A description of ROADMs is given from a system’s perspective. ROADM types and architectures are described, and how they are likely to evolve. A discussion is given for how bit rates beyond 100 Gb/s are likely to be realized and the ROADM requirements to support these bit rates. The paper concludes with a discussion on optical power management and control plane functionality to fully automate a ROADM network.
The term reconfigurable optical add-drop multiplexer (ROADM) can have different meanings, depending on the context. It may refer to an optical module that mounts into a circuit pack, or it may be a small rack-mount subsystem, with a basic user interface for configuring and monitoring the status of the device. In other cases a ROADM may refer to a full networking platform comprised of both hardware and software subsystems that takes up an entire rack. Regardless of the context, a ROADM is a subsystem (large or small) that allows for the dynamic configuration of how wavelengths add, drop or pass through the subsystem.

Early generation ROADMs have largely been built using wavelength blocker or planer lightwave circuit (PLC) technology, whereas the latest generation of ROADMs use wavelength selective switch (WSS) modules. Through significant advances in functional integration, ROADMs can now be deployed in very small footprints with significant cost and energy savings. Nonetheless, practical and cost effective full ROADM agility continues to be elusive, with the need for further improvements and advancements in ROADM technologies.

Wavelength Selective Switch – The Heart of a ROADM

The function of a WSS, which is the core building block of current generation ROADMs, is illustrated in Figure 1.

The actual technology used to realize a WSS varies among WSS vendors, but generally makes use of either liquid crystal (LC) elements and/or micro-electro-mechanical-systems (MEMS) mirrors to steer and/or attenuate each wavelength. The use of MEMS mirrors can provide very fast switching speeds of a few ms, but can be prone to insertion loss drift in the absence of closed-loop attenuation control. LC elements can provide excellent open-loop stability, but generally have a slower switching time, especially at low temperature.

The primary function of a WSS is to independently switch each of M wavelengths between a common port and one of N switching ports, with per-wavelength attenuation control. WSSs with N=2, 4, 5, 8 or 9 switching ports are common, while devices with up to N=23 are also available from some WSS vendors. Most WSSs implemented in systems today operate on either a 100 GHz or 50 GHz ITU grid in the C or L band.

Some WSSs have integrated isolators and pass light in one direction only, whereas others are reciprocal devices. The application of a given WSS would designate the common port as either an input or output, and switching ports as outputs or inputs, respectively.

With some WSSs it is possible to divide the power of a given wavelength and route it to more than one switching port simultaneously. Splitting the light in the WSS itself to achieve optical multicasting, however, complicates optical power management for a system. Moreover, as all of the ROADM architectures described in the following sections inherently support optical multicast without the need for the WSS itself to have this capability, optical multicast functionality in a WSS offers little value.
Colored Versus Colorless Access Ports

Examples of ROADM architectures with colored versus colorless access ports are shown in Figure 2.

![Diagram of ROADM architectures with colored versus colorless access ports](image)

**Figure 2: ROADM with: a) colored access ports; b) colorless access ports.**

Colored access ports imply that physical access ports (add or drop) are assigned to a specific wavelength, i.e., each access port can only pass one “color” or wavelength of light. This means that once the physical fiber connections are made between a given transceiver and a ROADM access port, the wavelength assigned to the transceiver cannot be changed dynamically or remotely, i.e., one must physically change the fiber connectivity between the transceiver and access ports in order to change the wavelength routed to or from the transceiver.

Colorless access ports can pass any wavelength, allowing the wavelength routed to a transceiver to be changed dynamically and remotely. For add ports, this implies transmitters would be fully tunable.

ROADMs with colored access ports are referred to as colored ROADMs, while those with colorless access ports are referred to as colorless ROADMs.

Many other architectures are possible to achieve a colorless ROADM. For example, the demultiplexer in Figure 2a could be replaced by a 1:N WSS, or a passive splitter connecting to an array of tunable filters, and the multiplexer replaced with a passive combiner connecting to tunable transmitters. Different architectures have their respective advantages and disadvantages, such as the insertion loss experienced by wavelengths, or whether or not per-wavelength attenuation control is provided for access ports.

Add-drop capacity is also a consideration for colored versus colorless ROADMs. For example, up to 100% add-drop capacity is easily achieved for the structure shown in Figure 2a, as full channel multiplexers based on athermalized arrayed waveguide (AAWG) technology are readily available. The add/drop capacity when using colorless access ports, however, is usually limited to a reduced number of ports, as high add/drop capacity colorless ROADMs require more components, making them prohibitively expensive to deploy for many applications.
Multi-Degree ROADMs

Two-degree ROADMs have an East and West facing direction, i.e., two DWDM trunk directions, and are commonly used in linear or ring topologies. A given direction generally has one fiber for the transmit DWDM line signal, and one for the receive DWDM line signal, and the fiber pair that serves a given direction is referred to as a degree. The ROADMs shown in Figure 2 are examples of a 2-degree ROADM, although the structure would be duplicated to serve both directions, as illustrated in Figure 3 for a colored ROADM.

ROADMs with more than two degrees are generally referred to as multi-degree. A typical architecture for a 4-degree ROADM with colored access ports is shown in Figure 4a. The access structure can be modified to make the ROADM colorless, as shown in Figure 4b, although fewer access ports would typically be provided. Note that the access ports in Figure 4 are constrained to a given direction.

In general, an N-degree ROADM can be realized using N Nx1 WSSs, with each WSS serving a given degree, while additional WSSs may be used to realize colorless access ports.

By changing the access structure in Figure 4 to serve an additional degree, an (N+1)-degree wavelength cross-connect (WXC) can be realized using N+1 Nx1 WSSs, as illustrated in Figure 5 for a 5-degree WXC.

The ROADM and WXC structures shown in Figure 4 and Figure 5, respectively, realize the basic ROADM and WXC constructs shown in Figure 6. Constructs with fewer or more degrees are similarly possible using WSSs with a different number of switching ports.
The constructs shown in Figure 6 can be combined to build even higher-degree ROADMs, as illustrated in Figure 7. Although N-degree ROADMs can be built using WSSs with fewer than N switching ports in this way, the architecture can result in wavelength contention over interlinks, as a given wavelength can be used only once on an interlink. For example, if a given wavelength is switched between directions C and G in Figure 7a, it cannot also be switched between directions D and F, as the wavelength would already be in use over the interlink. The wavelength, however, could be reused between directions B and E, or A and F, for example.
Colorless, Directionless and Contentionless ROADM

For the ROADM architectures shown in Figure 4, each transceiver remains hard wired to a given direction, referred to as a directional ROADM. Hence, changing the assigned direction of a transceiver would require a site visit to physically change the fiber connectivity between the transceiver and access ports for a given direction.

To achieve both colorless and directionless functionality, additional WSSs can be used [1]. For example, the access ports for the 4-degree ROADM shown in Figure 4 can be made directionless using the access structures shown in Figure 8.

In the drop structure of Figure 8, a 4x1 WSS is used to pick the direction of a given wavelength, while a second WSS is used to achieve M colorless drop ports. In the add structure, the combined add signals are simply broadcast to all directions, and the WSS serving a given direction is then used to select the specific wavelength(s) to be added to that direction. The add structure could alternatively be realized using the drop structure in reverse.

It is also possible to realize a colored, directionless ROADM by simply replacing the 1xM WSS and passive combiner in Figure 8 with a wavelength demultiplexer and multiplexer, respectively.

A functional limitation of the directionless access structures shown in Figure 8 is that access wavelengths are not contentionless. Specifically, a given wavelength can be added/dropped from one direction only, i.e., cannot be simultaneously added/dropped from other directions. This contention only applies to the re-use of access wavelengths, and not pass-through wavelengths.

To achieve colorless, directionless and contentionless (CDC) functionality, NxM WSSs or broadcast-and-select modules can be used in the access structures [1], as shown in Figure 9. Although the functionality of an NxM WSS or broadcast-and-select module can be realized using multiple discrete components, they are not yet commercially available as integrated modules.
The number of access ports offered by the structures shown in Figure 9 is likely to be practically limited to a low number, such as 4, 8 or possibly 16. To realize a CDC ROADM with higher access port density, the structure shown in Figure 10 can be used, which could alternatively use broadcast-and-select modules in the access structures [2]. This architecture would allow access port capacity to be added in a modular way without affecting existing services. In addition, because ingress wavelengths from a given line direction are routed using a WSS to other directions, rather than broadcasted using a passive splitter, the blocking extinction ratio for express wavelengths would be much improved. A higher blocking extinction ratio mitigates in-band interference effects, which could otherwise become a significant impairment in heavily-loaded, large mesh networks employing many multi-degree ROADMs. Another advantage of the structure shown in Figure 10 is that the insertion loss for express and access wavelengths can be kept low, avoiding the need for additional amplifiers.
Another way to achieve full CDC functionality is to attach an NxM non-blocking photonic switch to the colored access ports shown in Figure 4a, as illustrated in Figure 11. Here, N is equal to the cumulative number of colored ports from all multiplexers (add) or demultiplexers (drop), and M is equal to the desired add/drop capacity. Setting M=N results in a CDC ROADM with 100% add/drop capacity. Similarly, a smaller photonic switch could be attached to the colorless access ports in Figure 4b to achieve full CDC functionality.

An advantage of the architecture shown in Figure 11 is that it is backward compatible with the existing structures shown in Figure 4, i.e., an existing colored or colorless ROADM can be upgraded to a full CDC ROADM by attaching photonic cross-connect switches to the access ports, assuming the footprint and price point eventually become acceptable for such switches. Moreover, this structure should be able to maintain low insertion loss in the access structure, even for 100% access capacity, avoiding the need for optical amplifiers in the access structure.

Figure 10: Increasing the number of access ports on a CDC ROADM.

Figure 11: 4-degree ROADM with CDC access ports.
Next-Generation WSS

Realizing the CDC ROADMs described in the previous section requires multiple WSSs, multiplexers, demultiplexers, splitters and optical switches. The footprint and cost of such structures make them prohibitive in many, if not most, networks. What is ideally needed is a new class of WSS module that achieves the functionality shown in Figure 12.

Such a module would allow any wavelength, or combination of wavelengths, to be switched between any port and any other port, with no constraints on wavelength re-use. To realize a CDC ROADM, each port would simply assume the role of access port (add or drop) or trunk port (ingress or egress).

Although the device in Figure 12 is conceptually simple, no one has yet been able to develop it. However, high levels of photonic integration, such as demonstrated in [3], may one day make such a device possible. The reliability would have to be extremely high.

The Benefit of CDC ROADMs

To illustrate the benefit of a CDC ROADM, consider the mesh network shown in Figure 13, with an existing optical circuit between ROADM nodes R1 and R7 along the indicated path.

Let us now consider the network flexibility possible using directional colored (non-CDC) ROADMs versus CDC ROADMs.

For a non-CDC ROADM network the circuit is directionally assigned to spans s1 and s6, and fixed to a given wavelength. Hence, without manual re-fibering, the circuit must traverse spans s1 and s6. This means automatic mesh restoration is possible for a failure on span s4, but not for a failure on span s1 or s6, or a power failure at node R2 or R4. Similarly, when optimizing network loading and resource allocation, optical circuits can be remotely reconfigured to take different routes within the core, but not at the circuit edge nodes R1 and R7.

For a CDC ROADM network the circuit can be remotely assigned to any wavelength and/or direction at the circuit terminating nodes. Hence, optical mesh restoration is not only possible for a failure on span s4, but also a failure on span s1 or s6, or a power failure at node R2 or R4. Similarly, when optimizing network loading and resource allocation, optical circuits can be remotely reconfigured to take different routes, not only within the core, but at the circuit edge nodes, providing full flexibility to optimize network loading.

If automated optical mesh restoration and/or optical circuit routing/re-configuration is important, then CDC ROADMs provide a clear benefit.
Other Considerations for CDC ROADMs

Although the capital cost of a CDC ROADM network is generally significantly more than a non-CDC ROADM network, the operational cost can be significantly less, depending on how the network is used and how it evolves. Of course, hybrid approaches are also possible. For example, only some ROADMs within a network may need full CDC functionality, or may only need a subset of CDC functionality, e.g., a colored directionless ROADM.

Another important consideration for CDC ROADMs is that networks are continuing to evolve toward a more packet-centric transport paradigm, where connection-oriented packet technologies such as MPLS-TP or PBB-TE are used to traffic engineer packet circuits through a network. These are able to take full advantage of packet aggregation and statistical multiplexing, which can significantly reduce the number of wavelengths needed to support the actual traffic demand. Moreover, they offer fast linear and ring protection schemes at layer 2, such as ITU-T G.8031 and G.8032, respectively, which may mitigate the need for optical mesh restoration in the DWDM transport layer.

CDC Regeneration

CDC ROADMs allow for fully automated reconfiguration of optical circuits. However, when a new optical circuit is configured, either when adding a new service or enabling an alternate path as a part of network restoration or load balancing, the new circuit may not be viable without optical-electrical-optical (OEO) regeneration. Although it is generally desirable to choose an available optical path that does not require OEO regeneration, this is not always possible due to optical signal-to-noise ratio (OSNR) limitations and/or the buildup of other impairments, such as residual dispersion, polarization effects, etc. To address this, a CDC regenerator can be used. For example, a small CDC regenerator pool could be deployed at select ROADM sites, as illustrated in Figure 14 for a four-degree ROADM. Note that these would be standby resources that would only be used for new optical circuits that require OEO regeneration, allowing for fully automatic and remote circuit provisioning in such cases.

The number of available CDC regenerators would not need to be large, and they would not need to be present at every node, particularly if few circuits would ever require regeneration. As they are used up, additional standby CDC regenerators could be deployed when convenient, without affecting existing services.

![Figure 14: CDC regen pool.](image-url)
Flexible Bandwidth ROADMs and Transmission Beyond 100 Gb/s

Some WSS vendors have recently announced flexible bandwidth (FB) WSS products, suitable to build “gridless” ROADMs. These devices can switch and/or adjust their passband at 25 GHz, or even 12.5 GHz, granularity, and have no deadband in-between adjacent channels or pixels.

It should be pointed out that “fixed” 100 GHz or 50 GHz ROADMs have flexible bandwidth to some extent, just at a coarse granularity and possibly with some dead space in-between adjacent channels.

FB ROADMs allow the passband center and/or passband width for a given channel to be dynamically adjusted, as shown in Figure 15, where a channel may be realized using one or more constituent wavelengths or carriers. For example, a single laser may be used to generate multiple frequency-locked carriers at a certain frequency spacing, which are then synchronously modulated and transmitted in a contiguous, widened passband to realize high bit-rate transmission, known as a superchannel [4].

An argument for FB ROADMs is that they future-proof a network to support transmission formats operating at bit rates greater than 100 Gb/s, under the assumption that such transmission schemes will require wider bandwidths than available on today’s 100 GHz or 50 GHz ITU DWDM systems. The following discusses how transmission beyond 100 Gb/s may be realized, and whether or not FB ROADMs will be required.

Modulation Format for 100 Gb/s Serial Transmission

The de-facto transmission format for serial 100 Gb/s uses dual-polarization with quadrature phase-shift keying (DP-QPSK) modulation and coherent detection. This format may also be referred to as coherent polarized QPSK (CP-QPSK), or polarization-division-multiplexed QPSK (PDM-QPSK). The Optical Interworking Forum (OIF) has promoted this format [5], and essentially all component and equipment vendors are aligned on its adoption.

PDM-QPSK leverages all four dimensions of the available signal space in a singlemode fiber – two orthogonally polarized modes, and two orthogonal signals (in-phase and quadrature, called I and Q) for each polarized mode, resulting in a transmission rate that is four times the symbol rate. The actual signaling for the I and Q components, however, still amounts to two-state, i.e., binary, allowing it to achieve noise-limited performance comparable to other pure binary modulation formats operating at the same symbol rate. Moreover, by using coherent detection, both magnitude and phase information for the received optical signal are available, allowing for dynamic electrical compensation of dispersion. Because of this, PDM-QPSK can actually outperform pure binary modulation methods operating at the same symbol rate with respect to dispersion tolerance.
The bandwidth required for PDM-QPSK is approximately equal to the symbol rate, making 100 Gb/s transmission compatible with existing 50 GHz ITU DWDM systems [6]; hence, FB ROADMs are not required for 100 Gb/s transmission.

It has been demonstrated that PDM-QPSK performs better when there is no bulk dispersion compensation in the line system [7]. However, that is only true for dispersion compensating fiber (DCF), a legacy technology, whereas periodic fiber Bragg grating (FBG) dispersion compensation modules (DCMs) are now common. Unlike DCF, these have a channelized response with large group delay variation across each channelized passband, but negligible group delay variation between channels. That means the transmission line behaves like an uncompensated system from an inter-channel interaction standpoint, while providing optical dispersion compensation for each channel. This property of periodic FBG DCMs leads to better performance for a PDM-QPSK signal compared to a system with no in-line compensation [8, 9]. In this regard, the channelized aspect of 100 GHz or 50 GHz systems is actually beneficial to PDM-QPSK.

**Transmission Above 100 Gb/s**

Simply increasing the speed of electronic components to achieve higher transmission speeds is not practical due to physical limitations.

Optical time division multiplexing (OTDM) can be used to obtain a higher transmission speed, but that approach uses narrow time-interleaved pulses that are not suitable for long-haul transmission, as high-speed OTDM signals are extremely sensitive to impairments such as fiber dispersion. Moreover, despite being an active area of research for many years, OTDM is yet to see any real commercial application in optical transport networks.

Transmission above 100 Gb/s can be achieved by increasing the number of levels in the I and Q signal components [10, 11]. For example, 16-QAM with polarization multiplexing would allow the bit rate to be doubled to 200 Gb/s without increasing the symbol rate, allowing such a modulation format to remain compatible with a 50 GHz ITU grid. Again, there is no requirement for FB ROADMs in this scenario. However, because the required signal-to-noise ratio (SNR) increases as the number of levels in a multi-level signal increases, from a practical standpoint it is unlikely that long-haul transmission rates higher than 100 Gb/s will be commercially realized over 50 GHz ITU infrastructure using multi-level modulation of a single carrier alone. Evidence of this is provided in the following paragraphs.

A viable approach to achieve long-haul transmission above 100 Gb/s is to use multiple carriers to realize a multi-carrier superchannel [4]. FB ROADMs could potentially play a role here, as the minimum carrier spacing can be as low as the symbol rate for such signals, e.g., ~25 GHz with each carrier operating at ~100 Gb/s. In addition to the need for flexible bandwidth when using such superchannels, the output power rating of optical amplifiers would have to be considered and sized accordingly to accommodate an increased number of carriers.

The product of bit rate and distance has often been used as a metric for the transmission capacity of a single-carrier channel. For ultra-high capacity transmission, we can similarly use a metric given by the product of spectral efficiency and distance. Figure 16 shows the spectral efficiency-distance product in (bits/s/Hz) km for various transmission experiments reported in the OFC 2011 postdeadline sessions.

Figure 16 demonstrates that the highest spectral efficiency-distance products were achieved using QPSK, i.e., 4-QAM. Hence, for future commercial systems, it is reasonable to assume that PDM-QPSK will be used for each constituent carrier in a multi-carrier channel or superchannel.
It is not necessary to use a wide, single contiguous bandwidth to support a multi-carrier channel, or for the constituent carriers to be spectrally adjacent and/or frequency locked. In other words, multiple DWDM lanes can be bonded together to achieve the desired transmission rate, with each lane operating independently at 100 Gb/s, for example. In this case we need only be concerned with the required bandwidth for each constituent carrier in the parallel stream, not the stream as a whole. With this view, a 1 Tb/s transceiver might look like that shown in Figure 17.

Note that the “splitting” function for the received DWDM signal shown in Figure 17 is generalized, as it could be realized using an internal or external wavelength demultiplexer, 1x10 WSS, or could simply be a passive splitter such that the coherent receiver extracts the desired carrier.

There are many practical advantages for the transceiver shown in Figure 17. For one, it leverages an existing modulation format and multi-lane interface technologies. Moreover, it is compatible with existing 50 GHz DWDM infrastructure. If a tunable laser were used for each constituent carrier, it would allow any combination of DWDM wavelengths to be used for a given high-speed circuit, essentially doing for DWDM what virtual concatenation (VCAT) did for SONET/SDH. Alternatively, an array of fixed wavelength lasers could be used, or the array of carriers could be tuned as a group, which may result in a lower cost transceiver if a fixed or constrained wavelength plan is acceptable. As with lower speed devices, such as XFPs, a tunable transceiver would avoid the inventory problem associated with fixed optics.

A multi-lane approach can also scale to rates higher than 1 Tb/s. For example, the entire DWDM capacity of a fiber, or even multiple fibers, could serve as one big parallel bit pipe to interconnect high-capacity switches, while maintaining backward compatibility with existing transport infrastructure.

An important consideration for a multi-carrier channel, particularly for Ethernet, is that the failure of one or more parallel lanes should not result in failure of the entire channel. One solution would be to have the multiple carriers or lanes act as a link aggregation group (LAG), but that would result in trunk utilization inefficiencies that are well known for LAGs. A better solution would be to implement the multi-lane protocol in a way that allows surviving parallel lanes to continue to carry all Ethernet frames as a single flow, albeit at a slightly reduced trunk capacity. This could potentially be done with in-band signaling, or with out-of-band control signaling used to coordinate which lanes are active and good between the transmitter and receiver of a channel.

Figure 16: Achieved spectral efficiency versus distance for transmission experiments reported in the OFC 2011 postdeadline sessions. All experiments used polarization division multiplexing and coherent detection. Each point shows the achieved spectral efficiency-distance product, along with the number of QAM levels in the signal (QPSK=4-QAM).
There are two fundamental considerations for transmission beyond 100 Gb/s. First are the needs of a L2+ switch. From the switch’s perspective, it simply needs high capacity trunk/port connections and doesn’t care how that is achieved over physical fiber, e.g., serial versus parallel lanes. The second consideration is spectral efficiency, or more specifically the spectral efficiency-distance product.

Although FB ROADMs could potentially support higher spectral efficiency transmission, they are not required to achieve transmission above 100 Gb/s. Moreover, their incompatibility with existing channelized DWDM infrastructure, operational complications, likely higher costs and interoperability issues between different vendor’s equipment, may be a significant barrier to the rapid commercial acceptance of FB ROADMs. A reasonable scenario may be to use multi-carrier channels based on channelized constituent carriers for ROADM networks in terrestrial applications, keeping them backward compatible with existing DWDM infrastructure, and to use un-channelized (continuous band) superchannels in point-to-point applications, such as undersea, where wide bandwidths are naturally available and ultimate spectral efficiency is highly desirable.

Optical Power Management and Control

Much of the focus with ROADMs is on their ability to be remotely reconfigured from a wavelength switching perspective. One of the most important features of a ROADM, however, is its ability to independently adjust optical power levels with per-wavelength granularity. Moreover, this can be fully automated, often referred to as automatic power balancing (APB). Without APB, managing power levels, particularly in larger networks with long optical circuits, can become an intractable problem.

At each span input, the optical power level for each wavelength must be maintained at a set target level to ensure the end-to-end circuit’s OSNR is adequate. Power levels must also be maintained to ensure no optical amplifier in the system saturates under full wavelength loading, and that the receive power level is within the required dynamic range of the receiver. Inter and intra channel nonlinear effects, and adjacent and non-adjacent channel crosstalk, also require power levels to be controlled to set targets as a part of an overall power management strategy.
Sources of Power Variation

There are many network conditions that can cause optical power levels to vary. One major contributor is the loading-dependent, cascaded spectral response of optical amplifiers. To illustrate this, consider a typical gain-flattened EDFA with a spectral gain response that exhibits ripple between 0.5 and 1 dB peak-to-peak. This ripple has both a systematic and random component that accumulates as EDFAs are cascaded, as shown in Figure 18. Note that up to 20 cascaded amplifier stages is not uncommon for longer optical circuits, considering line amplifiers and that each ROADM node itself would normally have both a preamp and postamp, and that some amplifiers may be multi-stage. Hence, cascaded spectral ripple can easily exceed 10 dB in many cases.

EDFAs in a DWDM system usually operate in a gain controlled mode, where each EDFA controls its gain to a setpoint based on total power measured at its input and output. Because the gain of each EDFA is based on composite power, the actual gain experienced by each wavelength depends on the wavelength loading condition, as illustrated in Figure 19. For a given gain setting of a single-stage EDFA, the spectral gain profile not only moves up or down with the input loading condition, but also tilts due to a physical characteristic called dynamic gain tilt that is intrinsic to every EDFA.

The loading-dependent, spectral response for a cascade of EDFAs can cause wavelength power levels for existing services to fluctuate significantly as other wavelengths are added or removed from the system.

Inter channel power exchange due to stimulated Raman scattering (SRS) also occurs in each span and accumulates along a cascade of spans. Similar to cascaded EDFAs, this too leads to a spectral gain profile that varies with the channel loading conditions.

Polarization dependent loss or gain of fiber and other system components can also result in power variation. For example, in addition to the overall end-to-end state of polarization varying with time, any manipulation of the fiber, especially close to the transmitter, can affect the launch polarization state of the transmitted signal, causing variation in the overall system gain.
In addition to the wavelength loading and polarization dependent power variation described above, there are also mechanisms that result in fixed spectral power variation among wavelengths, including the spectral dependent loss of fiber itself, or non-uniform spectral loss through channelized devices such as multiplexers, demultiplexers and DCMs. Even within the passband of a given channel there is spectral loss variation, which can translate to power variation in the presence of any laser drift.

**Manual Versus Automatic Power Balancing**

In smaller optical networks with fixed OADMs it is common to manually balance power levels using fixed attenuator pads. When a new circuit is added, fixed attenuator pads may be placed at the transmitter, receiver, and/or at certain OADM locations along the way in order to achieve the desired power level at various points along the circuit’s path. In some cases, existing circuits may also need their power levels to be manually re-balanced, due to a change in wavelength loading conditions, as other circuits are added or removed. For small networks, particularly those with few or no optical amplifiers and short optical circuits, manual power balancing may be manageable and appropriate. For larger networks with many amplifiers and where optical circuits may traverse many nodes, manual power balancing can become difficult, if not impossible, resulting in service degradation or outages and high operational expenditures. For such networks, the APB capabilities alone of a ROADM can justify their capital expense.

**Fault Tolerance and Response**

An important consideration for the APB function of a ROADM is its behavior during power transients and fault conditions. Each ROADM vendor implements their own APB algorithms and power management strategy, which respond differently and result in different behaviors to various fault conditions.

As new circuits are added or removed, or wavelengths suddenly disappear due to fault conditions such as a fiber pull, a well-designed APB algorithm and power management strategy would minimize the dynamic perturbation of other wavelengths. Moreover, the APB algorithm should not respond to channelized noise from optical amplifiers, as that could lead to high system gain for missing signals, which could damage a receiver when the signal is applied.
Another consideration is how the APB algorithm responds to amplifiers that approach saturation during heavy or full wavelength loading. It is generally an objective to make use of the full output power capabilities of an optical amplifier under full wavelength loading in order to achieve the highest possible system OSNR. However, it is also an objective to not allow the amplifier to saturate, i.e., attempt to exceed the output power rating of the amplifier, as that leads to problematic gain reduction and tilt in the amplifier. A well designed APB algorithm would allow these two objectives to be met simultaneously, with a well-controlled response under full loading.

Because wavelengths may traverse many ROADMs, the overall cascaded response of the APB algorithm is important during both normal and faulted conditions. Again, a well-designed APB algorithm and power management strategy would ensure a well-controlled cascaded response.

The Role of a Control Plane in ROADM Networks

Management and control of an intelligent optical network would generally make use of most or all of the architectural layers shown in Figure 20. A given layer or “plane” is a conceptual construct with associated functionality, as described below.

Management Plane - Represents the infrastructure used to manage the network from an operation, administration and maintenance (OAM) standpoint. It provides the interfaces and underlying infrastructure to configure the network and monitor performance and alarms. An element management system (EMS), network management system (NMS), Web craft interface and command line interface (CLI) are all tools that are typically associated with a management plane.

Control Plane - Automates functionality within the network, such as adding or removing optical circuits and mesh restoration. It encompasses inter-node and inter-component signaling protocols, topology discovery and resource advertising and reservation, path computation and routing calculations and information exchange, and automated link state management. The control plane provides interfaces to the management plane via manageable objects, allowing the management plane to administer the control plane.

Automated Optical Layer - The automated optical layer is closely coupled to the control plane and may be considered a sub-part of it. It makes automatic adjustments within a network to control optical power levels to set targets. Automatic power balancing is part of this layer. This layer may also include an automated link controller that, for example, adjusts optical amplifier gains and/or bulk VOAs within a link to optimize the overall OSNR for the link.

Data Communications Network (DCN) - Provides the infrastructure for transporting management and control plane information between devices. The DCN may be provided by infrastructure that is separate from the transport network it serves, but often makes use of components that are part of the transport system, such as communication channels provided by OTN and/or SONET/SDH overhead bytes, sub-wavelength channels in Ethernet aggregation or muxponder cards, or a dedicated optical supervisory channel (OSC) wavelength. Routers and/or L2 switches may also be integrated within the transport equipment to support a DCN.

Transport Plane - The architectural aspects of a system that directly support the transport of services and service continuity. An important part of the transport plane is often represented by overhead bytes that accompany a service stream to support OAM and reliable transport of the service instance, such as with OTN or SONET/SDH signals. Various aspects of service OAM (SOAM) overhead bytes support other layers. Common functionality
provided by the transport plane includes signal trace monitoring, tandem connection monitoring and fault localization, remote fault indication, signal quality monitoring and alarming, forward error correction, payload type and mapping indication, and automatic protection switching.

**Data Plane** - Represents the actual user data itself, i.e., the information bits contained in the data stream of an optical circuit carrying a service or multiplex of services.

The following sections focus on the role of a control plane to automate circuit provisioning in ROADM networks.

**Static Network Control**

With static network control, the network operator manually configures each ROADM and other devices in a circuit’s path via a management interface.

Setting up a circuit manually requires knowledge of available resources, such as physical equipment and which wavelengths are available on each link. A suitable path has to be manually selected, and the resulting OSNR, residual dispersion and other cumulative impairments for the chosen path must be evaluated to ensure the circuit is viable. In some cases regenerators are required, and their location would be determined manually.

With static control, much of the information needed to set up a new optical circuit may be maintained in a separate data base, spreadsheet or some other tool(s) and/or extracted through the management interface. For some networks, operators prefer to use static control, as it is often sufficient and easily understood, particularly for smaller networks.

Because optical power levels are sensitive to channel loading conditions in long-haul, optically-amplified systems, automatic power balancing is still usually desired and needed when using static control. Without it, honoring service level agreements (SLAs) could be difficult, if not impossible.

**Dynamic Network Control**

The concept of a control plane is generally associated with dynamic or automated network control. A control plane, depending on its scope, automates most or all of the processes described above for static network control.

For optical transport systems, the control plane serves connection requests and automates the process of adding or removing optical circuits, often referred to as automated A-to-Z circuit provisioning, as illustrated in Figure 21 and described below.
A request to set up a circuit may be initiated by a person via a management interface that directly manages the network, or via protocol messages sent to a user-network interface (UNI) or network-network interface (NNI) [12, 13]. Next, one or more viable paths are automatically computed by a path computation element (PCE), taking into account resource availability and any routing constraints. The viability of a path must consider all network impairments, and if optical-electrical-optical (OEO) regeneration is required for the circuit, then the suitable placement and reservation of regenerators must also occur.

Once one or more viable paths are computed, one would be selected for the new circuit, and automated signaling would then be used to configure each component in the path, including tunable transceivers and ROADMs. After verifying circuit continuity, the user would be informed that the circuit setup is complete. A circuit service management interface could then be used to maintain and monitor the performance of the circuit for the life of the service.

An architectural model and framework for an automatically switched optical network (ASON) is provided in ITU-T G.8080 [14].

The Role of GMPLS

For Internet Protocol (IP) and Multi-Protocol Label Switching (MPLS) networks, the IETF has specified a number of protocols for distributed control, such as IS-IS, OSPF, RSVP and LDP. Traditionally, these protocols were used for packet networks, with protocol messages carried along with the data in the data plane. By adding extensions to these protocols, and the ability for them to operate independently of the data plane, the protocols were “generalized,” allowing them to be used with any type of network, referred to as generalized MPLS (GMPLS) [15, 16]. Hence, GMPLS can be used to control networks that switch fibers, wavelengths, time slots in a TDM network, or packets in a packet-based network, or any mix of these.

Strictly speaking, the term GMPLS refers to an architectural concept whereby a label and label switched path (LSP) are generalized, so they can apply to any network type and switching technology. Hence, the concept of GMPLS itself does not mandate any specific protocol. The IETF, however, has defined a suite of protocols, through extensions to existing MPLS protocols, to achieve the objectives of GMPLS [15]. This may be referred to as the GMPLS protocol suite or stack, which can be used to realize a GMPLS network.

The ASON architectural reference model in ITU-T G.8080 describes automatic switching within an optical network; however, there is no specific protocol requirement to realize an ASON network. Nonetheless, it is often assumed that the GMPLS protocol suite defined by the IETF would be used. For this reason, it is common to see reference made to an “ASON/GMPLS” control plane, or to even use the terms ASON and GMPLS interchangeably when referring to automated optical networks.

Distributed Versus Centralized Dynamic Control

The GMPLS protocol suite defined by the IETF is generally associated with distributed control. With it, nodes automatically discover the topology and functional capabilities of each other, and each node has the same view of the network as any other node. Any changes to the network are automatically flooded to all nodes within the network. Although such distributed control is used widely in router-based networks, its direct application to optical transport networks is more challenging.

Distributed control offers the advantage of high resiliency, as it dynamically adjusts to accommodate the current state of a network. However, all nodes must be compliant with the protocols used, and flooding of state information in larger networks, and/or due to frequent network changes, can pose network scalability issues.

With centralized control, a central application has a complete view of a network domain and its constituent components. It can completely automate the task of setting up and/or tearing down circuits, and can effectively integrate with a circuit service manager and intelligent PCE. It is generally considered to be a “dynamic” mode of control, as it is largely able to achieve the same objectives as distributed control. Because centralized control automates the tasks that would otherwise be done manually via a management interface, it may be referred to as NMS or EMS driven control.
Centralized control only requires computational resources at the main controller, and any redundant controllers used to protect against a failure of the main controller. Any required software upgrades can often be confined to the centralized controller, versus having to upgrade every node.

Although centralized control implies that path computation and overall network visibility and control are centralized, all equipment within the network must be able to interoperate with the centralized controller. Hence, there is generally a “distributed” embedded component to centralized control, and the protocols used by the main controller and embedded components may use parts of the GMPLS protocol suite.

**Impairment-Aware Path Computation**

The PCE must account for all routing constraints, such as which wavelengths are available on each link, the available resources at each node, and the capabilities and topological association and connectivity of resources. For optical networks that use ROADMs and optical amplifiers, the PCE must also be able to accurately predict the achievable performance of a candidate optical circuit.

To determine if a circuit is viable, the PCE must know the fiber type, loss and length of each span, and the optical power level of every wavelength at the input to every span. This implies that power levels must be controlled to known set points by the automated optical layer. The PCE must be able to derive the system OSNR and residual dispersion for a circuit. Accurate models must be employed for components such as transmitters, receivers and filters, along with models for all sources of noise and fiber nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). Appropriate margins must also be allocated for polarization dependent loss (PDL), polarization mode dispersion (PMD), and any other static and/or dynamic impairments. Taking all of these considerations into account is known as impairment-aware path computation or routing.

Although a distributed PCE architecture is possible, an intelligent PCE with full impairment-aware routing capabilities may best be done by a centralized PCE that has full visibility of a network domain. Hence, a centralized control plane and PCE with redundant servers is a reasonable strategy for all-optical circuit routing within an autonomous domain. This is quite feasible for a given system vendor’s equipment that makes up a given domain, as they would know the detailed characteristics of their transmission equipment and could, therefore, provide a PCE for networks built using their equipment. Routing optical circuits without OEO regeneration between carrier domains, or between sub-domains built from different vendor’s equipment, however, is generally much more difficult.
Summary

WSS-based ROADMs are an essential part of modern optical networks. They allow for scalable networks with enhanced agility and network automation. The initial capital expense for ROADMs can be offset by significant savings in operational expenditures, making the overall network cost of ownership potentially much lower.

ROADMs with colored access ports are most common today, as they support automated power management and allow for remotely controlled wavelength switching within the network. Although CDC ROADMs offer increased agility and automation at the termination points of a circuit, their higher capital cost and reduced access port density continue to make them prohibitive in many applications. Continued advancements in integration should eventually make CDC ROADMs more common.

It is not yet clear whether or not FB ROADMs will become widely accepted and deployed in optical networks. Although they offer a potential improvement in spectral efficiency, they are not required to achieve transmission rates above 100 Gb/s. The adopted method to realize high-speed transmission, such as 1 Tb/s and beyond, will likely use multi-carrier channels or superchannels, with each carrier using PDM-QPSK. The only real requirement for such signals is that the transport infrastructure is able to transport each constituent carrier in the channel.

Realizing the full benefit of a ROADM network makes use of an automated optical layer and intelligent control plane. Both static (manual) and dynamic (automatic) network control are possible, with dynamic control being either centralized or distributed. A key component of the control plane is an impairment-aware PCE.
References


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About Optelian

Optelian provides Intuitive Packet Optical Networking™ to deliver next generation services. Our solutions are enabled by the modular Optelian FLEX Architecture™ to deliver services from access to core, passive to packet, and 100M to 100G. Intuitive Packet Optical Networking enables Service Driven Networking, allowing operators to rapidly deliver services while optimizing network capacity. We enable intuitive service management through a simplified infrastructure that virtualizes network and technology complexity.

With agile design capabilities and North American manufacturing, Optelian can meet custom requirements to suit any network. Combined with professional services to ensure your network is optimally planned and deployed, along with world-class customer support, Optelian delivers the technology and services that enable intuitive next generation networks. For more information, visit www.optelian.com, and follow us on Twitter @Optelian.