all coherent wavelengths can be simplified by just using optical couplers and photonic switches with large port counts, as shown in Fig. 7. In this design each receiver is flooded by all channels from one degree via the photonic switch. This is the simplest design, but potential receiver overload and noise penalties need to be considered.

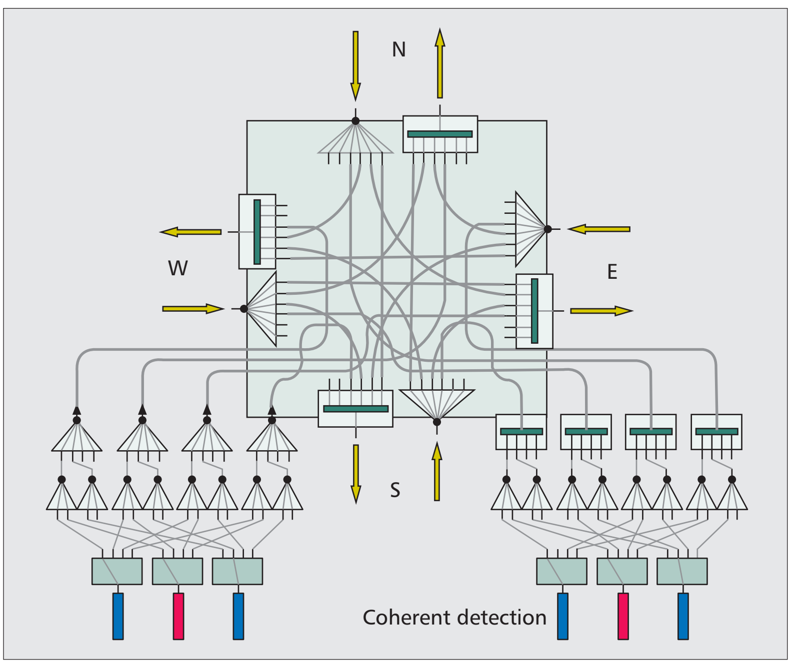

Figure 6. *ROADM design with coherent detection (banded).*

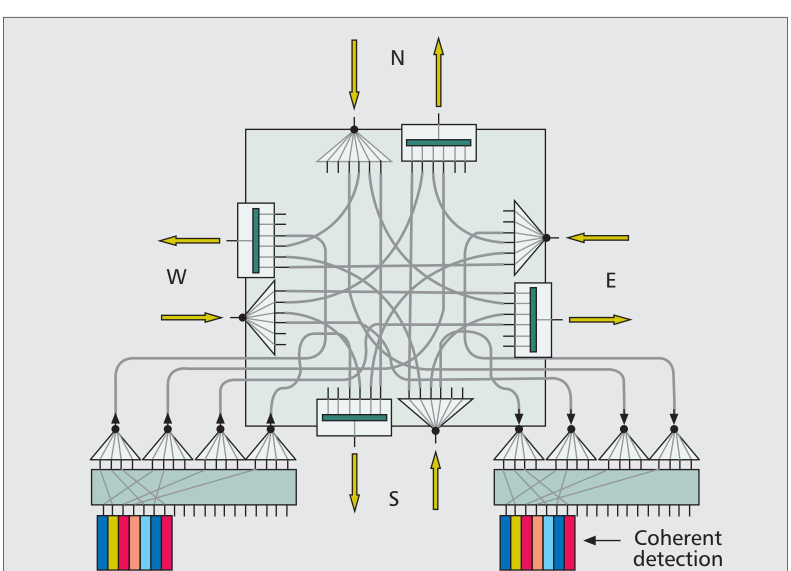

Figure 7. *ROADM design with coherent detection (all access).*

Scaling to Beyond 100 Gb/s with Flexible Channel Bandwidth

A ROADM provides flexibility to switch optical channels that traditionally have center frequencies as defined by the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) grid. According to ITU-T G.694.1, the frequency of an optical channel is defined with respect to a reference frequency of 193.10 THz, or 1552.52 nm in wavelength. The frequency difference between adjacent optical channels, referred to as channel spacing, can range from 12.5 to 100 GHz and wider. 100 and 50 GHz are common channel spacings used in optical networks today. Most tunable lasers used in transmitters are designed to have frequency locking mechanisms that align the frequency of the channel with the grid. As the data rate of an optical channel continues to increase, advanced modulation has successfully squeezed 40 Gb/s channels and 100 Gb/s channels into a 50 GHz channel spacing, that was originally designed for 10 Gb/s channels. To fit channels with high data rates into small channel bandwidths, especially for the 100 Gb/s signals, the modulation format has moved away from classical on-off keying. Multilevel amplitude and phase modulation have been introduced to reduce the overall optical bandwidth of a channel. The most prominent example is the PM-QPSK format generally used for 100 Gb/s channels. Since with PM-QPSK the symbol rate of the 100 Gb/s signal is only one fourth the data rate [19], the modulated signal fits into a 50 GHz channel. By using 50 GHz channel spacing for 100 Gb/s channels, the optical spectral efficiency has increased 10 times to 2 b/s/Hz when compared to supporting 10 Gb/s signals.

Foreseeing higher channel data rates and greater spectral efficiency requirements in the near future, innovation in ROADM designs will be required as shown by the concepts of tunable channel bandwidth [12] and "elastic optical path" [20]. Since an increase in spectral efficiency of the modulation format requires an exponential increase in SNR [18] it is not likely that channels with data rates beyond 100 Gb/s will be designed with a 50 GHz channel spacing for long-haul network transmission distances. Flexibility to increase the symbol rate as well as spectral efficiency will allow optimizing the reach of long-haul optical channels with a data rate higher than 100 Gb/s such as 400 Gb/s and 1 Tb/s. To further increase spectral efficiency, the required bandwidth of these channels with ultra-high data rates should be minimized. For example, the bandwidth of a 400 Gb/s channel (using PM 16-QAM with 56–64 Gbaud) is likely to require only a 75 GHz channel spacing, while a 1 Tb/s channel (using PM 32-QAM with 112–128 Gbaud) would require only a 150 GHz channel

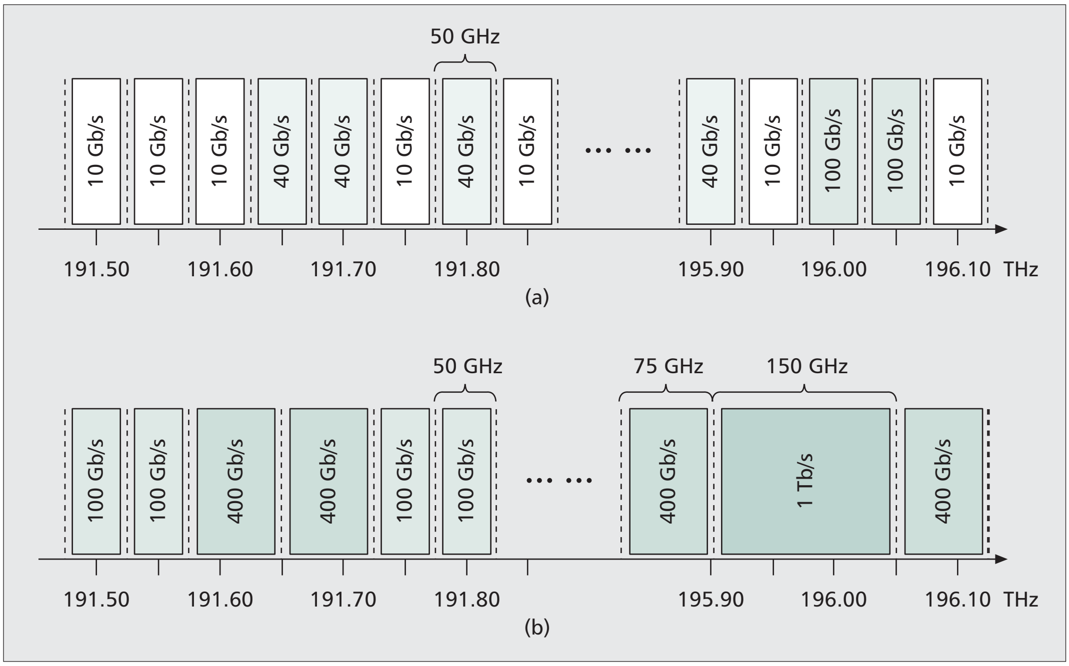

Figure 8. *C-band 50 GHz a) fixed grid; b) flexible grid.*

spacing. This development imposes a fundamental change in ROADM design, since current ROADMs have fixed and equal channel spacing with the center frequencies of the channels anchored to the ITU-T grid. A transport system supporting mixed channels with data rates of 100 Gb/s, 400 Gb/s, and 1 Tb/s will require ROADMs that support flexible add/drop bandwidths and tunable lasers that lock to frequencies with subchannel spacing (e.g,. 12.5 GHz) , as different channels may have different bandwidths. The concept of flexible add/drop bandwidth has already been introduced in ROADM designs [21, 22], and LCoS or digital MEMS technology, mentioned above, can meet the flexible bandwidth requirement. Figure 8 shows a comparison of the fixed ITU-T grid and a flexible grid for the C-band. When implementing a flexible grid, issues such as nonlinearity from mixed signal formats ,and bit rates and optical power control when the number of channels varies dynamically must be considered. Also, operational and management issues such as channel numbering and bandwidth assignment need to be addressed. ROADMs with flexible bandwidth designs will be able to support dynamic add/drop of channels beyond 100 Gb/s.

ROADMs with ASON/GMPLS Control Plane

ROADM nodes with embedded control plane capabilities, automatically switched optical networks (ASONs), or generalized GMPLS, simplify network operation by implementing management functions for automation with software distributed in the transport network. Transport nodes with mesh routing, and colorless and directionless add/drop enhance control plane functionality by supporting dynamic provisioning and restoration of light paths [23, 24]. Implementation of a control plane, however, must consider both optical and electrical switching attributes to take full advantage of dynamic capabilities. For example, in the case of optical switching, services can be rate and format independent but are impacted by physical layer impairments such as OSNR, dispersion, and nonlinearities. For OTN switching, services are rate- and format-dependent but not limited by physical impairments. The OTN hierarchy (G.709) provides fixed containers of various rates as well as mappings for common services such as Ethernet and SONET. The standard has been newly enhanced to support 1.25 Gb/s tributary slots that support direct mapping of Gigabit Ethernet. Multiple tributary slots can be combined with an ODUflex mapping to allow flexible bandwidth allocation in increments of 1.25 Gb/s [25].

Multidegree ROADMs facilitate mesh topology, enabling multiple routes between endpoints. Colorless and directionless add/drop allow the control plane to select a services wavelength and fiber degree. Managing full ROADM features and capabilities is complex as there are many architecture implementations from which to choose. The link resource management component of the control plane is responsible for the management of the transport resources. The functions that are automated include discovery of network topology, resources, and services, end-to-end light path routing for optimal resource utilization, flow-through service provisioning, and mesh restoration. Automation enables a self-running network and reduces operational expenses by minimizing the manual and time-intensive procedures required in the provisioning process. Capital cost is improved by eliminating stranded resources through high-quality inventory databases generated by the control plane auto-discovery process. Optimizing network-wide resource utilization by constraint-based path routing and integrated traffic engi-

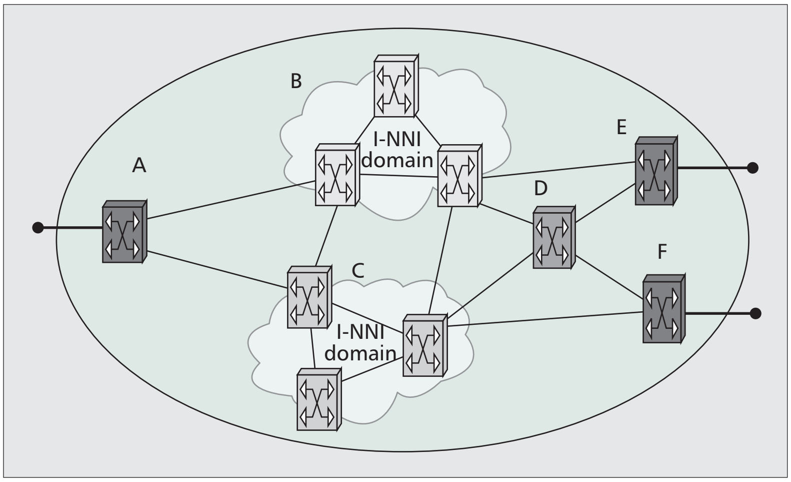

Figure 9. *Optical network with dynamic ROADM nodes [25].*

neering across network domains improves cost through greater network efficiency.

Protection and Restoration

Figure 9 shows a multidegree ROADM network with multidomain connectivity. Links between nodes represent both data plane and logical control plane connectivity. In case of network failure, restoration must repair an end-to-end connection by rerouting the connection away from failures affecting the link, node, or entire domain. Restoration can be based on dedicated preplanned routes or routes can be calculated dynamically after a failure is detected. Traditionally, dedicated routes will support faster restoration, but are very resource intensive. With a dynamic optical network, restoration resources can be shared between services, thus requiring significantly less resources. Dynamic mesh restoration algorithms must understand optical network characteristics to determine whether a reroute can be accomplished without adding regeneration. Since restoration and administrative rerouting rely on the same principles, control-plane-based restoration can provide operators with the ability for end-to-end planned maintenance activity. By using user-constrained rerouting, operators can reroute connections where maintenance activity is planned. When a WSS or photonic switch routes wavelengths in an ROADM-based network, the switching speed has not been critical, since wavelength switching is used for provisioning. The switching times for currently available switches varies from a few milliseconds to several seconds. For applications where wavelength reconfiguration is used for protection or restoration, fast switching times will be required.

Lightpath Characterization of ROADM-Based Networks

To guarantee the performance of an optical channel, it is important to know the key characteristics of a selected light path [8, 26–29]. Although ROADM based networks provide much more flexibility in setting up light paths, they also require careful characterization of the light paths in the network. When a network is commissioned, traditional fiber characterization for parameters such as loss, CD, and PMD is performed for each span. The amplifier infrastructure and basic light-path characteristics are then designed based on this data [30]. These measurements provide a base-line for network performance but in-service measurements can be used to validate network performance. When the network is in-service, span loss and light-path-based CD, PMD, OSNR, and Q measurements can be used by embedded lightpath routing software to validate the performance of a newly provisioned path and track performance over the lifetime of the system. The digital signal processor used in a coherent receiver can provide lightpath measurements without the need for additional system hardware.

In-service lightpath characterization can be used to measure accumulated properties from the source ROADM node to the sink ROADM node and provides a true end-to-end measurement, including both fiber and node characteristics. In-service measurement, however, must not disturb live working channels in the network. Optical parameters such as fiber loss, group delay, polarization dependence, and transmission latency should be included in any in-service characterization for ROADM-based transport networks. Such characterization may be important to identify the cause of any performance degradation [31].

Pass Band Shape of an Optical Channel

The pass band shape of an optical channel in an ROADM-based network can affect performance, especially in applications where many nodes are cascaded [32]. Since the shape of the ROADM passband is not ideal, as more and more nodes are cascaded, the bandwidth becomes progressively narrower. Center wavelength accuracy, temperature drifting, and the specific shape of the pass band all contribute to the narrowing. For example, in one experiment a light path with 50 GHz channel spacing has approximately a 45 GHz bandwidth (at the 3 dB point) at the first ROADM. The bandwidth drops 19 percent when the signal passes the fifth ROADM in the lightpath, and drops another 6 percent when it passes the 10th ROADM. By the 20th ROADM the bandwidth has dropped to 31 GHz [33]. With a cascade of 20 ROADMs, a small penalty will occur due to intersymbol interference since the symbol rate of a 100 Gb/s PM-QPSK signal is about 28–32 Gbaud.

Group Delay and Polarization Dependence of an Optical Channel

Group delay and group delay variation are important characteristics of an optical channel in an ROADM-based network. Group delay is mainly caused by the fibers in the lightpath,

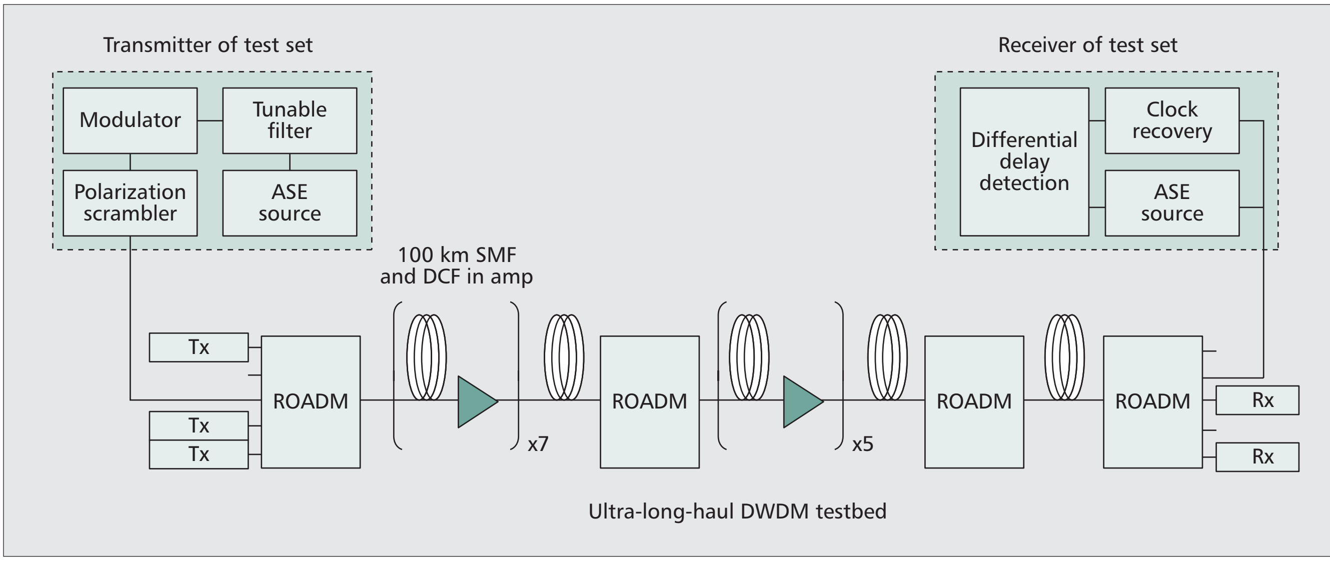

Figure 10. *In-service group delay and pass band characterization.*

while group delay variation is caused by the optical components in the nodes along the light path. The chromatic dispersion of the lightpath is the derivative of the group delay with respect to wavelength. Coherent detection with digital signal processing is able to compensate for large dispersion values in a lightpath (of more than 2000 km of standard single-mode fiber). Various in-service dispersion measurements have been reported [34–38]. In a recent report group delay variation was measured within optical channels in a ROADM-based DWDM test bed with 1500 km light paths [39] as shown in Fig. 10.

The polarization-dependent characteristics for a lightpath include PMD and PDG/PDL (polarization-dependent gain or polarization-dependent loss). The advanced coherent modulation format has shown very high PMD tolerance (mean differential group delay, or DGD, 20–30 ps). In one experiment a 92 Gb/s coherent channel maintained error-free transmission for differential group delays (first order PMD effect) up to 107 ps [40]. PDG or PDL impair high-speed transmission, since the polarization-dependent properties impact the receiving signal quality of the constellation.

Conclusion

As optical transport networks move toward highly dynamic mesh-based topologies, a flexible optical node architecture is key to optimizing network designs. Multidegree ROADMs to support mesh topologies, and colorless, directionless, and contentionless add/drop structures will provide the required flexibility. As capacity demands continue to increase, flexible channel bandwidth will be needed to optimize reach for channels with data rates beyond 100 Gb/s. Lightpath characterization will validate network parameters to guarantee that channel performance in a meshed network is maintained. Finally, the embedded control plane is important to simplify network operation by providing automated provisioning and restoration, resulting in a highly reliable and scalable optical transport network.

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