IEC TR 62343-6-4

Edition 1.0 2017-01

TECHNICAL REPORT

colour inside

Dynamic modules –
Part 6-4: Design guides – Reconfigurable optical add/drop multiplexer

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FOREWORD

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IEC TR 62343-6-4, which is a Technical Report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
86C/1400/DTR	86C/1420/RVC

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62343 series, published under the general title *Dynamic modules*, can be found on the IEC website.

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DYNAMIC MODULES –

Part 6-4: Design guides – Reconfigurable optical add/drop multiplexer

1 Scope

This part of IEC 62343, which is a Technical Report on reconfigurable optical add/drop multiplexers (ROADMs), provides a description of the ROADMs in dynamic optical networks and related optical component and module technologies, including wavelength selective switches (WSSs).

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.2 Abbreviated terms

AWG	arrayed waveguide grating
CDC	colourless, directionless and contentionless
demux	demultiplexer
DWDM	dense wavelength division multiplexing
DLP	digital light processor
EDFA	erbium doped fibre amplifier
IPLC	integrated planar lightwave circuit
LC	liquid crystal
LCD	liquid crystal device
LCOS	liquid crystal on silicon
LH	long haul
MEMS	micro-electromechanical systems
MPD	monitor photo-diode
mux	multiplexer
OA	optical amplifier
OEO	optical-electrical-optical
OCM	optical channel monitor

OADM	optical add drop multiplexer
PDL	polarization dependent loss
PLC	planar lightwave circuit
PMD	polarization mode dispersion
ROADM	reconfigurable optical add/drop multiplexer
TF	tuneable filter
TRx	transceiver
Rx	receiver
3R	regeneration, retiming and reshaping
Tx	transmitter
ULH	ultra long haul
VOA	variable optical attenuator
WSS	wavelength selective switch
WB	wavelength blocker
WDM	wavelength division multiplexing

4 Reconfigurable optical add/drop multiplexer

4.1 Background

Optical networks are evolving to address both the rapid growth in capacity demand and highly efficient and seamless connectivity requirements. While high data rate DWDM channels at 40 Gb/s and 100 Gb/s are being introduced in the network to grow the capacity to multiple Tb/s per fibre, the uncertainty in traffic demand and the emergence of bandwidth-hungry applications like video-on-demand have turned the industry's focus to dynamic, reconfigurable optical networks. Telecommunication carriers and content providers require switching nodes at their central offices in order to route, switch and monitor the optical wavelength channels as they traverse the optical network. These switching nodes, as shown in Figure 1, are called reconfigurable optical add/drop multiplexers (ROADMs), and they are the key nodal sub-systems used in implementing modern optical communication infrastructure.

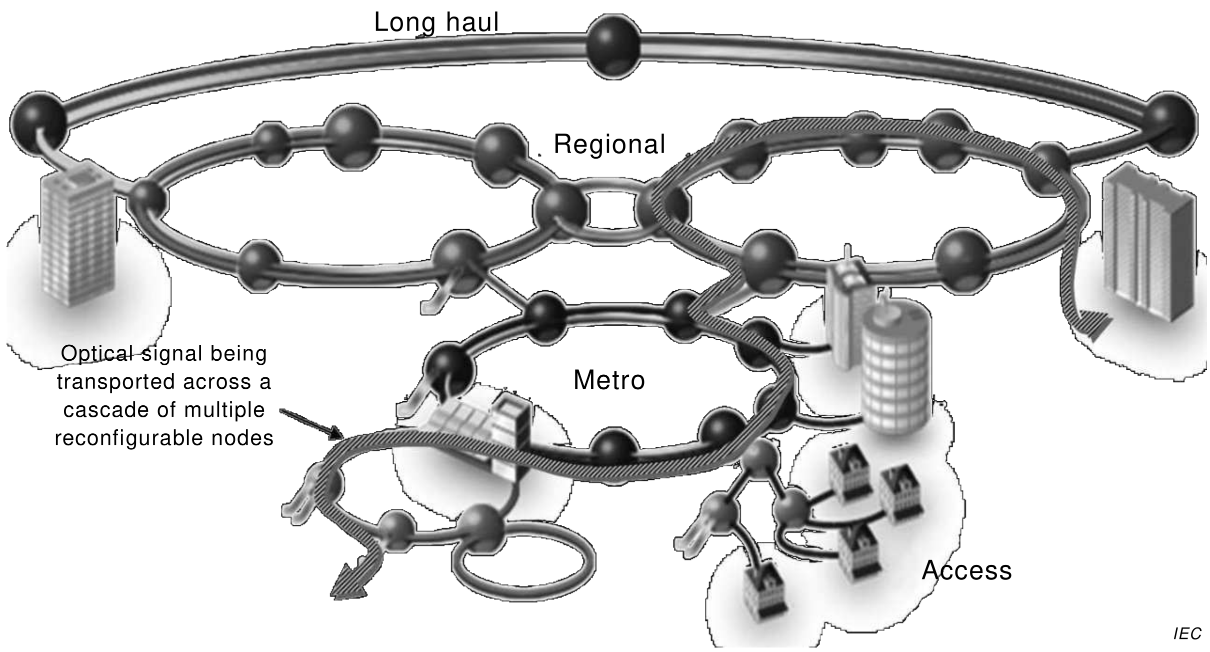


Figure 1 – Reconfigurable optical network

Different segments of the optical network, long haul (LH)/ultra long haul (ULH), regional, metro and access, are schematically shown in Figure 1. Generally, the long haul network is optimized for point-to-point traffic with a predictable traffic pattern. The regional and metro networks are characterized by having the bandwidth scalability of long haul with the service flexibility of the access network. In this segment of the network, the traffic pattern tends to be more dynamic and less predictable, requiring the network to have greater flexibility. While ROADMs were first introduced in the LH/ULH part of the network, it is the metro and regional segment where they offer the highest value proposition.

In addition to ease of service provisioning and network reconfigurability, optically routed networks reduce the need for unnecessary processing of through-traffic by eliminating the signal conversion from the optical to the electronic domain and back to the optical domain for retransmission, thereby significantly reducing cost. Elimination of signal conversion to the electronic domain makes ROADM nodes transparent to traffic data rate and modulation format, enabling easy network capacity upgrade without impacting the live traffic, a key requirement of service providers. They also include the important function of signal monitoring and power balancing. For dynamic optical networks, it is increasingly important to co-optimize different networking aspects, such as optical layer flexibility and signal impairments.

4.2 Optical network evolution

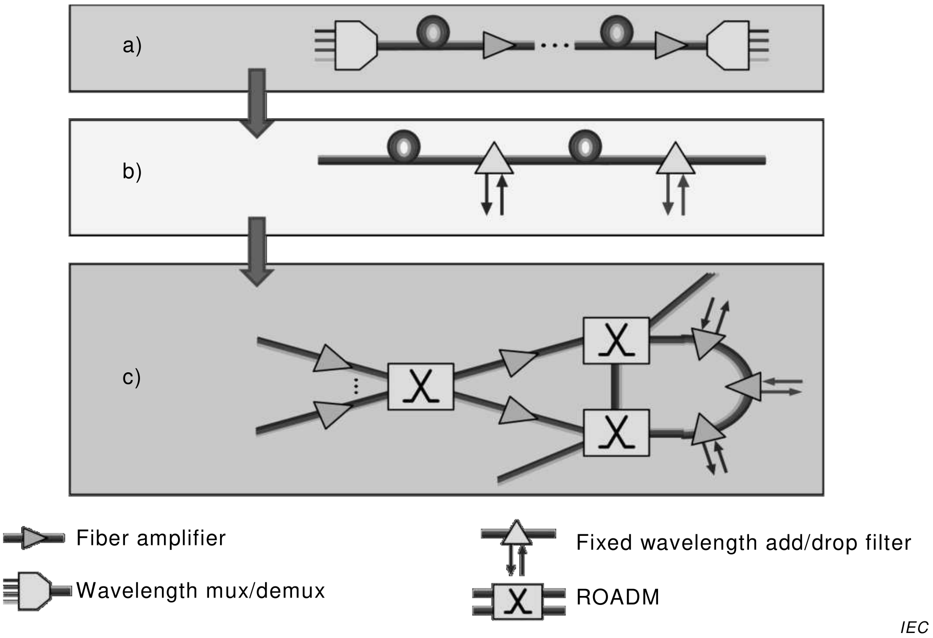
Evolution of wavelength division multiplexing (WDM) transmission networks is illustrated in Figure 2. Networks have evolved from transmission systems consisting of point-to-point WDM links to modern dynamic and reconfigurable networks. As illustrated in part (a) of Figure 2, the earliest WDM systems included point-to-point high capacity links interconnecting terminal equipment. Transmission links consisted of periodic fibre spans and optical amplifiers for compensating link loss. All wavelengths entering the node are terminated via optical-electrical-optical (O-E-O) conversion at the network nodal points, where the optical channels are demultiplexed via an arrayed waveguide grating (AWG) element, for example, and each wavelength is directed to a receiver of a separate transponder that converts the DWDM signals to the electrical domain, and then to a client optical signal at 1 310 nm for short reach interconnect. Similarly, the egress traffic from the node is sent on a fibre link and is originated from multiplexed DWDM wavelengths from transponders connected to 1 310 nm client short reach interfaces.

The node is equipped to handle two types of traffic:

a) express traffic, which after passing through the node is directed to its final destination via another WDM link intersecting the node;
b) add/drop traffic, which is either terminated at the node or originates from the node.

As mentioned earlier, all traffic through the node is mediated via 1 310 nm links, and the express and add/drop wavelength channels are predetermined by hard-wired connections. The benefits of this architecture include full 3R (regeneration, retiming and reshaping) regeneration and wavelength conversion of all the optical signals leading to pristine signals from the node, multi-vendor equipment interoperability via a commonly used 1 310 nm client interface, and signal quality monitoring in the electrical domain, for example via overhead bytes.

The main drawback of this architecture is that any reconfiguration of the node will require manual intervention by changing the patch cords. In addition, the architecture is not scalable, since the transponders are data rate specific. The network cannot therefore be upgraded to handle higher data rate traffic without replacing all the transponders. The rapid and unpredictable growth of network traffic from today’s internet requires the network to be dynamic and flexible in supporting new growth areas.



Key

a) point-to-point transport network

b) fixed wavelength add/drop filter based network

c) ROADM networks

Figure 2 – Evolution of optical networks from point-to-point to reconfigurable WDM

In order to increase network flexibility for growing traffic demand in the networks, optical add drop multiplexers (OADMs) were introduced. The initial OADMs that were commercially available in the mid-1990s were not configurable and were achieved via fixed filters. As shown in part (b) of Figure 2, these provided fixed WDM connectivity between multiple nodes. The introduction of fixed OADMs helped reduce the cost of the network by eliminating the need of OEO conversion for the express optical channels. However, the network designer needed to predetermine which wavelengths would be dropped at a node, since the OADM would remain fixed in this configuration. This posed a severe limitation because the service providers could not adapt to unpredictable deviations to network capacity demand. Moreover, provisioning of new channels created the additional complication of adequately balancing the power of all the WDM channels without affecting service on the live channels, through optical amplifier transients, for example. This led to cumbersome controlled and manual turning up of channels, negating the benefits derived from the elimination of transponders at the nodes.

Subsequent availability of fully configurable OADMs (part (c) of Figure 2) enabled network operators to configure any wavelength as transiting or add/drop, without affecting any of the existing traffic on the OADM. OADMs with this flexibility and configurability were termed reconfigurable-OADMs (ROADMs).

The functionality of a ROADM node is illustrated in Figure 3, which shows a two-degree node consisting of a pair of input and output fibres entering a network node, for example east to west. Usually, there is another pair of fibres (not shown in the figure) carrying traffic the other direction (west to east). The wavelength channels entering the node from the east side are shown to have different power levels. The channels are dispersed by the first module and selectively routed either to the express path to continue further or to the local drop ports. The module also includes variable optical attenuators that adjust the power of the channels in conjunction with an optical power monitor shown in the second module. The express channels out of the first module and the locally added channels are combined by the second module. Optical attenuators in the add path are used to adjust the power of these channel so that all the channels egressing from the node have equal power. The ROADM node is thus able to accomplish selective routing of the wavelength channels to the express path, carry out the wavelength drop and add function, and finally monitor and balance the power of optical channels sent on the output fibre.

The above example as shown in Figure 3 refers to a two-degree node. ROADMs enable wavelength routing in higher degree nodes consisting of fibre connections in other directions. A four-degree node, for example, will have fibres connecting east, west, north and south directions. ROADMs can interconnect wavelengths coming from different directions in the optical domain. This enables mesh networking at the optical node, which can be managed cost effectively and is agnostic to data rate and modulation format. ROADMs are a key enabler of the modern 100 Gbit/s and 400 Gbit/s coherent transport networks, which use different modulation formats such as QPSK and 16QAM.

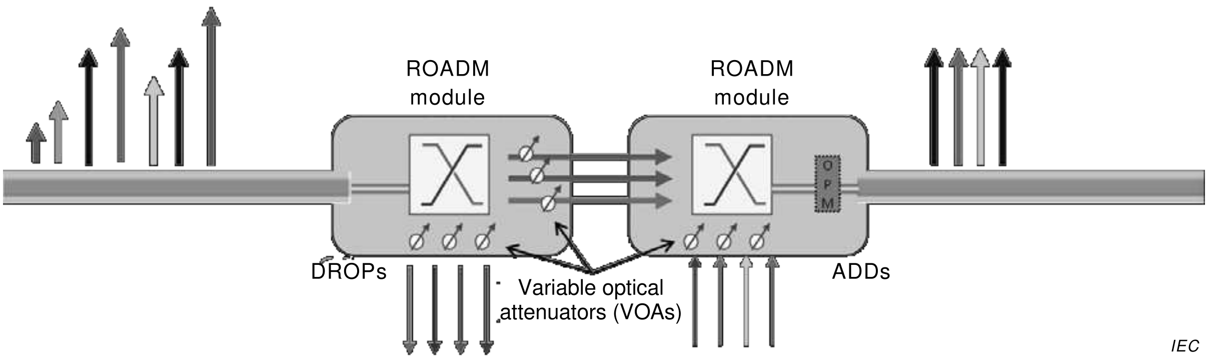


Figure 3 – Schematic of a ROADM node showing functions of wavelength pass-through add or drop, channel power equalization, and optical channel monitoring (OCM)

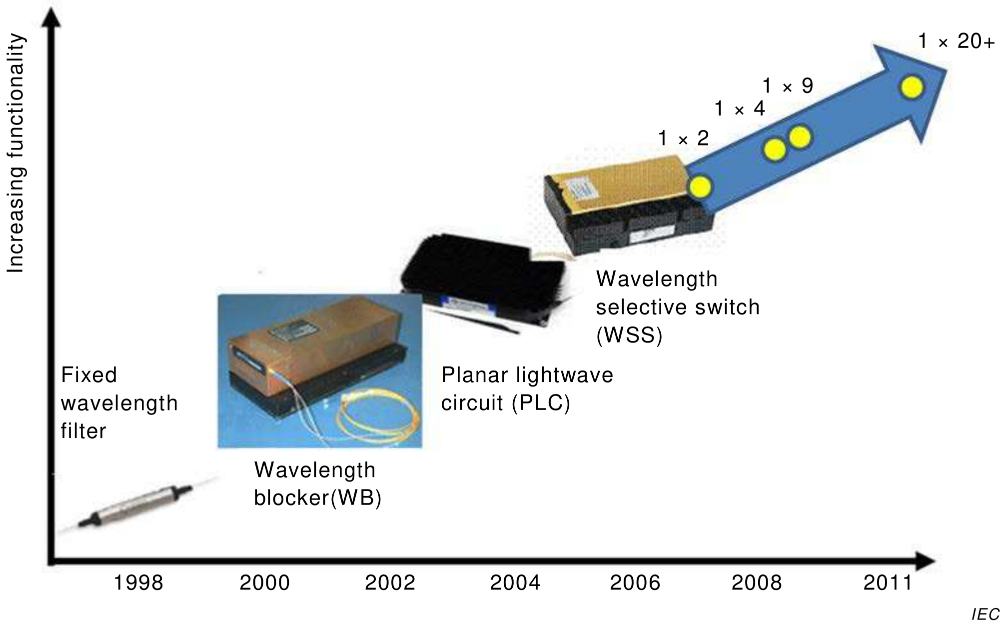
ROADM networks are architected with the goal of having a dynamic photonic layer capable of rapid wavelength routing. ROADMs have been widely deployed in intercity and metro core networks in the last decade. Optical bypass and remote configurability in ROADM networks led to fewer router interfaces and reduction in manual fibre patching, thereby lowering the overall cost per bit compared to static networks. When a new wavelength connection is needed in a static network, the transponders and regenerators are individually wired into the network manually via a laborious process. Some of the barriers and limitations to ROADM introduction in the network include the inflexible introduction of interconnections on the client side between the transponders and subtending electronic equipment such as the routers and switches. Another barrier has been the network control software, which is designed without the concept of a dynamic wavelength and can be very difficult to change and update. The third major barrier is related to the business model for ROADM based networks: at present, monetizing these dynamic networks to pay for the additional cost remains a challenge.

Deployment of ROADMs has increased rapidly in recent years. Essentially all new metro, regional and long haul WDM systems developed by equipment manufacturers and new deployments offer ROADM-based wavelength agility as a key feature. The deployments planned by Tier-1 carriers globally require reconfigurable wavelength agility to reduce operational expenses and increase service flexibility. In order to avoid failures due to signal degradation, the optical amplifiers (OAs) for these networks need to be “agile” by incorporating fast gain control and ability to adjust the OA operating conditions quickly in response to changes in the network and number of wavelength channels. It was noted in an industry report that deployment of ROADMs and agile EDFAs is correlated and has enabled the transition from fixed to dynamic optical networks. Since 2010, ROADM and EDFA module deployments were predominantly (over 85 %) dynamic and agile, and only a small number (~15 %) had fixed characteristics.

4.3 ROADM subsystem technologies evolution

4.3.1 General

The evolution of ROADM component technologies is depicted in Figure 4. As shown, ROADMs have progressed several technology generations: starting from simple filters in the 1990s to wavelength blockers (WBs) and planar lightwave circuits (PLC) based devices in the early 2000s to the current wavelength selective switches (WSS). The number of ports in wavelength selective switch based ROADMs has increased from 1 x 2 to 1 x 9 to 1 x 20. The ROADM subsystem technologies are described below.



Source: Brandon Collings, OFC 2011

Figure 4 – Evolution of ROADM technologies

4.3.2 Wavelength blocker based ROADMs

The era of ROADM began with wavelength blocker based ROADMs as shown in Figure 5. These are capable of blocking individual wavelengths and passing the rest. This is very convenient for 2-degree ROADMs. The add/drop function is passive, and there are no cascaded AWGs in the express path. This improved cascadability because of broader passbands. Moreover, built-in attenuation provided additional functionality, which is very useful in equalizing the channel powers. A 2-degree ROADM is shown in Figure 6.

However, these devices still have coloured and directional add/drop fibres. Wavelength blockers are two-port devices with one input port and one output port. The multi-wavelength signal entering the input port is demultiplexed by a diffraction grating, and each wavelength can be independently attenuated by using a MEMS or LC elements. The wavelength channels can be suitably blocked by attenuation to greater than 30 dB.

These were the first devices to enable ROADMs in 2000. Control of wavelength channel power and support of broadcast and select architecture made them very successful.

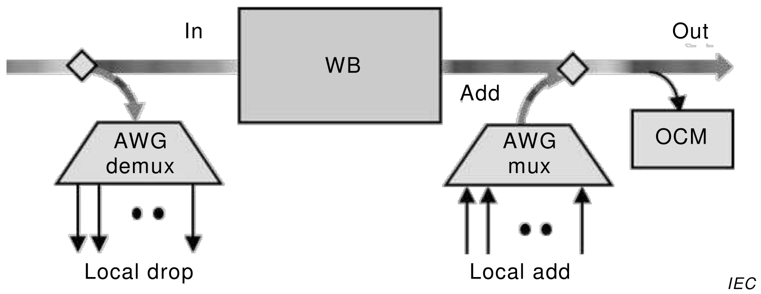


Figure 5 – Wavelength blocker based ROADM architecture

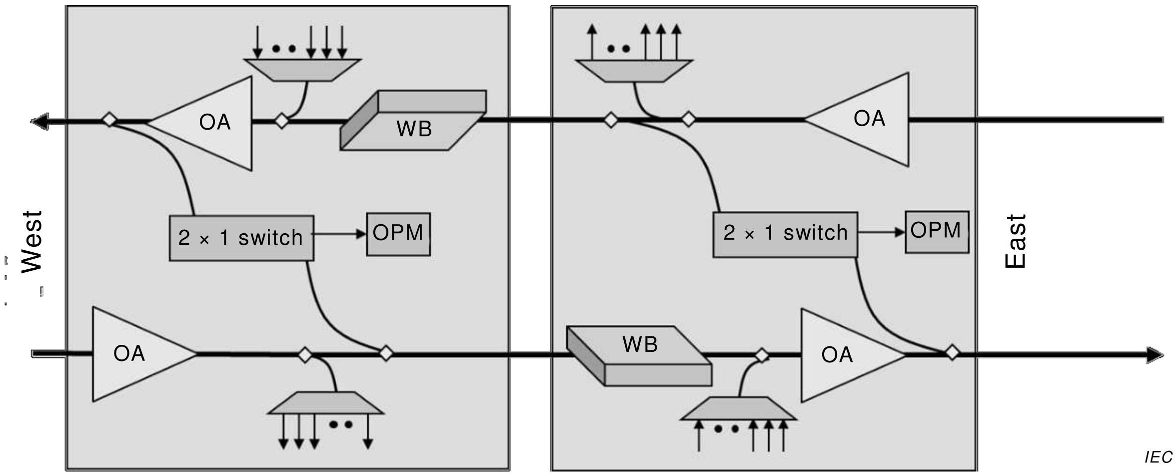


Figure 6 – 2-degree ROADM node architecture with wavelength blocker, dynamic OAs and shared OCMs

4.3.3 Integrated planar lightwave circuits (IPLC) based ROADMs

A very popular early design for ROADMs is based on planar lightwave circuits (PLC) technology. In this approach, an array of PLC based 2 x 2 switches is nested between a demultiplexer and multiplexer (Figure 7) to provide optical bypass functionality based on arrayed waveguide gratings. In AWGs, the multiplexing and demultiplexing of WDM channels (shown as 1 to *n*) is done in waveguides integrated onto a single substrate, so fewer fibre connections are needed. As technology advanced, so did the level of integration, with some component vendors eventually integrating all the key functions required into a single substrate using PLC technology.

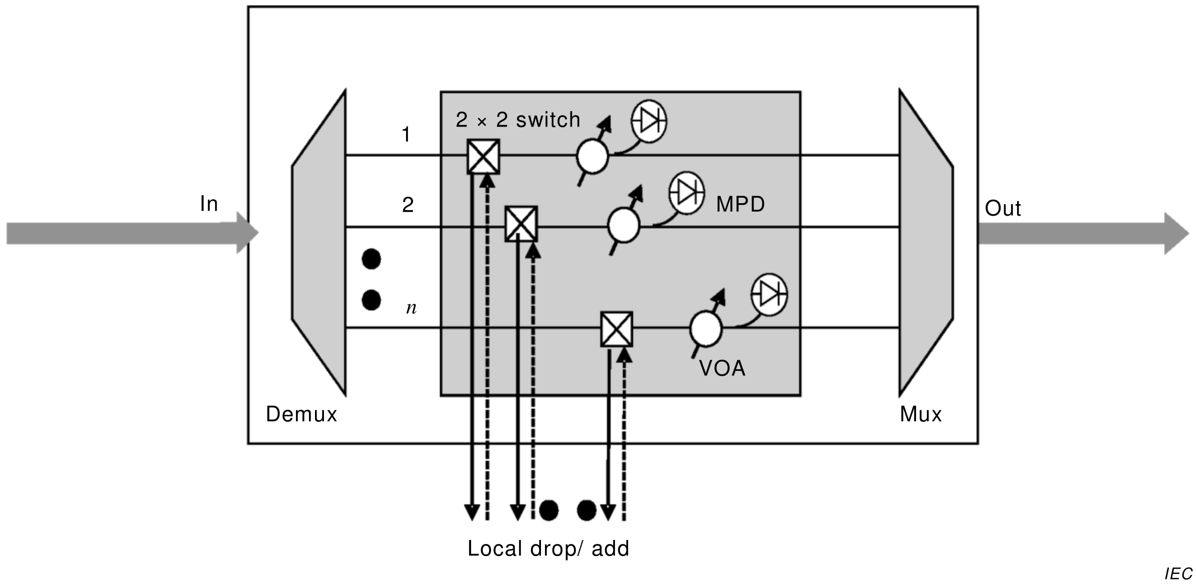


Figure 7 – PLC based ROADM architecture

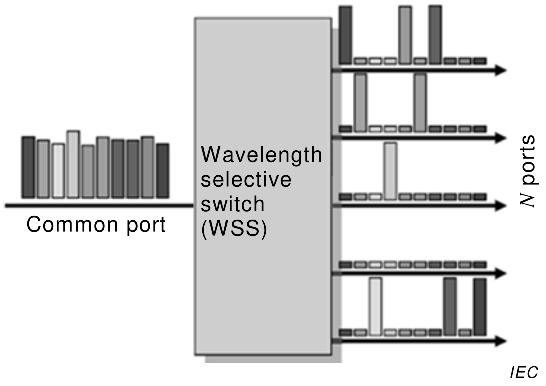
The main limitation of this design is that it supports only two fibre route directions or pairs. Moreover, because of the large number of parallel optical paths inside the device, multi-path interference occurs. Because of the passband characteristics of the AWGs, cascading can cause significant bandwidth narrowing. Finally, the add/drop fibres are predefined to be a specific wavelength channel and a specific direction (coloured and directional). Despite these limitations, these early ROADMs achieved success and were deployed in smaller metro rings.

4.3.4 Wavelength selective switches

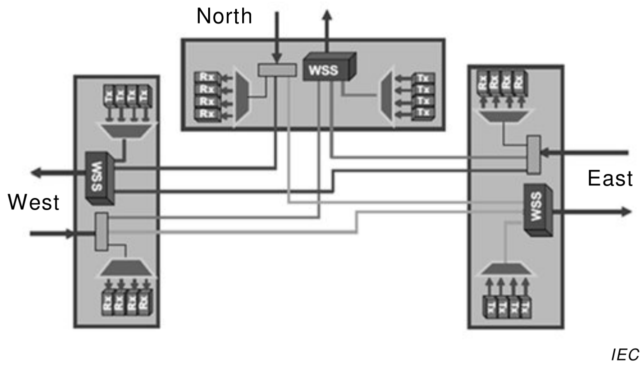
State of the art technology for ROADMs is a wavelength selective switch (WSS). The function of a 1 x N WSS is shown schematically in Figure 8 (a). The device consists of a dispersive element that internally separates the WDM channels arriving at the common port of the WSS and, by using switching elements, routes each individual channel to one of the N selected output fibre ports. Thus, the WSS can be used to route the incoming wavelengths selectively to any of the N ports. In addition, there are variable optical attenuators included in the path of individual wavelengths inside the WSS module, which can provide a power equalization function. Likewise, an N x 1 WSS device can selectively route individual wavelengths from multiple DWDM input fibres and route these to a common output fibre. Usually with software control, the WSS can dynamically select individual wavelengths from multiple DWDM input fibres and switch these to a common output fibre, or vice versa. As mentioned earlier, the WSS can also equalize the optical power of individual wavelengths exiting the output fibre(s) to improve transmission performance. The WSS can be implemented using a variety of different technologies, including liquid crystal devices (LCD) and micro-electromechanical systems (MEMS). These are described in Annex A.

Architecture of a WSS based ROADM with 3 degrees is depicted in Figure 8 (b). The node is designed to route the WDM signals arriving from any of the three directions to either of the local drop ports or to one of the remaining directions. For example, a WDM signal arriving at the node from the west can be either selectively directed to the local drop port or expressed to the north or west fibre ports. This functionality is achieved by splitting the arriving signals by a 1 x 3 passive coupler. Two of the three replicas of the signal are directed to the respective WSSs for routing signals to the north or west directions, and one is connected to AWG for local drop. The AWG demultiplexes all the arriving channels to their respective ports. The drop ports have plugged in receiver modules (Rx) for the signals designated to be dropped at the port. This is known as broadcast and select architecture. The wavelength of the signal at the drop port is predetermined by the AWG port, and is therefore “coloured”. Moreover, specific drop ports can receive WDM signals from only one direction and hence are “directional”. Likewise, transmitters (Tx) are added on the add ports to add new wavelengths.

The transmitter ports are similarly fixed in wavelength by the AWG port and can transmit only in a specific direction. This ROADM architecture is coloured and directional. The architecture of colourless and directionless ROADM is described in 4.4.3.



a) 1 x *N* wavelength selective switch functionality



b) Architecture of a WSS 3-degree ROADM node

Figure 8 – ROADM architecture incorporating a WSS

In addition to wavelength routing and switching and channel power equalization, WSS ROADMs also provide service channel management and provisioning, protection and restoration functions.

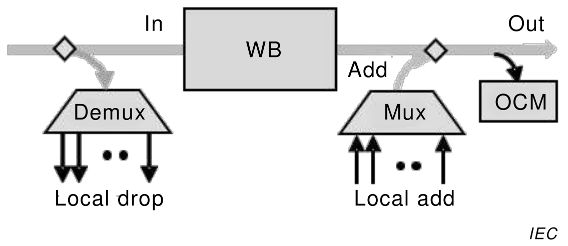
4.4 ROADM architecture

4.4.1 Broadcast and select architecture

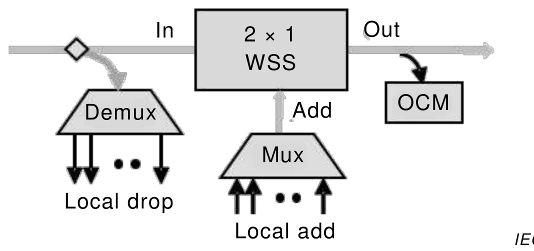
As discussed earlier, the ROADM enables a flexible transport node, which typically consists of optical amplifiers, optical switching elements, a multiplexer or demultiplexer element such as AWG or WSS, and transponder line cards such as for 10 G Ethernet. The mux/demux provides the connection point between the composite WDM layer and the individual channels or wavelengths, which are implemented with transponder and muxponder units. One of the early architectures employed in ROADMs consists of a broadcast and select approach, where a copy of all WDM channels entering the WDM node is split by a passive coupler and directed to AWG, which demultiplexes the channels. The selected channels are received at the node by attaching receivers. Examples of the broadcast and select approach architecture using different devices (WB, 2 x 1 WSS, *N* x 1 WSS and PLC) are shown in Figure 9.

ROADM node architecture based on WB is shown in Figure 9 a). A fibre carrying multichannel DWDM signals enters the node, and the optical power is immediately split to provide paths for wavelengths that transit through the node and dropped wavelengths that get routed to a demultiplexer. The through traffic enters a WB, which has only one input port and one output port, so there is no switching function. Under remote control, it either passes through, equalizes, or blocks (extinguishes) either some or all wavelengths. New wavelengths are added by passive combination after the WB. The WB blocks any wavelengths identical to the added wavelengths in order to avoid duplication of wavelengths carrying traffic. Discrete variable optical attenuators (VOAs) are used to equalize the optical power of the added wavelengths, and an optical channel monitor (OCM) provides feedback for the optical power equalization controls of the WSS and VOAs.

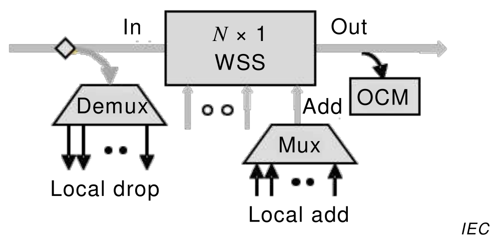
Figure 9 b) shows a variation on this architecture where the locally added wavelengths are still combined at a multiplexer but are now directed to the add port of a 2 x 1 WSS. The WSS selects specific wavelengths from either the in or add port and routes these to the out port for transmission to the next network node. The WSS in this architecture also equalizes the optical power of the added wavelengths, eliminating the need for discrete VOAs. Both architectures of Figure 9 a) and b) are termed "coloured", because the dropped and added wavelengths are associated with specific or fixed ports on the demultiplexers. The main advantage of these ROADM architectures is that the multiple wavelengths passing through the node are routed and equalized in an automated fashion. Figure 9 c) shows a two-degree ROADM configuration that eliminates the fixed physical associations for the dropped and added wavelengths with the demux and mux ports. The industry calls this feature "colourless", because any colour or wavelength can be directed to any drop port and from any add port.



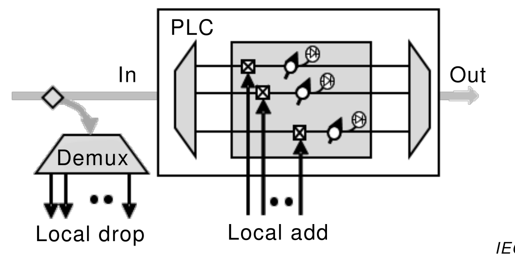
a) With wavelength blocker



b) With 2 x 1 WSS for 2-degree node



c) With N x 1 WSS for > 2-degree node



d) With PLC device

Key

a) with wavelength blocker

b) with 2 x 1 WSS for 2-degree node

c) with N x 1 WSS for > 2-degree node

d) with PLC device

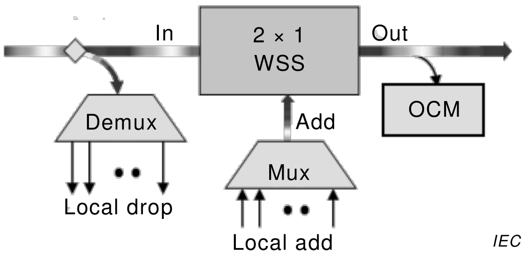
Figure 9 – Broadcast and select architecture of ROADMs

There are two general types of ROADMs: two-degree and multi-degree. As illustrated in Figure 10, the degree refers to the number of directions of data traffic supported by the ROADM node. In any direction, a pair of fibres is generally used, with each pair carrying traffic in alternate directions. There are twice as many fibres entering and exiting the ROADM as its degree. For example, a two-degree ROADM (Figure 10 a) and b)) is like a location on a highway with off and on ramps to drop off and accept local traffic.

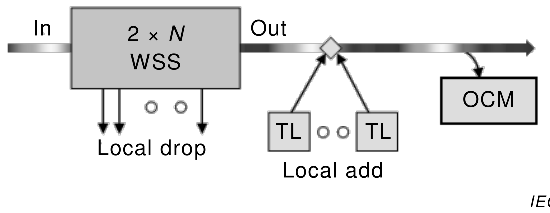
Its functions are to

– terminate an incoming DWDM fibre,
– drop specified wavelengths and, in most cases, block these wavelengths from propagating further,
– add local wavelengths,
– equalize the combined traffic of passed-through wavelengths and added wavelengths, and
– provide egress for this traffic towards the next ROADM node.

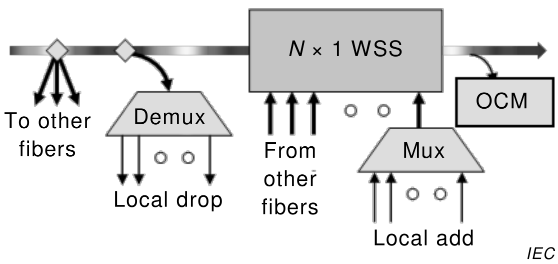
A multi-degree ROADM is like an interchange where highways meet and is used for interconnecting DWDM rings or for mesh networking. Its functions are to accept and rearrange wavelengths from the multiple fibres entering and leaving the multi-degree node, as well as adding and dropping local wavelength traffic.



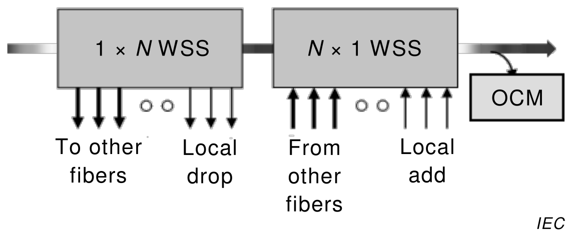
a) Two-degree, fixed add/drop



b) Two-degree, colourless add/drop



c) Multi-degree, fixed add/drop



d) Multi-degree, colourless add/drop

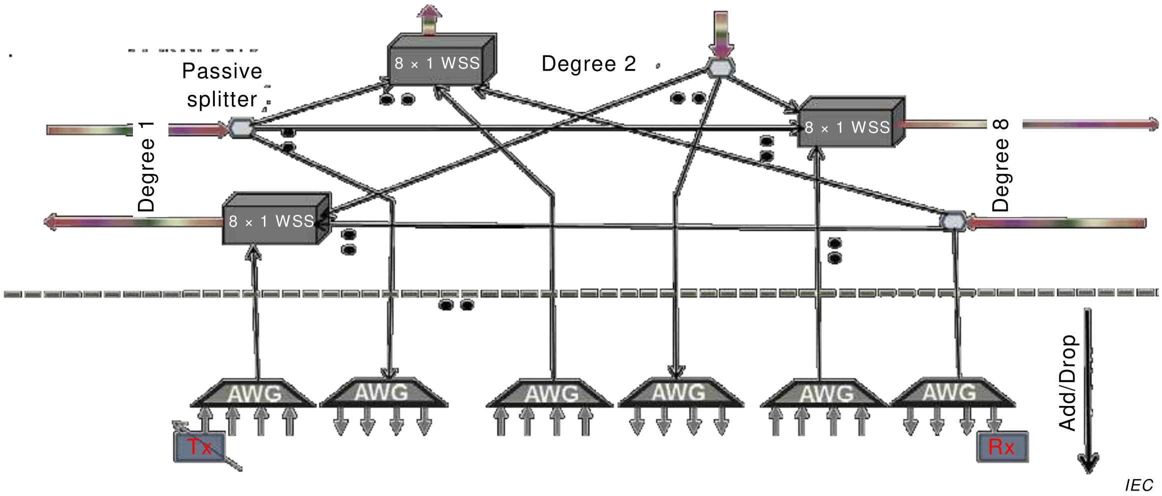
Key

a) two-degree, fixed add/drop
b) two-degree, colourless add/drop
c) multi-degree, fixed add/drop
d) multi-degree, colourless add/drop

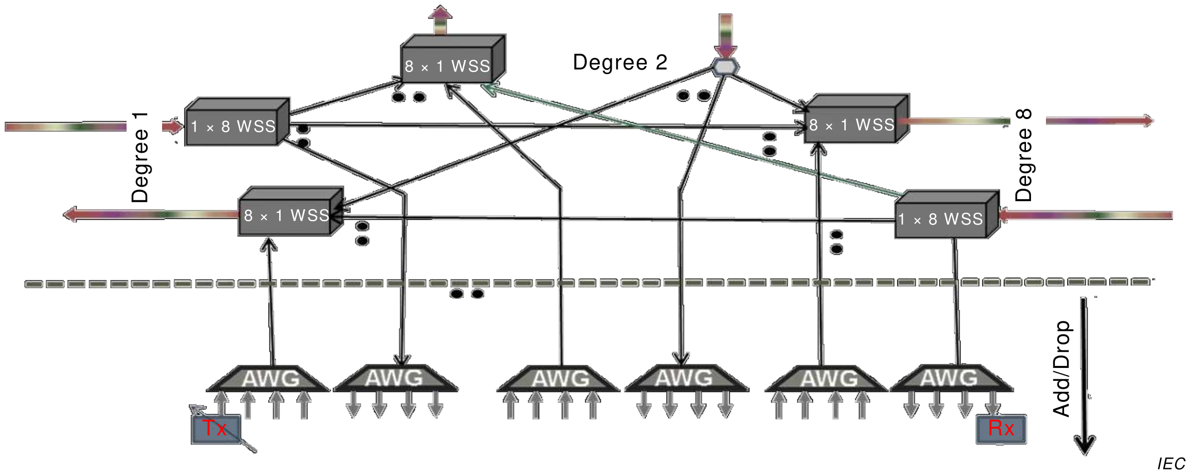
Figure 10 – ROADM architectures

4.4.2 Route and select architecture

Broadcast and select architecture described in 4.4.1 is suitable for ROADMs of smaller degrees. As the number of degrees increases, the loss of the passive coupler becomes very large and unsustainable. In large degree nodes, the passive couplers are replaced by a WSS to form a route and select architecture. This is schematically illustrated in Figure 11 (a) and Figure 11 (b). In this architecture, the passive splitter is replaced by a lower insertion loss WSS, and only selected WDM channels are directed to the drop port. With the availability of large port count WSS, route and select architecture is widely employed.



a) Broadcast and select



b) Route and select

Figure 11 – ROADM route and select architectures

4.4.3 Colourless, directionless and contentionless (CDC) functionality

4.4.3.1 General

ROADM subsystems enable an operator to configure the express and drop ports remotely to suitably direct any incoming wavelength channel. ROADMs at the network nodes are used to switch and route DWDM traffic in the optical domain without conversion to the electrical domain. As the nodes in the network evolve to higher degrees (> 2), network service providers are requiring ROADMs to CDC capabilities in order to provide full dynamic mesh networking as well as restoration and protection switching. Here are their characteristics:

– Colourless

  an add/drop port's wavelength can be provisioned

– Directionless

  an added/dropped channel can be provisioned to/from any network direction

– Contentionless

  multiple channels of the same wavelength are allowed within the same module

In addition to CDC features, these ROADMs are also expected to provide flexible bandwidth capability in order to support the larger bandwidth requirement of future 400 Gb/s and 1 Tb/s channels. This poses an additional challenge for the wavelength selective switches (WSS) constituting the ROADMs.

ROADMs can be broadly classified in the following generations:

– Past

  1st generation ROADMs introduced re-configurability in add/drop channels. However, these nodes were restricted to two directions.

– Present

  2nd generation ROADMs introduced the following features multi-degree capability, for example 4 or 8 directions per node. However, these nodes are "coloured" and "directional".

– Future

  3rd generation ROADMs will introduce more "mesh" features:

  - significant flexibility in provisioning and restoration;
  - colourless, directionless, contentionless and "gridless" (flexible spectrum).

Wavelength selective switches (WSS) with 1 x 9 and 9 x 1 functionality are key components of ROADM nodes today. However, to realize the next generation ROADM node shown in Figure 12 that supports colourless, directionless and contentionless capabilities, two new types of WSS will be needed: an 8 x 8 WSS and a 24 x 1 or 1 x 24 WSS. The 8 x 8 WSS is still some years away from implementation, and there are other less elegant ways to realize its functionality in the interim. On the other hand, the high port count 1 x 24 WSS can immediately fulfil demand for massive colourless local add/drop capability (shown in Figure 12), as well as support large multi-degree nodes and stacked ring interconnection.

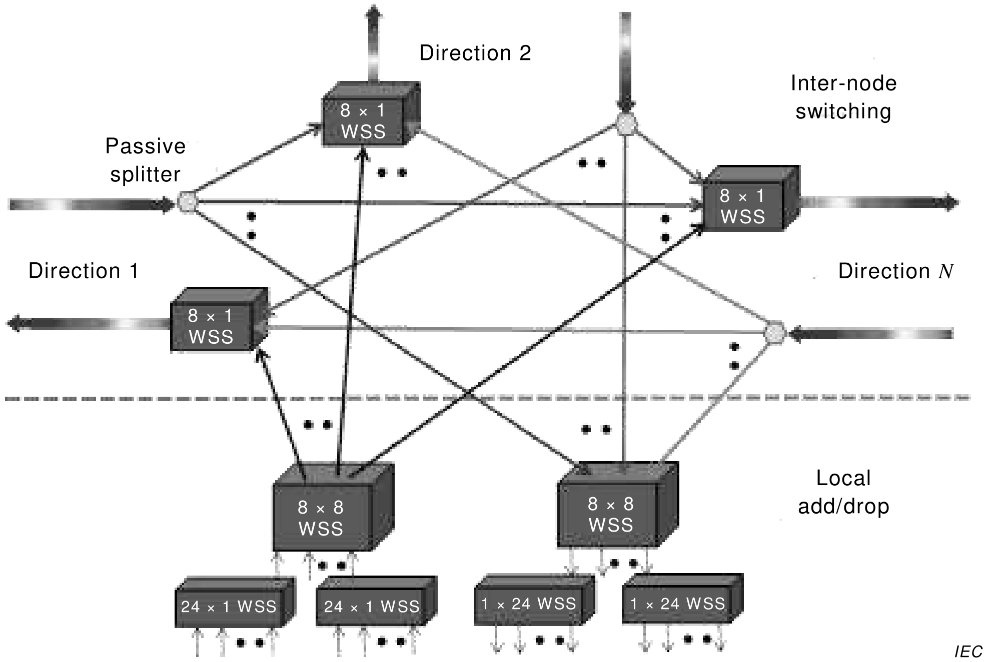


Figure 12 – 8 x 8 WSS and large port count 1 x 24 WSS based colourless, directionless and contentionless ROADM architecture

Two important directions for future WSS devices for supporting full mesh functionality are becoming evident. These include large port count 1 x N (N > 20) WSS and M x N WSS devices with M = 4, M = 8, N = 8 and N = 24.

Moreover, ROADM architecture will be simplified by the introduction of coherent detection, which automatically includes the wavelength channel selection function. This will obviate the need for wavelength selective filtering at the drop ports, making the architecture simpler and cheaper.

ROADMs have evolved from coloured and directional ROADMs to having full CDC functionality, as shown in Figure 13.

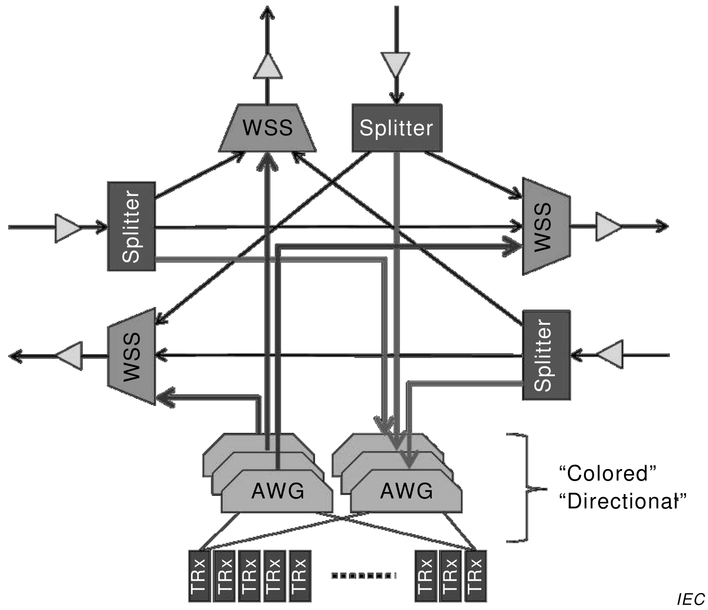


Figure 13 – Coloured and directional ROADM architecture including WSS, splitters, AWGs and transceivers (TRx)

4.4.3.2 Colourless and directional

Transponders are permanently connected to an add/drop port but can be remotely tuned to any wavelength. However, they can only carry traffic in one predetermined direction, and that cannot be changed remotely without onsite intervention. A typical current multi-degree node uses broadcast and select architecture consisting of 1 x N WSSs, 1 x M splitters and AWGs. This node is coloured and directional. This is because the wavelength channels of the AWGs are fixed on each port.

4.4.3.3 Colourless and directionless

Transponders are permanently connected to an add/drop port but can be remotely tuned to any wavelength and any direction. However, only one wavelength per add/drop tree can be used at a time, leading to wavelength blocking (also referred to as wavelength contention).

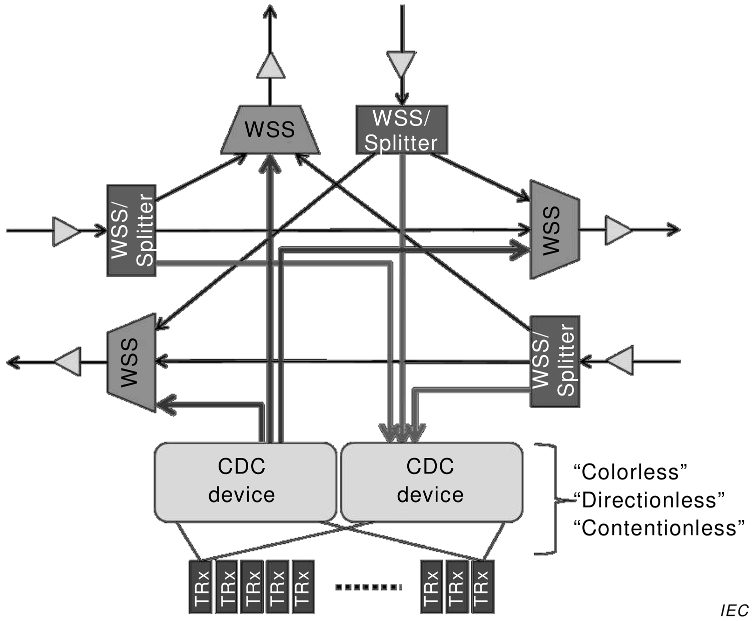


Figure 14 – Colourless, directionless and contentionless ROADM architecture

4.4.3.4 Colourless, directionless and contentionless

The next generation multi-degree node, depicted in Figure 14, requires a CDC device that can connect any wavelength channel in any direction without wavelength contention, and there are technologies available to realize CDC devices for these networks. Transponders permanently connected to an add/drop port can be remotely tuned to any wavelength and pass any direction. Up to N wavelengths can be repeated per add/drop tree, eliminating wavelength contention.

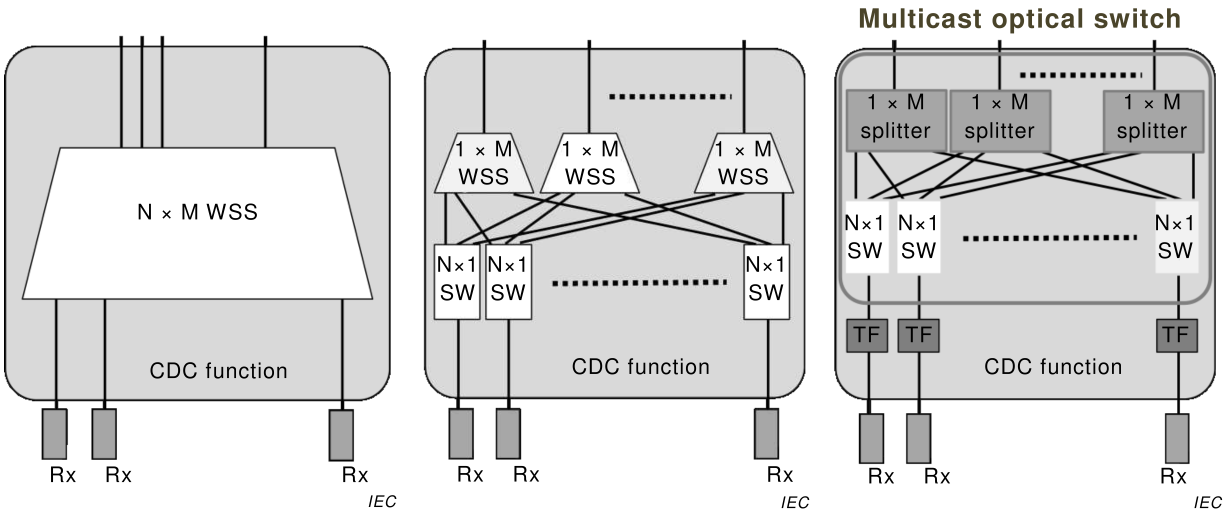
There are three potential technologies for CDC devices being discussed now:

– N x M WSS is still a challenging technology to realize and use;

– combination of 1 x M WSSs and N x 1 switches is possible, but cost will be high;

– combination of 1 x M splitters, N x 1 switches and tuneable filters is competitive in terms of balance of performance and cost.

These are shown in Figure 15. A multicast optical switch is the part including 1 x M splitters and N x 1 switches. Introduction of coherent detection will be expected for multicast optical switch architecture to be simple, because it automatically includes the wavelength channel selection function.



e) With N x M WSS

f) With a combination of 1 x M WSS and N x 1 switch

g) Multicast optical switch consisting of 1 x M splitter and N x 1 switches combined with tuneable filters (TFs) for channel selection

Figure 15 – Technologies for contentionless architecture

4.4.3.5 Flexible grid ROADMs

The introduction of higher data-rate channels at 400 Gb/s and 1 Tb/s in the future will require reconsideration of the wavelength grid. The 50-GHz ITU-T grid is adequate to support the currently prevalent channels at bit rates of 10 Gb/s, 40 Gb/s and 100 Gb/s. The transmission bandwidth requirement for each WDM channel fits well within the available 50-GHz bandwidth for each channel centred on the ITU grid. In the case of future 400-Gb/s and 1-Tb/s channels, the bandwidth requirements (a) will be higher than 50 GHz and (b) may not be a multiple of 50 GHz. For example, a 400-G channel might need 80 GHz of bandwidth, which in the current grid will need two contiguous channels of 50 GHz each (total 100 GHz). This will result in significant waste, thereby lowering spectral efficiency. Smaller granularity on the ITU-T grid, for example with 12,5 GHz channel separation, will reduce bandwidth waste, since now 7 slots of 12,5 GHz each (total 87,5 GHz) will be sufficient. In this case, the bandwidth inefficiency will be reduced.

For ROADMs supporting the efficient bandwidth management of next generation higher bit rate optical networks, the following major issues have to be addressed in order to meet the flexible spectrum allocation requirement.

– The spectral gap (dips and peaks) between the channels will have to be negligible, such that when several channels are combined to form a larger bandwidth channel, it will have flat top passband characteristics conducive to the error-free transmission of optical channels.
– Current 50 GHz channelized WSS devices will not be sufficient and would have to change to a finer channel separation of 12,5 GHz, each with the same bandwidth. This will result in more efficient bandwidth usage, enhancing the spectral efficiency.

Network management tools will have to evolve to be able to dynamically allocate and manage different amounts of bandwidth for a multi-rate signal environment, traversing the nodes of the network.

5 WSS performance characteristics

As discussed earlier, WSS is a key element of the present day ROADMs. ROADM performance characteristics are determined by the WSS parameters. A typical list of WSS parameters is given in Table 1.

Table 1 – List of key WSS parameters

Parameters	Units
Insertion loss	dB
Number of channels	
Channel spacing	GHz
Bandpass	GHz
3-dB passband width	
Adjacent channel crosstalk	dB
Adjacent channel port isolation	dB
Insertion loss ripple	dB
PDL	dB
PMD	ps
Switching time	ms
Power consumption	W
NOTE For more details, see IEC 62343-3-3.	

Annex A
(informative)

ROADM (WSS) component technologies

A.1 General description

ROADMs have progressed through several technology generations: starting from simple filters in the 1990s to wavelength blockers (WBs) and planar lightwave circuits (PLC) based devices in the early 2000s to the current wavelength selective switches (WSS). In this annex, component technologies for the ROADM subsystems are described. PLC devices that rely on AWG mux/demux are discussed first. In the following clauses, switching technologies based on MEMS, LCOS LC and DLP are discussed. These are implemented in a WSS in conjunction with a dispersive element such as a grating, which spatially separate the wavelengths before they are selectively deflected to the output fibre port(s).

A.2 PLC technology

Early design for ROADMs is based on planar lightwave circuits employing silica on silicon technology. A functional diagram of PLC based ROADM is described in Figure 7. An example of silica-based PLC device for ROADMs is shown in Figure A.1. This figure depicts integration of an arrayed waveguide grating multi/demultiplexers, thermo-optic switches and variable optical attenuators. An array of PLC based thermally actuated 2 x 2 switches is nested between a demultiplexer and multiplexer to provide optical bypass functionality based on arrayed waveguide gratings. In AWGs, the switches and attenuators are thermally actuated and employ Mach-Zehnder interferometers, which allow relatively fast switching time (~1 ms), enabling optical protection switching applications. The multiplexing and demultiplexing of channels in a WDM aggregate of colours is done in waveguides integrated onto a single substrate, so fewer fibre connections are needed. As technology advanced, so did the level of integration, with component vendors eventually integrating all the key functions required into a single substrate using PLC technology.

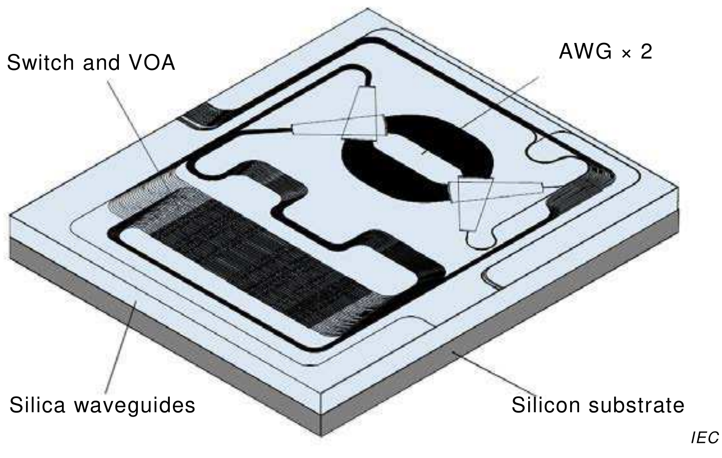


Figure A.1 – Example of PLC devices for ROADM systems

One limitation of PLC technology design is that it only supports two degree ROADMs. The add/drop fibre ports are pre-assigned to a specific wavelength channel and a specific direction (coloured and directional). Moreover, because of the large number of parallel optical paths inside the device, it is prone to multi path interference through any leakage of optical power through AWG ports. Additionally, because of the passband characteristics of the AWGs, cascading of these devices in a network can cause significant bandwidth narrowing. Despite these limitations, PLC ROADMs were successfully deployed early on in smaller metro rings.

A.3 MEMS (micro-electromechanical system) technology

Figure A.2 shows the generic schematic of the internal configuration of a 1 x N WSS employing MEMS technology as a switching engine. The input and output ports of WSS consist of an array of optical fibres. The topmost optical fibre in the array is for the input port, whereas the other fibres are for the output ports. The light from the input port is directed to a reflection grating, and different WDM channels are diffracted at different angles. A spherical mirror focuses the diffracted wavelengths on different elements of the MEMS mirror with individual WDM channels spatially separated and falling on separate mirrors, as shown in Figure A.3. The switching and attenuation functions are realized by adjusting the tilt angle of the MEMS mirrors.

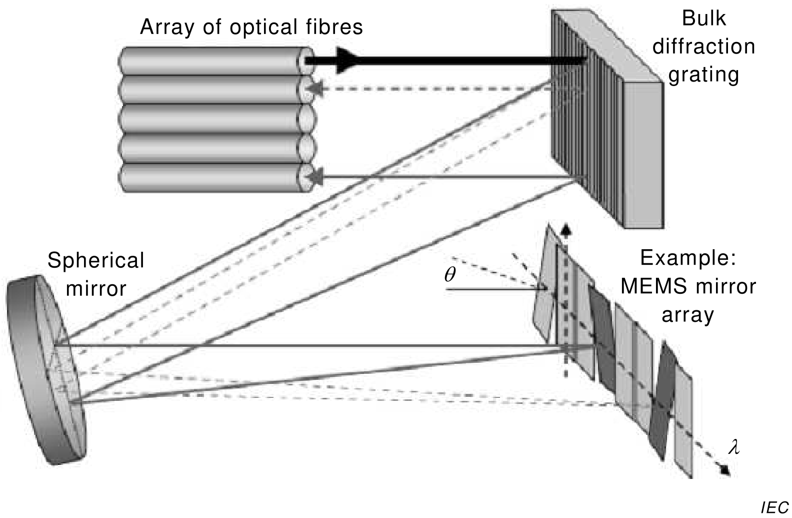


Figure A.2 – Generic internal configuration of WSS (example, MEMS based)

The array of MEMS micromirrors is fabricated in silicon using standard lithographic processes of the semiconductor industry. Each mirror has a highly reflecting coating and can be tilted in two directions by the application of voltage to the electrodes due to electrostatic attraction. Angular deflection of the beam in one direction selects the output port and can be used to direct the wavelength channel to the desired output fibre port, while the second direction can slightly detune the coupling of light to the fibre port and create attenuation. The second tilt direction is also useful in hitless switching of signals to a desired output port. In order to achieve this, the beam is first directed away from the output fibres and the mirror is adjusted in the first direction to reach the desired output port. The tilt in the second direction is then adjusted to couple the light to the output port.

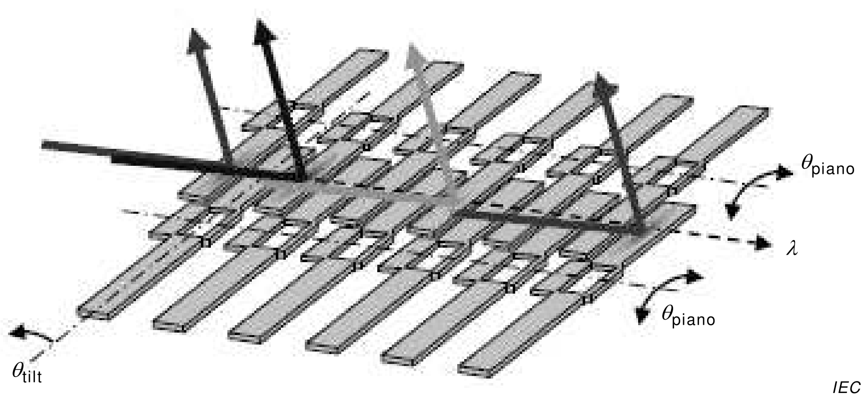


Figure A.3 – Switching engine of MEMS

MEMS devices are polarization insensitive and have low scattering due to a minimal number of optical surfaces. Silicon hinges are generally very stable with an almost negligible amount of creep. There is also a negligible amount of friction or physical contact for high reliability. Small mechanical disturbances, however, can sometime cause inaccuracy in the attenuation setting. Also, due to the discreet mirrors in the array, there is limitation in the operation in flexible wavelength grid and channel plan. However, MEMS WSS technology is proven highly reliable and is widely deployed.

A.4 LCD (liquid crystal device) technology

In a liquid crystal WSS device, the LC cell selectively controls the polarization state of the transmitted light by application of a control voltage. Randomly polarized light input is separated into two orthogonal polarizations. The function of the LCD is to rotate the polarization plane of the light. The LC layer is followed by a birefringent material, which acts as a polarization beam splitter. By controlling the polarization state of the light, it can be deflected into one of the two directions, and thus the 1 x 2 switching functionality can be achieved. Therefore, by stacking of N LC and birefringent wedges, $2N$ discrete beam angles into output ports will be achieved.

Figure A.4 shows the switching engine of LC based WSS. As described above, the optical elements consist of the LC and a birefringent wedge crystal. The function of the LCD here is to rotate the polarization plane of light. By changing the rotation angle, the switching function is realized similarly to the MEMS switch. An array of such deflection engines is aligned to the wavelength dispersion direction following the dispersive element, such as a grating. Additionally, partial or full polarization rotation can provide power attenuation or a blocking function. However, the output port combination and ratios are not independent.

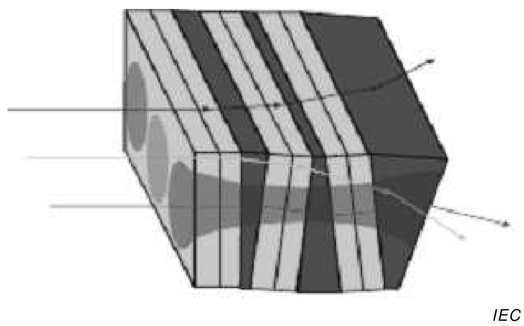


Figure A.4 – LC switching engine

The LC switching device has a minimum beam size since, while passing through the stack of LCs and wedges, the optical beam must remain collimated through the entire stack of LC cells and polarization components. This leads to a minimum beam radius and hence a minimum optics size. Moreover, since the optical beams passes through a large number of optical surfaces, it accumulates scatter.

A.5 LCOS (liquid crystal on silicon)

LCOS consists of liquid crystal (LC) display technology that incorporates drive circuitry in a silicon substrate adjacent to the liquid crystal layer. The active substrate enables large 2D arrays of pixels to be addressed independently. These devices have a large array of two dimensional optical phase modulators. Usually there are multiple pixel columns per wavelength channel in LCOS devices. A 2π phase shift acts like a tilted mirror for a single wavelength. By controlling the phase of each pixel, beam steering can be implemented by creating linear optical phase retardation in the direction of the intended deflection. This is similar to a tilting mirror steering a beam by imparting a linearly increasing phase.

Figure A.5 shows the switching engine of LCOS based WSS. There are many small sized pixels. LCOS behaves similarly to passed array. The pixel size is smaller than the beam spot size. The other axis of the array is aligned with the wavelength dispersion direction.

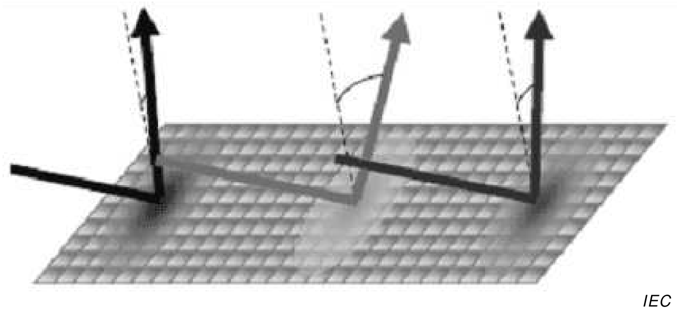


Figure A.5 – LCOS switching engine

LCOS-based WSS devices have been used in high port count ($N = 20$) ROADMS and are widely deployed in optical networks.

A.6 DLP (digital light processor) mirror arrays

DLP mirror technology is based on display technology for projectors. It consists of a 2D array of single tilt axis and 2-tilt position mirrors. Each wavelength channel after diffraction is directed to the 2D array mirrors. As shown in Figure A.6, the beam spot size is larger than the mirror size. All mirrors for a given wavelength are actuated to the same binary state, deflecting the entire beam. Usually, multiple bounces are required for attenuation higher port devices with $N > 2$. Since it is a reflective device, it is polarization insensitive; however, diffraction from mirror edges, substrate reflections, and imperfect phase matching between mirrors can cause poor isolation and increased IL. Multiple bounces will improve isolation but can also further increase IL.

Figure A.6 shows the switching engine of DLP based WSS. The DLP acts as a phased array. The most general application of the DLP is for large screen projection. The mirror size is smaller than the beam size, as in the LCOS. The mirrors tilt in two directions.

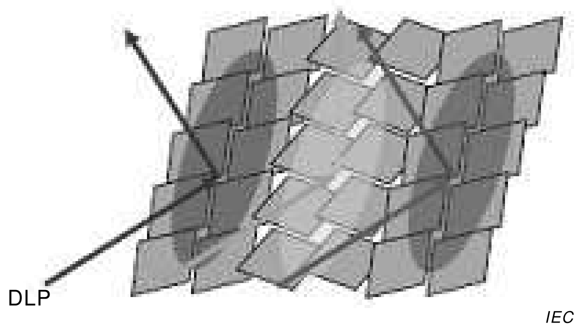


Figure A.6 – DLP switching engine

A.7 Feature comparison of each switching engine technology

Table A.1 compares the features of WSSs having different switch engine technologies.

Table A.1 – WSS switch engine feature comparison

Feature	PLC	MEMS	LCOS	LC	LC + MEMS	DLP
50 GHz and 100 GHz channel spacing	Yes	Yes	Yes	Yes	Yes	Yes
High port count (≥ 16)	No	Yes	Yes	Yes	Yes	No
Flexible spectrum	No	No	Yes	No	No	Yes
Wide flat bandwidth	No	Yes	Yes	Yes	Yes	Yes
Low loss	-	Yes	Yes	No	Yes	No
Small size	No	Yes	Yes	No	No	Yes
Fast switching speed	Yes	No	No	No	No	Yes
High port isolation	Yes	Yes	No	No	Yes	No
Attenuation accuracy	Yes	No	Yes	Yes	Yes	Yes

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