NEW PARADIGMS IN
OPTICAL COMMUNICATIONS AND NETWORKS

New Devices Enabling Software-Defined Optical Networks

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ABSTRACT

Next-generation ROADM networks are incorporating an extensive range of new features and capabilities including colorless, directionless, and contentionless multiplexing and demultiplexing, flexible spectrum channel definition, and higher-order modulation formats. To efficiently support these new features, both new ROADM node architectures along with complementary optical components and technologies are being synergistically designed. In this article, we describe these new architectures, components, and technologies, and how they work together to support these features in a compact and cost-efficient manner.

INTRODUCTION

Optical networking has evolved through many generations, from unamplified, repeated single-wavelength-per-fiber links to wavelength-agile reconfigurable optical add/drop multiplex (ROADM)-enabled mesh networks. Each generation has provided a range of new features and capabilities, each time providing network operators with the ability to design, deploy, operate, and scale their networks with improved efficiencies and lower overall costs of ownership.

The current generation of ROADM networks leverages the wavelength selectable switch (WSS) and provides software-controlled wavelength channel cross-connecting capabilities through each optically meshed node. Additional network connectivity can be seamlessly introduced into the existing mesh network by simply installing new degrees to selectively and opportunistically increase capacity as traffic topology demands evolve. These capabilities let network operators efficiently scale their networks, accommodate unpredictable growth, and delay the deployment of expensive new infrastructure.

However, typically this agility is only utilized when provisioning new wavelengths or connectivity as altering either the route or wavelength of an existing channel is operationally intensive. Essentially, doing so amounts to the decommissioning of the existing channel followed by the recommissioning of a new channel despite the fact that the same endpoint transponders may be unchanged. Therefore, once wavelength channels are provisioned and deployed, they are generally not modified during their service lifetime. Thus, the flexibility of modern ROADM networks is usually a benefit only during the provisioning of new capacity.

While the agility of modern ROADM networks provides the flexibility to accommodate unanticipated traffic growth, as that traffic topology evolves and the network connectivity is augmented, hot spots and inefficiencies in the traffic topology commonly emerge. Alleviating these hot spots or migrating traffic to achieve a traffic topology more efficiently matched to the physical network topology requires migrating the route and possibly the wavelength of channels. As previously mentioned, given the complexity of such operations, typically they are simply not executed. This restricts the ability to improve the cost efficiency and extend the lifetime of the network.

Furthermore, planned and unplanned network outages occur, forcing network operators to provision several layers of redundancies along with the electronic traffic switching mechanisms to manage these redundancies to ensure the service is protected. Implementing and maintaining these redundancies drives up the total cost of delivering services, given the hardware and operational costs of the additional equipment as well as the need to rapidly repair outages to restore sufficient amounts of redundancy [1].

To significantly address these issues, the ability to efficiently, reliably, and dynamically reconfigure both the wavelength and route of optical channels through the network entirely through management software — without any manual intervention — is needed [2]. Specifically, this capability is enabled by colorless and directionless multiplexing and demultiplexing, which enable the wavelength (colorless) and route that channel uses to enter/leave a terminal node (directionless) to be flexibly provisioned within the management control plane and without any physical intervention [1]. This enables operators to quickly and reliably rebalance network traffic loads, route traffic around expected and unexpected outages, and further unlock the benefits of generalized multiprotocol label switching (GMPLS), automatically switched optical networking (ASON), and OpenFlow control plane

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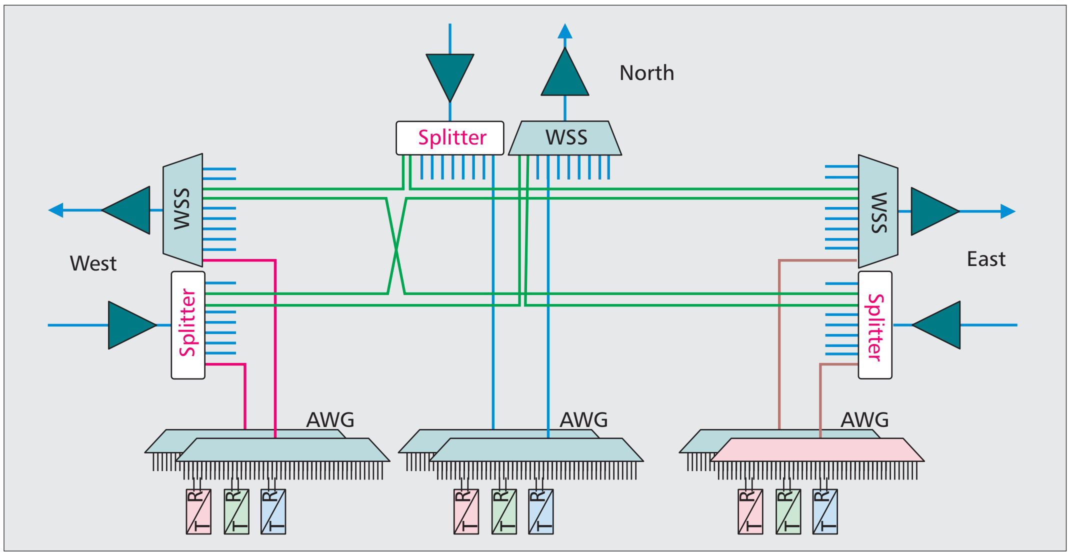

Figure 1. *A diagram of a three- degree broadcast-and-select ROADM node architecture including independent arrayed waveguide grating (AWG) multiplexers and demultiplexers for each degree .*

A critical function of the WSS is to manage how wavelength channels are physically routed through the network, and, equivalently, it is also the element responsible for preventing wavelength channels from going in unwanted directions and potentially interfering with other channels.

technologies to activate and optimize the capacity. This improves the efficiency of the network, enables some reduction in the amount of redundancy equipment required to sufficiently protect services [2], and relaxes the need to make expensive emergency infrastructure repairs.

For several network generations, the International Telecommunication Union (ITU)-defined 50 and 100 GHz frequency grids have standardized wavelength channel center locations within the optically amplified C-band [3]. This has enabled straightforward channel management and has simplified optical device design by leveraging the precisely periodic channel locations. However, a 100 Gb/s dual process quadrature phase shift keying (DP-QPSK) signal generally consumes the majority of the bandwidth available within a 50 GHz channel, and the ability to continue to significantly increase the amount of data carried within that channel (within the same network design) may be fundamentally limited [4].

Departing from the 50 or 100 GHz channel grid and flexibly provisioning channel bandwidths with management software allows higher-data-rate superchannels and enables capitalization on the fundamental trade-off between reach and spectral efficiency [5]. This flexibility is commonly referred to as flexible spectrum. It enables channels that require shorter reaches to leverage more spectrally efficient modulation formats, which consume less optical bandwidth as well as allow for the wider bandwidth channels necessary to carry high-capacity channels over longer distances. This provides network operators the flexibility to maximize network efficiency and scale network capacity by selecting the proper transmission technology and channel bandwidth for the reach and capacity required.

Implementing this next generation of self-aware software-defined optical network capabilities requires new approaches, both to how networks are architected and the optical devices needed to implement them. A new portfolio of optical components is needed, including: WSSs, optical channel monitors, multicast switches, optical amplifier (OA) arrays, and transponders. In this article, we describe these new components, what new capabilities and requirements they have, and how they work in new architectures to create next-generation ROADM network nodes.

CORE NODE ARCHITECTURE

The current generation of ROADM networks uses a single WSS per degree in a broadcast-and-select architecture. The WSS selects which wavelength channels are to express through that respective degree and optically blocks the rest (Fig. 1). A single multiplexer structure per degree, able to multiplex all possible channels, combines all locally added channels for that degree; therefore, only a single port on each WSS is needed to support that multiplexer. Channel demultiplexing is accomplished using generally the same elements, only used in the reverse direction.

However, colorless and directionless multiplexers and demultiplexers support traffic from all the degrees and have a limited number of add/drop channel ports per module (discussed in greater detail below). Each module requires an independent connection to each degree, and scaling the overall capacity of the node requires connecting multiple colorless and directionless modules to independent ports within each degree. The number of WSS ports must thus be increased beyond simply the maximum number of degrees supported.

A critical function of the WSS is to manage how wavelength channels are physically routed through the network, and, equivalently, it is also the element responsible for preventing wavelength channels from going in unwanted directions and potentially interfering with other channels. The ability of a WSS to prevent channel energy from going in unwanted directions is commonly referred to as *isolation* and is typically in the range of 35–45 dB for conventional 9-port

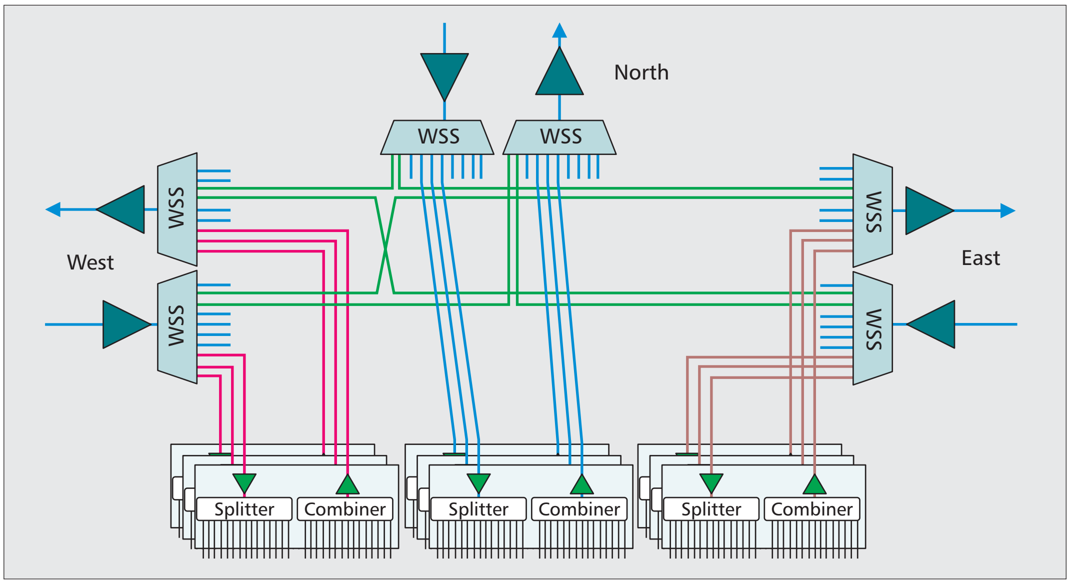

Figure 2. *A diagram of a three-degree route-and-select ROADM node architecture including independent filterless power combiner and splitter multiplexer and demultiplexer modules for each degree.*

Replacing a broadcasting power splitter with a WSS provides the ability to limit the channels directed to each demultiplexer to only those channels intended to be detected by the receivers within each respective demultiplexer.

WSSs. Thus, small amounts of channel energy leak through within each node and accumulate with each successive node, subsequently interfering with an active wavelength channel [6]. This interference, in combination with the optical noise generated by optical amplification, is a primary source of signal degradation and limitation of the transmission distance of a link. In order to maximize transmission distance, it is desirable that the WSSs provide sufficient isolation such that the accumulation of interfering signal power does not significantly contribute to limiting the transmission distance. For formats such as 100G DP-QPSK, WSS isolation levels of 35 dB generally accomplish this goal. However, higher-order modulation, such as DP-16-quadrature amplitude modulation (QAM,) tolerates approximately around 7 dB less optical signal interference than DP-QPSK [7]. Thus, in the current architecture shown in Fig. 1, the isolation of the WSS must be increased by nominally 7 dB assuming a network of similar scale.

Constructing a high-port-count flexible-spectrum WSS with the above mentioned higher isolation in an acceptable form factor and with a practical cost is challenging. However, replacing the broadcasting power splitter with a WSS adds a second layer of isolation in preventing channel energy from going in unwanted directions. Thus, the isolation that each WSS device must individually provide can be reduced, while the total isolation, the combined isolation of both WSSs, can be increased. This very significant reduction in needed isolation per device enables realizing high-port-count flexible-spectrum WSS devices in a practical form factor and with a preferable cost point relative to an analogous single WSS with equivalently high isolation. Figure 2 illustrates this route-and-select architecture, which includes two WSSs per degree, reducing the needed isolation per WSS device. Additionally, as a WSS imparts around 4 dB less loss than a 1 × 8 power splitter, the total optical loss through the node can be reduced, requiring less compensating optical gain and consequently less optical noise. This loss advantage increases further when considering larger splitters.

The most cost-effective implementation of colorless and directionless demultiplexing relies on a combination of filterless power splitters and coherent receiver technology. The splitters provide multiple signals to several receivers, and each receiver isolates and recovers its desired channel. Limiting the number of channels reaching each receiver improves performance and reduces the cost, size, and power consumption of the requisite OAs needed to strengthen the channels prior to the power splitter. Replacing a broadcasting power splitter with a WSS provides the ability to limit the channels directed to each demultiplexer to only those channels intended to be detected by the receivers within each respective demultiplexer.

Critical to the route-and-select architecture is the ability to provide two independent WSSs per degree with minimal cost, size, and power dissipation. Today's WSSs leverage free-space optics, with a significant portion of the WSS cost being driven by mechanical design and packaging that ensure an environmentally stable and highly reliable product. An attractive approach is to integrate two WSSs within a single package, reusing much of the optical infrastructure to gain considerable space and cost savings. Components that integrate two independent 20-port WSSs, incorporate flexible spectrum, and meet the necessary isolation requirements to support advanced high-spectral-efficiency modulation formats such as DP-16-QAM are commercially available in the market today and are the cornerstones for next-generation ROADM network platforms.

COLORLESS, DIRECTIONLESS, AND FLEXIBLE SPECTRUM-COMPATIBLE MULTIPLEXING AND DEMULTIPLEXING

Supporting flexible spectrum, and colorless and directionless multiplexing and demultiplexing

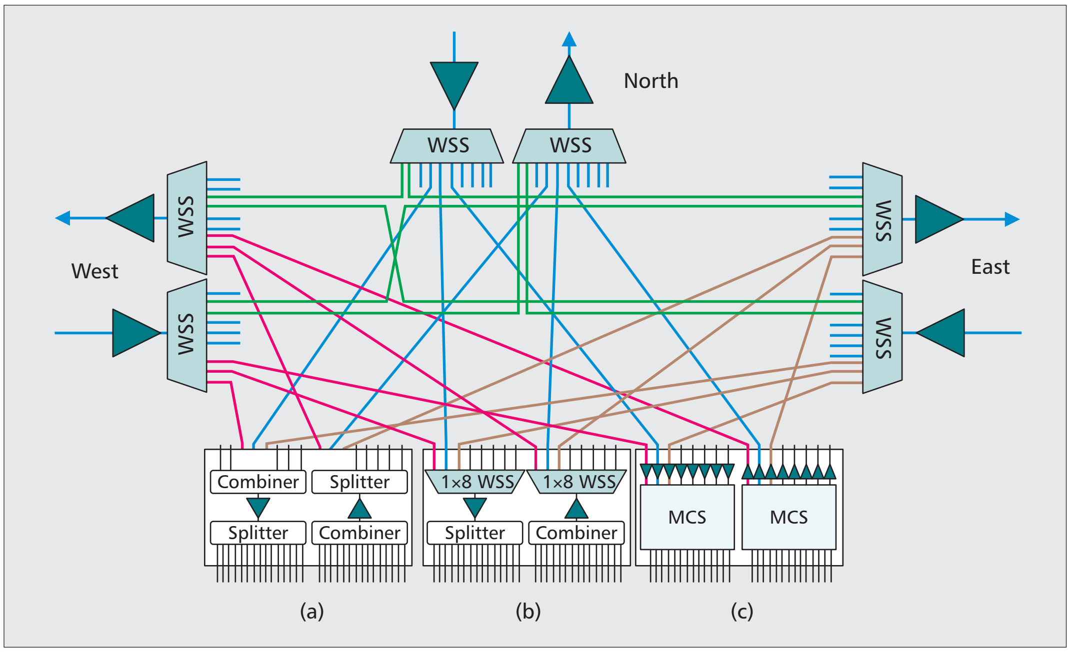

Figure 3. *Three-degree route-and-select ROADM node architecture illustrating three examples of colorless and directionless multiplexing and demultiplexing implementations: a) back-to-back power splitters and combiners; b) back-to-back WSS and power splitter/combiner; c) multicast switch.*

Two approaches to implementing these arrays are emerging. The first uses a single, independent, modest power pump per OA. The second uses a single, higher power pump followed by a 1:M variable ratio splitter tree to provide controllable pump power to each of the OAs.

requires new implementation approaches. For channel demultiplexing, leveraging the highly effective channel selecting capability of coherent detection lets simple, compact, and low-cost power splitters distribute multiple wavelength channels to a multitude of coherent receivers. Each receiver then selects the channel intended to be received. This approach, shown in Fig. 2, is very simple to implement, and provides a natural colorless and flexible spectrum functionality as no optical filtering is included.

To include the directionless functionality, there are three general approaches, each shown in Fig. 3. The first two options (Figs. 3a and 3b) rely on either a power splitter or WSS to combine the respective wavelengths coming from each degree to a single fiber. These wavelengths are then typically amplified with a small OA before being power split to a multitude of coherent receivers. The drawback of these two configurations is that only one channel of a given wavelength can be present, resulting in wavelength contention among the channels received within that module.

The third approach (Fig. 3c) removes this contention by using a multicasting switch (MCS). The MCS consists of an M-wide array of 1:N power splitters, the outputs of which are shuffled to the inputs of an N-wide array of M:1 selection switches. When used for the demultiplexing function, each switch allows only the channels originating from one degree to reach the respective coherent receiver, thereby preventing any interference between channels operating at the same wavelength and enabling multiple same-wavelength channels to be demultiplexed within the module. MCS devices supporting up to 8 degrees (M) and up to 16 receiver ports (N) are commercially available today and are generally based on planar-lightwave circuitry technologies. As the same device is used in the reverse direction for multiplexing, two independent $M \times N$ MCS devices are typically co-packaged for cost and space efficiencies.

A drawback to using power splitting is the significant insertion loss power splitters naturally possess. To ensure sufficient power levels at either the receiver (demultiplexing) or the node degree (multiplexing), amplification is necessary to offset these losses. For non-MCS approaches, a single optical amplifier can be used as all channels conveniently pass through a single fiber at a location appropriate for amplification. However, when using an MCS, a single fiber location is not present (as this would preclude the contentionless capability), and an array of amplifiers must be employed as shown in Figure 3c. Each OA need only amplify a finite number of channels, that is, those to be received within the respective module as limited by the upstream routing WSS. Therefore, the OA can be simpler in design and require less output signal and pump power than if all C-band channels were present. Furthermore, as the maximum number of channels present across the OA array inputs (M) is generally equal to the number of drop ports (N), the power output of the OAs can generally be partitioned according to how the channels are provisioned across the array.

Two approaches to implementing these arrays are emerging. The first uses a single, independent, modest power pump per OA. The second uses a single higher-power pump followed by a 1:M variable ratio splitter tree to provide controllable pump power to each of the OAs. This second approach has the potential to offer cost, size, and power dissipation savings over the multiple-pump approach, but requires a novel variable pump splitter element [8].

When using filterless power couplers as mul-

	DP-BPSK	DP-QPSK	DP-16-QAM
Capacity in 50 GHz channel	50 Gb/s	100 Gb/s	200 Gb/s
Approximate reach	9000 km	3000 km	600 km
Approximate local oscillator linewidth	MHz	~500 kHz	< 300 kHz
Isolation		Needed	+7 dB vs. QPSK

Table 1. *General comparison of the capacity, reach, required linewidth, and isolation for DP-BPSK, DP-QPSK and DP-16QAM assuming each is operated around 30 Gbaud [7, 10].*

tiplexers, it is critical that the optical signals from every transmitter be properly conditioned to confine their output signal power to its respective allocated channel bandwidth as any out-of-bandwidth power and noise can accumulate and directly interfere with other signals. This places two significant requirements on the output characteristics of the transmitters.

First, the spectral width of the modulated output signal must be limited to the spectral region in which it is assigned. This is particularly the case for superchannels where adjacent wavelength channels (or wavelength carriers) can be spectrally spaced by roughly their Giga-baud rate [5]. Without steps to limit the bandwidth, the spectral width of the modulated signal will generally exceed this bandwidth. A current approach is to precondition the electronic modulation drive signal by implementing a combination of digital filtering and digital-to-analog converters so as to restrict the higher-frequency components of the resulting modulated optical signal [9]. With this approach, tightly spaced optical carriers can be multiplexed with minimal interference using low-cost power couplers and without the added complexity, cost, and loss of a tunable optical channel filter.

Second, any side-mode or spontaneously emitted noise originating from the transmitter's tunable laser or amplifier must be minimized as all such noise will accumulate when passively combining multiple wavelength sources. The tolerable level of interference depends on the specifics of the network scale, the number of sources combined, and the modulation format; however, increasing the side-mode suppression ratio of tunable lasers toward 50 dB or better is an emerging trend.

FLEXIBLE MODULATION FORMAT TRANSPONDERS

As previously mentioned, the industry is encroaching on some fundamental limits with respect to the trade-off between the spectral efficiency and reach of a modulation format within a nominally designed transport system [4]. Therefore, there is rising interest in leveraging different formats to maximize spectral density based on the needed reach for a given link or network. Specifically, DP-binary phase shift keying (BPSK), DP-QPSK, and DP-16-QAM formats are of interest as all three formats can generally be generated and received using the same transmitter and coherent receiver hardware designs [9]. DP-16-QAM and DP-QPSK have four and two times more spectral efficiency than DP-BPSK, respectively, but consequently have significantly different approximate reaches, as shown in Table 1.

A flexible transponder requires an appropriately flexible, coherent pre- and post-processor with digital-to-analog converters to create the appropriate electrical modulator drive signal, a similar requirement as needed to spectrally limit the transmitted optical signal bandwidth. Thus, minimal alterations may be necessary within the coherent receiver other than ensuring an appropriate-line-width local oscillator, resulting in a single transponder that can be provisioned to any of the three formats, letting operators maximize the spectral efficiency of their networks. This can be done either during the initial provisioning process or dynamically as network traffic evolves.

FLEXIBLE SPECTRUM TUNABLE LASERS

Lasers that are tunable across the full C-band have become broadly adopted as they provide full coverage of all network channels using a single part, thus dramatically simplifying operations and sparing requirements. Within the standardized 50 GHz channel grid, these lasers need only tune to the channel centers that are well defined and precisely spaced with a 50 GHz periodicity. Tunable laser technology, more specifically the wavelocker design and calibration process, takes full advantage of this periodicity to simplify both hardware design and the calibration process.

However, within a flexible spectrum network, such well defined frequency locations for the signal wavelengths do not exist. Even with a 12.5 GHz periodicity standardization of flexible spectrum channel edges resulting in a 6.25 GHz periodicity of channel centers [3], the locations of wavelength carriers within multicarrier superchannels do not systematically align to any channel center, thus requiring tunable lasers configurable to virtually any frequency within the C-band.

This fine-tuning granularity is typically not a problem for the tuning control mechanisms of the laser itself, but it does complicate the wavelocking mechanism as well as the complexity of the calibration process. Tunable lasers designed for a 50 GHz tuning capability leverage wavelocker designs that provide a usable wavelength error feedback signal only within periodic regions around each 50 GHz channel center. However, between these regions, suitable feedback is not available. To provide practically continuous tunability, the wavelength locker assembly must be augmented to provide wavelength error feedback at essentially all C-band frequencies. This generally requires incorporating multiple wavelocker elements with complementary periodic areas of coverage such that suitable wavelength error feedback is always available from a minimum of one element.

OPTICAL CHANNEL MONITORING

In a flexible spectrum network, channels can start and stop at arbitrary wavelengths while possessing a variety of widths. Thus, optical channel monitors (OCMs) need to be able to measure optical power in finer spectral increments, probably 12.5 GHz in width, and across continuous channels of arbitrary widths. This means that the OCM hardware must be capable of scanning continuously across the C-band while making power measurements at provisionable intervals. This contrasts with the design of many of today's OCMs, with optical filters capturing all the power within a 50 GHz channel in a single measurement.

The key function of an OCM is to measure wavelength channel powers. This data serves as feedback information to power equalization algorithms that maintain channel power levels at an optimum level. In 50 GHz channel systems, each channel is controlled independently and with a single equalization amplitude parameter for each channel. However, in flexible spectrum networks, particularly when wide superchannels are employed, power imbalance can occur across a wide channel due to amplifier gain ripple, nonlinear processes, or non-flat device loss profiles. Therefore, the OCM must measure power across such channels with sufficient spectral and power resolution to detect spectrally dependent power imbalances. Such imbalances can then be equalized by implementing complementary intrachannel, spectrally dependent attenuation profiles within the flexible spectrum WSS.

Finally, the rate at which the OCM executes its measurements generally dictates the rate at which the power equalization algorithms can iterate and converge. These algorithms determine how quickly a new wavelength can be provisioned, get its power stabilized, and be put into service. Therefore, increasing the OCM measurement rate provides the valuable ability to more quickly turn up services and reroute existing wavelength channels within restoration or load balancing applications. Typically, commercially available OCMs generally operate with a scan interval of around 250 ms, enabling wavelength channel turn-up on the order of seconds to tens of seconds.

TRANSPORT SYSTEMS WITH IMPROVED OSNR

Continuing to increase spectral efficiency faces some fundamental challenges, as previously mentioned. One of the primary limitations on the reach of a given signal is the degradation of its optical signal-to-noise ratio (OSNR) as it propagates through the transport system. Therefore, optical transport networks that reduce the rate of this degradation could transport signals further while maintaining a similar OSNR, enabling the transmission of higher-spectral-efficiency formats. Leveraging counter-propagating Raman amplification to offset some of the transmission fiber loss in combination with conventional Erbium doped fiber amplifiers (EDFAs) is an attractive implementation as it can increase the OSNR of a signal by roughly 3–5 dB within a link depending on the fiber type, quality, and Raman pumping scheme employed.

To maximize OSNR and system performance, the Raman gain must be sufficiently spectrally flat, dictating a multiple-wavelength pump assembly with sufficient depolarization and sufficiently broad pump line widths to avoid degradation from stimulated Brillioun scattering. Transient suppression, already a critical performance requirement for conventional EDFAs, must also be incorporated into the Raman gain control algorithms as well.

SUMMARY

Evolving to next-generation ROADM networks requires new node architectures along with an advanced portfolio of optical components and devices designed to support the flexibility and efficiency enhancing features. A key part of the implementation is the route-and-select architecture, which drastically reduces the isolation required within each high-port-count WSS device. This reduced isolation requirement enables more practical and economical construction of integrated high-port-count WSSs critical to enabling scalable, colorless, and directionless multiplexing and demultiplexing, flexible spectrum, and greater overall isolation for more spectrally efficient modulation formats.

Implementing the contentionless, colorless, and directionless feature requires additional new devices such as MCSs and OA arrays as well as new transponder capabilities including spectrally shaped low-noise transmitters and channel filtering coherent receivers.

Implementing the contentionless, colorless, and directionless feature requires additional new devices such as MCSs and OA arrays as well as new transponder capabilities, including spectrally shaped low-noise transmitters and channel filtering coherent receivers. Finally, OCMs designed to monitor arbitrary width flexible spectrum channels, tunable lasers with fine granularity tuning, and Raman amplification technology to improve signal OSNR are needed to fully leverage the benefits of flexible spectrum and more spectrally efficient modulation formats.

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BIOGRAPHY

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