Master of Science in Internetworking

Capstone Project

On

Open Line System components, use cases, and challenges

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Abstract

An Open Line System helps network operators to cope with the rapid growth in the optical networking industry and helps to scale backbone network capacity efficiently. It also reduces the problem of vendor lock-in that empowers operators to deploy a cost-effective, scalable, and highly adaptive network. This report explains the evolution of the optical network. It discusses the significant components and use cases of the Open Line System. It also throws some light on the challenges of deploying an Open Line System.

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Last, I thank all my cordial friends for always being there for me.

1. Introduction

In the late 1960s, Pulse Code Modulation (PCM) was introduced for telephony systems, and network communications were being changed into digital technology. The demand for an immense bit rate was also increasing. Plesiochronous Digital Hierarchy (PDH) was a first-generation digital transmission system introduced by ITU-T to meet the increasing demand for higher bit rates. It was designed to carry voice and data. After a certain period, the PDH system could not accommodate high-capacity bandwidth and could not support traffic growth. Synchronous Optical Network (SONET), defined by ANSI, and Synchronous Digital Hierarchy (SDH), defined by ITU-T, were then designed. It has many benefits when compared to PDH. The data transmitted by the SONET signal are organized at a constant bit rate. But IP and ATM are bursty. So, the fixed-rate signal is inappropriate for them. Therefore, a specific scheme for packet transport over SONET has been defined that is ATM over SONET and IP over SONET.

During the 21st century, there was exponential growth in internet activities and multimedia communications, which created an increasing demand for network capacity, bandwidth, and transmission rates that exceed traditional TDM limits. Wavelength Division Multiplexing (DWDM) is an optical multiplexing technology designed to increase bandwidth capacity by sending multiple streams of data across a single network. This increases bandwidth and the amount of information that can be handled by a network, allowing for up to 100G to be distributed across each channel. This gives businesses the opportunity to send and receive information to or from data centers in significantly less time and at a lower cost. The introduction of coherent optical interfaces dramatically expanded network capacity, while at the same time lowering the cost per bit for optical networks. With the optical networking industry's technical achievements, each vendor developed their own mix of coherent DSP specifications, optical interfaces specifications, and forward error correction (FEC) algorithms. It prevented interoperability between vendor transponders. This creates the problem of vendor lock-in.

An open line system (OLS) is an optical system used in telecommunication that solves the problem of vendor lock-in and allows for the configuration of a network that uses best parts from a variety of different vendors and manufacturers. This allows for consumer to use APIs provided by their OLS provider to leverage open-source solutions and develop more efficient networks at a lower cost. Additionally, network operators can expect to see reduction in power costs and consumption across the OLS's user-friendly automatic optical set-up.

Despite progress, challenges exist for open line systems (OLS). Multi-vendor OLS requires the network operator to take more responsibility for the management, control, and planning software. There is also extra task of testing equipment from different vendors and linking them together. As it is a new technology, skill and technical know-how may be one of the challenges.

2. The evolution of optical network

2.1 Plesiochronous Digital Hierarchy (PDH)

Plesiochronous Digital Hierarchy (PDH) was developed originally for telephone networks. Also, it supports digital voice channels running at 64kbpsPDH uses time-division multiplexing.

Multiplexing techniques in PDH: To transmit multiple of 2Mbps data from one point to another, data streams are multiplexed in groups of four by taking one bit from every stream. In multiplexing, the transmitter adds additional bits so that receiving end can decode which bits belong to a particular 2Mbps stream of data and regenerate the original data streams. The additional bits that are added are called "stuffing bits" or "justification bits."

PDH Synchronization: In PDH, every device has a different clock which occurs errors during synchronization. The solution to preventing this error is inserting and removing surfing bits to the frame, which is called bit stuffing.

Limitations of PDH:

Every manufacturer used its standards in PDH, which made it difficult to connect different networks. The table below shows different hierarchies adopted by the United States, Europe, and Japan.

Level	US (T-)	Europe (E-)	Japan
0	0.064 Mbps	0.064 Mbps	0.064 Mbps
1	1.544 Mbps	2.048 Mbps	1.544 Mbps
2	6.312 Mbps	8.488 Mbps	6.312 Mbps
3	44.736 Mbps	34.368 Mbps	32.064 Mbps
4	274.176 Mbps	139.264 Mbps	97.928 Mbps

- The difficulty of identifying individual channels in a higher bitstream order means that multiplexing has to be performed for high bit-rate channels down through all multiplexing levels until the ideal rate is located, which requires a lot of multiplexing cost.
- The maximum capacity for PDH is 566 Mbps, so PDH is unsuitable for high-capacity or high-bandwidth connections.
- PDH only supports point-to-point configurations, and it does not support hubs.

2.2 Synchronous Optical Network (SONET) / Synchronous Digital Hierarchy (SDH)

By using PDH, interoperability amongst different providers was very difficult. SONET/SDH was designed to provide standard access to the optical transmission medium. Synchronous Optical Network (SONET) was the American standard, and Synchronous Digital Hierarchy (SDH) was the European standard. It uses time division multiplexing. SONET/SDH provided a vendor-independent and sophisticated structure resulting in the development of new applications, new network equipment, and management flexibility than the PDH. It also reduces hardware complexities by eliminating the number of multiplexers and allows single-stage multiplexing and de-multiplexing.

SONET Frame structure: SONET uses a specific 90-byte * 9-row frame format to carry data with a basic frame time of 125microsecond. There are overhead and payload bytes in the 90-byte * 9-row frame structure. The first three columns of the SONET frame are used for section and line overhead, respectively. In the frame structure, the upper three rows of the first three columns are used for section overhead (SOH), and the lower six rows are used for line overhead (LOH). The remaining part of the frame is called the synchronous payload envelope (SPE), which contains the user data and path overhead (POH). The data transmitted by the SONET signal are organized at a constant bit rate.

SONET channels are synchronous. The synchronization of the channels is maintained by pointers which indicate the starting byte position of each channel in the frame. These pointers are used for efficiently multiplexing digital signals within a single SONET frame. SONET provides a hierarchy of electrical signaling levels called synchronous transport signals (STSs). Each STS level (STS-l to STS-192) supports a certain data rate specified in Mbps. The corresponding optical signals to those electrical signals are known as optical carriers (OCs). In SDH, a similar system is called a synchronous transport module (STM). STM is to be compatible with existing European hierarchies, such as E lines, and with STS levels. The line rate of the lowest STM level, STM-l, is defined as 155.520 Mbps, which is exactly equal to STS-3.

STS	OC	Rate (Mbps)	STM
STS -1	OC – 1	51.840	
STS – 3	OC – 3	155.20	STM – 1
STS – 9	OC – 9	466.560	STM – 3
STS – 12	OC – 12	622.080	STM – 4
STS – 18	OC – IS	933.120	STM – 6
STS – 24	OC – 24	1244.160	STM – 8
STS – 36	OC – 36	1866.230	STM – 12
STS – 48	OC – 48	2488.320	STM – 16
STS – 96	OC – 96	4976.640	STM – 32
STS – 192	OC – 192	9953.280	STM – 64

SONET / SDH Network topology:

- Point-Point Link: Based on PDH systems that provide point-to-point connections, SDH replaced it with STM-4 line systems. This system uses regenerators to avoid transmission issues; no routing or de-multiplexing is done along the path.
- Ring Topology: This is the most used topology. The ring network is a route back to itself that facilitates the development of protocols that can detect if there is a failure in the fiber and re-establish connection quickly.
- Star Topology: The traffic in a star topology passes through a central hub where the hub is a Synchronous Digital Cross Connect.
- Linear Bus Topology: The Linear bus topology has great flexibility and is used when protection is not necessary

Advantages of SONET / SDH:

- The transmission rates of SONET / SDH can go up to 10Gbps, and it is easier to extract and insert low-bit rate channels into high-bit streams.
- SONET / SDH systems include auto backup and restore/repair mechanisms in case of failure, and a failure in a link or a network element does not mean the failure of the entire network.
- It provides a more simplified multiplexing and de-multiplexing technique.
- It supports multipoint networking.
- It has the capability of transporting existing PDH signals.
- It's a multivendor and supports different operators.
- The bandwidth of optical fiber can be increased without limit.

ATM over SONET / SDH

Asynchronous transfer mode (ATM) is a packet switch technology. In ATM, 53 bytes packets called the cell, are switched across an ATM transport network. ATM does not assign fixed time slots to realize information transfer between two endpoints like synchronous transfer mode (STM). ATM can transfer constant bit rate, variable bit rate, and unspecified bit rate data.

ATM can run on top of several services. In ATM, cells are mapped into synchronous payload envelope (SPE). Cells are placed one after another after the cell payload is scrambled. This is an additional scrambler to the scrambler used in SONET. It ensures that the SONET signal will have enough transitions to allow line rate clock recovery at the receiver. ATM equipment relies on a cyclic redundancy check (CRC) at the receiver end, to recover the cells. SPE is scanned on a sliding 5-byte window, and CRCs are computed. When a match occurs, synchronization is established, and scanning is stopped. The next CRC is checked by jumping 53 bytes ahead. Otherwise, a new synchronization scanning is started.

IP over SONET / SDH

IP is another packet network technology. Similar to ATMs, there are several interfaces over which IP protocols can run. IP over SONET/SDH interface consists of IP/PPP/HDLC over SONET. IP datagrams are encapsulated into Point-to-Point Protocol (PPP) packet. PPP protocol provides link error control and initialization. The PPP-encapsulated datagrams are then framed using high-level data link control (HDLC) and finally mapped into SONET SPE. The HDLC framed datagrams are then scrambled and placed one after another into SPE, just the similar way ATM cells are arranged.

2.3 Wavelength division multiplexing (WDM)

An optical network is a high-capacity network that uses light as an electromagnetic carrier wave to transmit information. The optical networks are classified into three generations depending on the physical-level technology employed. The first-generation networks were based on copper or microwave technologies, e.g., Ethernet, satellites, etc. The second-generation networks used copper or microwave links along with optical fibers. And finally, Wavelength Division Multiplexing (WDM) technology was developed, which generates the backbone of optical fiber communication.

WDM technology can multiplex multiple optical signals into a single fiber. Early fiber-optic transmission systems were used to put information onto strands of glass through simple pulses of light. A light was then flashed on and off to indicate digital ones and zeros. The actual light wavelength was from roughly 670 nm to 1550 nm. WDM uses multiple wavelengths to send data over the same medium. WDM has the following advantages:

i. Standard erbium-doped fiber amplifiers (EDFA) simultaneously amplify optical signals from 1530 nm to 1565 nm, thereby reducing system cost and complexity because individual wavelength channels do not need to be de-multiplexed and separately amplified.
ii. Many wavelength channels can be transmitted through a single fiber.
iii. The components of WDM are commercially available.

WDM is divided into three types known as

i. Bi-Directional Wave Division Multiplexing (BWDM),
ii. Coarse Wave Division Multiplexing (CWDM),
iii. Dense Wave Division Multiplexing (DWDM).

2.3.1 COARSE WAVELENGTH DIVISION MULTIPLEXING (CWDM)

A CWDM system commonly supports eight wavelengths per fiber and is designed for short-range communications. CWDM is based on 20-nm channel spacing from 1470 to 1610 nm. It is used on fiber spans up to 80km or less because optical amplifiers cannot be used with large spacing channels. CWDM is used for lower cost, lower capacity. Generally, CWDM is used for lower cost, lower capacity and shorter distance applications. More recently, the prices for both CWDM and DWDM components have become reasonably comparable. CWDM wavelengths are currently capable of transporting up to 10Gbps Ethernet and 16G Fiber Channel, and it is quite unlikely for this capacity to further increase in the future.

2.3.2 DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM)

DWDM supports more link capacity and distance than CWDM. DWDM is defined in terms of frequencies. DWDM meets the growing demand for bandwidth by multiplying the capacity of a single fiber. Applications such as the Internet, local area networks (LANs), and metropolitan area networks (MANs) benefited from the inexpensive and large transmission capacity offered by DWDM system providers. It also brings flexibility to the system that it can be connected directly to any signal format without requiring extra equipment.

DWDM increases the capacity of a fiber by first assigning incoming optical signals to a specific wavelength within a designated frequency band. The resulting signals are then multiplexed onto a single fiber. The system's interface is bit-rate and format independent as incoming signals never terminate in the optical layer. It makes it easy to integrate the DWDM technology with the current equipment available in the network. DWDM supports the Conventional band or C band spectrum which means it can typically transport up to 80 channels (wavelengths) and all 80 channels are in the 1550 nm region. A significant advantage of DWDM is that the protocol is not related to transmission speed. Therefore, IP, ATM, SONET/SDH, and Ethernet these protocols could be used, and transmission speed is between 100Mb/s to 2.5Gb/s. DWDM could transmit different data types at different speeds on the same channel.
ITU-T G.694.1 provides a frequency grid for DWDM applications, and supports a variety of channel spacing ranging from 12.5 GHz to 100 GHz and wider.

Spectrum width (GHz)	12.5	25	50	75	100
Wavelength spacing (nm)	0.1	0.2	0.4	0.6	0.8

DWDM 100GHz ITU-T Grid

Channel	Wavelength(nm)	Frequency(THz)	Channel	Wavelength(nm)	Frequency(THz)
1	1577.03	190.1	37	1547.72	193.7
2	1576.2	190.2	38	1546.92	193.8
3	1575.37	190.3	39	1546.12	193.9
4	1574.54	190.4	40	1545.32	194.0
5	1573.71	190.5	41	1544.53	194.1
6	1572.89	190.6	42	1543.73	194.2
7	1572.06	190.7	43	1542.94	194.3
8	1571.24	190.8	44	1542.14	194.4
9	1570.42	190.9	45	1541.35	194.5
10	1569.59	191.0	46	1540.56	194.6
11	1568.11	191.1	47	1539.77	194.7
12	1567.95	191.2	48	1538.98	194.8
13	1567.13	191.3	49	1538.19	194.9
14	1566.31	191.4	50	1537.4	195.0
15	1565.5	191.5	51	1536.61	195.1
16	1564.68	191.6	52	1535.82	195.2

17	1563.86	191.7	53	1535.04	195.3
18	1563.05	191.8	54	1534.25	195.4
19	1562.23	191.9	55	1533.47	195.5
20	1561.41	192.0	56	1532.68	195.6
21	1560.61	192.1	57	1531.9	195.7
22	1559.79	192.2	58	1531.12	195.8
23	1558.98	192.3	59	1530.33	195.9
24	1558.17	192.4	60	1529.55	195.0
25	1557.36	192.5	61	1528.77	195.1
26	1556.55	192.6	62	1527.99	195.2
27	1555.75	192.7	63	1527.22	195.3
28	1554.94	192.8	64	1526.44	195.4
29	1554.13	192.9	65	1525.66	195.5
30	1553.33	193.0	66	1524.89	195.6
31	1552.52	193.1	67	1524.11	195.7
32	1551.72	193.2	68	1523.34	195.8
33	1550.92	193.3	69	1522.56	195.9
34	1550.12	193.4	70	1521.79	197.0
35	1549.32	193.5	71	1521.02	197.1
36	1548.51	193.6	72	1520.25	197.2

DWDM 50GHz ITU-T Grid

Channel	Wavelength(nm)	Frequency(THz)	Channel	Wavelength(nm)	Frequency(THz)
1	1577.03	190.1	37	1574.72	193.7
1.5	1576.61	190.15	37.5	1547.32	193.75
2	1576.2	190.2	38	1546.92	193.8
2.5	1575.78	190.25	38.5	1546.52	193.85
3	1575.37	190.3	39	1546.12	193.9
3.5	1574.95	190.35	39.5	1545.72	193.95
4	1574.54	190.4	40	1545.32	194
4.5	1574.13	190.45	40.5	1544.92	194.05
5	1573.71	190.5	41	1544.53	194.1
5.5	1573.3	190.55	41.5	1544.13	194.15
6	1572.89	190.6	42	1543.73	194.2
6.5	1572.48	190.65	42.5	1543.33	194.25
7	1572.06	190.7	43	1542.94	194.3
7.5	1571.65	190.75	43.5	1542.54	194.35
8	1571.24	190.8	44	1542.14	194.4
8.5	1570.83	190.85	44.5	1541.75	194.45
9	1570.42	190.9	45	1541.35	194.5
9.5	1570.01	190.95	45.5	1540.95	194.55
10	1569.59	191.0	46	1540.56	194.6
10.5	1569.18	191.05	46.5	1540.16	194.65
11	1568.11	191.1	47	1539.77	194.7
11.5	1568.36	191.15	47.5	1539.37	194.75
12	1567.95	191.2	48	1538.98	194.8

12.5	1567.54	191.25	48.5	1538.58	194.85
13	1567.13	191.3	49	1538.19	194.9
13.5	1566.72	191.35	49.5	1537.79	194.95
14	1566.31	191.4	50	1537.4	195
14.5	1565.9	191.45	50	1537	195.05
15	1565.5	191.5	50.5	1536.61	195.1
15.5	1565.09	191.55	51.5	1536.22	195.15
16	1564.68	191.6	52	1535.82	195.2
16.5	1564.27	191.65	52.5	1535.43	195.25
17	1563.86	191.7	53	1535.04	195.3
17.5	1563.45	191.75	53.5	1534.64	195.35
18	1563.05	191.8	54	1534.25	195.4
18.5	1562.64	191.85	56.5	1533.86	195.45
19	1562.23	191.9	55	1533.47	195.5
19.5	1561.83	191.95	55.5	1533.07	195.55
20	1561.41	192.0	56	1532.68	195.6
20.5	1561.01	192.05	56.5	1532.29	195.65
21	1560.61	192.1	57	1531.9	195.7
21.5	1560.2	192.15	57.5	1531.51	195.75
22	1559.79	192.2	58	1531.12	195.8
22.5	1559.39	192.25	58.5	1530.72	195.85
23	1558.98	192.3	59	1530.33	195.9
23.5	1558.58	192.35	59.5	1529.94	195.95
24	1558.17	192.4	60	1529.55	196
24.5	1557.77	192.45	60.5	1529.16	196.05
25	1557.36	192.5	61	1528.77	196.1
26.5	1556.96	192.55	61.5	1528.38	196.15
26	1556.55	192.6	62	1527.99	196.2
26.5	1556.15	192.65	62.5	1527.6	196.25
27	1555.75	192.7	63	1527.22	196.3
27.5	1555.34	192.75	63.5	1526.83	196.35
28	1554.94	192.8	64	1526.44	196.4
28.5	1554.54	192.85	64.5	1526.05	196.45
29	1554.13	192.9	65	1525.66	196.5
29.5	1553.73	192.95	65.5	1525.27	196.55
30	1553.33	193.0	66	1524.89	196.6
30.5	1552.93	193.05	66.5	1524.5	196.65
31	1552.52	193.1	67	1524.11	196.7
31.5	1552.12	193.15	67.5	1523.72	196.75
32	1551.72	193.2	68	1523.34	196.8
32.5	1551.32	193.25	68.5	1522.95	196.85
33	1550.92	193.3	69	1522.56	196.9
33.5	1550.52	193.35	69.5	1522.18	196.95
34	1550.12	193.4	70	1521.79	197.0
34.5	1549.72	193.45	70.5	1521.4	197.05
35	1549.32	193.5	71	1521.02	197.1
35.5	1548.91	193.55	71.5	1520.63	197.15
36	1548.51	193.6	72	1520.25	197.2

36.5	1548.11	193.65	72.5	1519.86	197.25

2.3.3 DWDM Components

Time-division multiplexing systems work by first doing the optical-to-electronic conversion, MUX, and DMUX in the electronic domain, and then the electronic-to-optical conversion. So, the throughput depends on the electronic domain's processing speed. On the other hand, WDM technologies are based on all-optical multiplexing and de-multiplexing.

i. **Multiplexer**: The multiplexer multiplex signal together and transmits them on a fiber. DWDM was started with 100 GHz channel spacing where 44 channels can be transmitted, it moved to 50 GHz channel spacing, where 88 channels can be transmitted. Now it supports flexible rate channel spacing (12.5 GHz). The multiplexer contains one wavelength-converting transponder for each wavelength signal it will carry. The basic functionality of a transponder is to perform O-E-O conversion. It receives a client's optical signal that may be on 850nm, 1310 nm or any other wavelength, and then it converts the optical signal to an electrical signal and reconverts into an optical signal using two diodes that are back-to-back connected in a transponder and assigns an ITU frequency to that signal. In DWDM, C and L bands are used. The C band is mostly used by all vendors but they are moving towards the L band. The C band's frequency range is 191.325 THz – 196.15 THz. The L band's frequency range is 186 THz – 190 THz.

ii. **Amplifier or intermediate line repeater:** The amplifier amplifies the signal. It is placed around every 80 – 100 km for compensating the signal loss while the signal travels along the fiber. EDFA, RAMAN, and semiconductor amplifiers are various types of amplifiers and EDFA and RAMAN are mostly used in DWDM systems.

iii. **Optical Cross Connect (OXC):** The OXC switches optical signals from input to output ports. These elements are usually considered wavelength insensitive, and unable to de-multiplex different wavelength signals on a given input fiber. The optical cross-connect is placed at nodes where a number of fiber pairs cross-connects and it also supports add and drop of local traffic.

iv. **Optical add-drop multiplexer**: The Add/Drop Multiplexer selectively adds/drops wavelengths without using any SONET/SDH terminal equipment. The Add/Drop Multiplexer can add new wavelengths to the network or drop some wavelengths at their terminating points. ADM has two types of implementations, the Fixed Wavelength Add/Drop Multiplexor and the Reconfigurable WDM.

v. **De-multiplexer**: The terminal de-multiplexer separates the multiplexed wavelength signal into individual signals and outputs them on separate fibers.

A key advantage of DWDM is that it is not protocol and bitrate-dependent. DWDM-based networks can carry data in ATM, SONET, SDH, IP, and Ethernet forms. Therefore, DWDM-based networks can transmit different data types at different speeds over an optical channel. DWDM system can simultaneously transmit voice, video, and multimedia data.

2.4 Signal Transparent Networks:

In a WDM link, the optical signals are de-multiplexed at each node, converted to electrical signals, switched, and re-transmitted as optical signals. The disadvantages of this approach, it limits the bandwidth for future upgrades and requires all optical signals to be converted, even though some optical signals simply pass through the node. Therefore, the next step was an all-optical network, which could eliminate unnecessary and costly electrical conversion processes.

In an all-optical network, the signals remain in the optical domain during transmission. The signal is only converted to the electrical domain when access to one of the baseband electrical signals is required or when the signal must be regenerated. As a result, an optical switch and optical wavelength converter are required. But optical wavelength converters are not commercially available and are highly expensive.

All-optical networks may only be suitable for small or constrained networks. Most transport networks are designed with ring architecture. It is relatively easy to manage optical rings. If the signal remained in the optical domain, wavelength contention might occur on adjacent rings. Also, dispersion and attenuation will go unchecked unless these effects are managed signal-by-signal, greatly complicating a network's administration and operation. As a result, the wavelength cross-connects may need to be signal transparent, not optically transparent. If the optical signals are converted to electrical signals when they traverse from one ring to the next, they may be transmitted using any available wavelength and avoid contention. It is much easier to re-amplify and reshape the signal in the electrical domain than in the optical domain. That is why all-optical networks may be deployed as signal-transparent networks rather than optically transparent networks.

A signal-transparent network is one in which the signal may be transmitted using wireless, optical, or electrical techniques but does not have a bit rate or signal format restriction. It is rather equivalent to an analog network. Thus any signal format, such as quadrature amplitude modulated, binary, multilevel, etc., operating at an arbitrary bit rate can be transmitted, and it does not exceed the analog bandwidth of any network component.

2.5 Wavelength Cross-connects

One component necessary for optical networks is a wavelength cross-connect (WXC), where any wavelength channel on an input fiber can be connected to any wavelength channel in the fiber, for all-optical WXC, an optical wavelength converter is required. It is possible to create electronic or optoelectronic WXC with existing commercially available components such as wavelength MUX/DeMUX and electronic and optoelectronic switch cores. Analog switches are required if signal transparency is to be maintained. Digital electronic switches need the data stream to operate at a particular bit rate and maintain a binary format.

2.6 Coherent Optics:

All optical transport networks transmit information by using lasers. Lasers send pulses of light through the glass and transmit information by controlling the power levels of the signal. The transmission is done by on-off-keying (OOK). It uses high power to transmit a "1" and low power to transmit a "0." This technology is called direct detect which is only good for transmitting information up to about 10 Gb/s per wavelength (OC-192). It is not enough to cope with the massive bandwidth required by today's networks. But this was important as it helped in the massive network upgrades from the late-1990s until 2010. To overcome the limitations of direct detect technology, the industry developed a technology called coherent optics capable of transmitting more information and transmitting over longer distances. There was an enormous rise in data transmission speeds using coherent transmission techniques during the last few decades. The development of optical amplifiers and wavelength division multiplexing made it possible for today's optical networks to transmit multiple high-speed data streams operating at different wavelengths through optical fiber cables over long distances. The continuous advances in optical networks have enabled many services, such as content streaming, mobile video, remote work, and cloud-based applications. New and emerging applications such as artificial intelligence(AI), and virtual and augmented reality experiences require more and more bandwidth and are driving the need for further massive scaling of network capacity over the next decade. The need for further scaling must accommodate new technologies that will continue to drive cost-effective increases in network capacity and also provide meaningful solutions that reduce network complexity, simplify operations, and facilitate service delivery. Coherent optics solves the network capacity problems network providers are facing today. Coherent optics is a specific type of laser technology service providers use to transmit large amounts of information over fiber optic networks. The advent of coherent transmission provided the ground-breaking leap to optical transmission technology for 400G, 600G, 800G, and terabit solutions.

Coherent optical transmission uses amplitude modulation and phase modulation of the light, to transmit more information through a fiber optic cable. Using digital signal processing(DSP) at both the transmitter and receiver, coherent optics also offers higher bit rates, greater degrees of flexibility, simpler photonic line systems, and better optical performance. Coherent technology makes it possible to use phase modulation to create a binary signal, instead of turning the laser on or off like direct detect technology. Changing the phase and amplitude of light makes it possible to indicate a 1 with a big wave and a 0 with a small wave. Using phase modulation, it is possible to shift the wave forward or backward, and add further information in the waveform based on different points, not just the crest and the trough. To create more or less intensity, it is also possible to change the horizontal and vertical polarization of the light. Quadratic amplitude modulation (QAM) utilizes all these techniques together and coherent technology utilizes a form of QAM called quadratic phase shift keying (QPSK) and transmit more information than direct detect technology or OOK. Early coherent systems used QPSK at 32GBaud, which means the state of the signal changes 32 billion times per second, and it can be 8, 16, 32, or 64 QAM. For instance, at 64 QAM at 64GBaud (64/64), on a single channel of light, it is possible to transmit 600 billion bits per second or 600Gbit per second. By repeating across 128 channels, today's fiber optic networks can transmit nearly 80tbps, over hundreds of kilometers of fiber, without electrical repeaters.

The first commercially available coherent systems were 40G which was followed by 100G later. These systems were line card and chassis-based and could support many line cards in each system. Over time, line card speeds increased to 200G and beyond. The demand to create even smaller, faster, and cheaper network components only increased as cloud provider networks grew exponentially. With the development of fiber optics rapidly changing technology, new form factors with increasing speeds are being introduced every year. In 1995 GBIC (Gigabit Interface Converter) was one of the first standards released by the Small Form Factor Committee for flexible hot-swappable transceivers. From 2001-2005, SFP (Small Form-factor Pluggable) transceivers were available, smaller version of GBIC with the same functionality. In 2006 SFP+ (Enhanced Small Form-factor Pluggable) was introduced which was an enhanced version of SFP with a higher data rate that brought speeds up to 10Gbps. SFP+ is supported by many network vendors and is still a dominant industry format with the latest update to the standard in 2013. In 2006 another transceiver named QSFP (Quad Small Form-factor Pluggable) is slightly bigger than SFP. The CFP (C form-factor pluggable) is a multi-source agreement (MSA) that was originally designed for 100 Gigabit systems. CFP transceivers support ultra-high bandwidth networks, which form the backbone of the Internet. Different CFP transceivers pluggable are, such as CFP2, CFP4, and CFP8 transceiver modules to support the high bandwidth requirements of data communication networks. Launched in 2012, QSFP+ (Enhanced Quad Small Form-factor Pluggable) is a 4-channel small hot-pluggable optical transceiver. Based on the same technology as QSFP+ and with the same physical dimensions, QSFP28 was launched in 2014 using 4-lanes of 25Gbps and SFP28, launched in 2014 was designed for speeds of up to 25Gbps. From 2015 till the present, CSFP (Compact Size SFP), QSFP56 and QSFP-DD (Quad Small Form-factor Pluggable Double Density) were released. In 2019, OSFP (Octal Small Form Factor Pluggable) was developed that supports bitrates of 400G and above. SFP-DD (Small Form-factor Pluggable Double Density) is one of the latest multisource agreement standards and one of the smallest form-factors that enable data centers to double port density and increase data rates.

In 2009 improvements were made to CFP, with the introduction of CFP2 in 2012. CFP2 is half the physical size of the original CFP specification and provides data rates from 100Gbps to 200Gbps, for distances from 10km to 2000km in amplified long-haul systems. Further innovations in the optics field introduced smaller components with lower power requirements. CFP2-ACO pluggable (analog coherent optics) is a relatively small CFP2 form factor. DSP technology evolved and one DSP chip can support multiple CFP2-ACO modules. By placing multiple DSPs within a box and they can serve multiple CFP2-ACOs. Cisco produced NCS 1002 that can transport 2Tbps within two rack units (3 inches), whereas a chassis-based system would require 12 rack units. These systems are much more power efficient and space savings. The CFP2-ACO is capable of handling analog signals only. It can receive a coherent analog signal from the DSP to be transmitted or pass a received coherent analog signal to the DSP to be converted to digital. CFP2-ACO systems reduce power consumption and reduce the cost of the equipment of the optical network, specifically the transponder. These systems have become the standard form of optical transport and have been adopted by almost all providers. With the introduction of CFP2-ACO-based systems, vendors have introduced new, faster systems that do not rely on DWDM pluggable. Coherent DWDM optics continued to develop further and CFP2-DCO (digital coherent optics) was introduced. In CFP2-DCO, the component size and power were reduced so that the optics and the DSP now reside within the CFP2 eliminating the need for a chassis to locate the DSP and enabling coherent DWDM transport directly from a router or switch.

2.6.1 400G-ZR, 400G-ZR+

400G-ZR and 400G-ZR+ use the same technology as the CFP2-DCO, but they are a much smaller version of the QSFP-DD form factor. Optical Internetworking Forum (OIF) was the first who created the 400ZR standard in March 2020. 400ZR is an interoperable networking Implementation Agreement (IA) that was aimed at short-reach, single-span fiber optic links for Data Center Interconnect (DCI). It defines a solution for transporting 400Gbps Ethernet over DCI links targeting a minimum of 80 km. It uses DWDM and higher-order modulation such as 16 QAM. Multi-Source Agreement (MSA) also defined a specification named open ROADM for a 400G DWDM pluggable, and it aimed at long optical reach (>120km), advanced forward error correction (known as FEC), and supports data rates (100G, 200G, 300G, or 400G). It uses DWDM and higher-order modulation such as 16 QAM. Though additional capabilities were achieved but it requires more power than the 15W specified for ZR. Therefore, Open ROADM's specification became known as ZR+. It is a relatively smaller form factor pluggable module that provides a comprehensive, open, and flexible coherent solution. This standard addresses hyper-scale data center applications for high-intensive edge and regional interconnects.

Specification	Data Rate	Modulation Type	Target Reach
400ZR	400G	DP-16QAM	120 km
400ZR +	400G	DP-16QAM	1400 km
	300G	DP-8QAM	2500 km
	200G	DP-QPSK	3000 km
	100G	DP-QPSK	8000 km

2.7 Open Line System

The introduction of coherent optical interfaces dramatically expanded network capacity, while at the same time lowering the cost per bit for optical networks. Since then, ongoing improvements in optical technology and coherent DSPs have increased wavelength capacities from 100G to over 600G per wavelength. New generations of multi-modulation, multi-baud rate transponders enable flexible WDM line interfaces with capacities close to Shannon limits on every optical route. While the optical networking industry's technical achievements over the last 10 years have been impressive, they were also based on proprietary implementations. Each vendor developed their own mix of coherent DSP specifications, optical interface specifications, and forward error correction (FEC) algorithms that prevented interoperability between vendor transponders. This creates the problem of vendor lock-in. Within this environment, it becomes difficult to upgrade the network as operators have to rely on their vendors to innovate quickly and ensure that individual components are easy to modify, and cost effective. Also, different components of the optical line system, such as amplifiers or multiplexer/de-multiplexer filters, have different lifespans. In such a scenario, taking advantage of the different lifecycles of these components is impossible. Open line systems (OLS) (amplifiers, in-line amplifiers) support transponders from different vendors, often referred to as "alien wavelengths," but the transponders at both ends of the network have to be paired from the same vendor. The key components of the Open line system include the ROADM switch, transponders, and pluggable optics. Reconfigurable Optical Add/Drop Multiplexer (ROADM) is the most complex physical component of an open line system, and wavelength selective switch (WSS) is the key component of ROADM. The components of OLS are controllable via open standards-based API and accessed via an SDN Controller. The main objective of OLS is to bring multiple vendors and network operators together so that they could agree to design networks that are scalable, cost-effective, and flexible. OLS architecture can be deployed using different vendors, provided they exist in the same network. It gives the opportunity to use transponders from different vendors at the end of each circuit. It prevents the problem of vendor lock-in. Coherent optics 400ZR and the Open ZR+ or 400ZR + were developed to meet the network demands of DCI and cloud operators using 100Gbps and 400Gbps. OLS offers a better alternative for carriers that want to transport OTN client signals. Open ZR+ and Open ROADM provide more benefits to data center operators, and technology is improving. The next chapter will discuss the different components of an open-line system.

3. Components of an Open Line System

3.1 Wavelength Selective Switch (WSS)

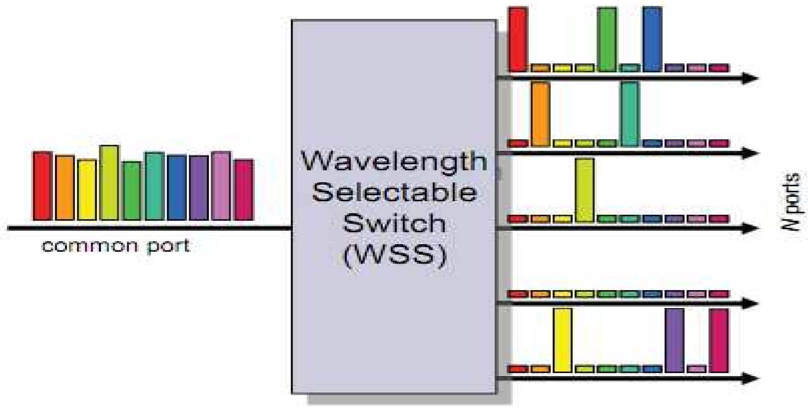
The optical add/drop multiplexer known as OADM is a DWDM networking device used to selectively add and drop optical signals into a transparent DWDM network. An optical multiplexer in OADM is used to couple two or multiple wavelengths into the same fiber. When a de-multiplexer is also placed and properly aligned back-to-back with a multiplexer, it means that two individual wavelengths exist between them. This makes it possible for OADM to add or drop individual wavelengths. An OADM can add one or multiple new signals to an existing multi-wavelength WDM signal, and pass those signals to another network path. The OADM can selectively drop wavelength from fiber, and thus separates the signals from that particular channel. It can again add the same wavelength to data flow in the same direction but with different data content.

OADMs are classified as Fixed Optical Add-Drop Multiplexers (FOADMs) and Reconfigurable Optical Add-Drop Multiplexers (ROADMs). FOADM was originally developed to enhance the delivery of express traffic through networks, without the requirement of expensive optical-to-electrical and electrical-to-optical conversion. FOADMs use fixed filters that can add/drop a selected wavelength and pass the remaining wavelengths through the node. The major drawback of FOADM is that the wavelength that has been selected, remains the same until human intervention changes it. In order to change traffic volume or patterns, there is a huge site-visit cost, and all the modification or reconfiguration has to be done manually, which is a time-consuming task. It is also limited to two directions.

In the early 2000s, ROADM was developed to adjust to the changing traffic demands easily. In ROADM, the wavelengths between the optical de-multiplexer/multiplexer can be dynamically directed from the outputs of the de-multiplexer to any of the inputs of the multiplexer. ROADMs enable remote configuration of light paths. In optical mesh-based networking, it supports more than two directions at sites. It can easily adjust which wavelengths to add and drop, and it has the ability to redirect wavelengths passing through the site. ROADM simplifies operations by automating the connections through an intermediate site, so there is no need to change a wavelength's path through the network manually.

The wavelength selective switch (WSS) is the key component in commercial ROADM systems. WSS can dynamically route, block, and attenuate all DWDM wavelengths within a network node. It has the functionality of de-multiplexing any of the individual wavelengths to the selected common or output ports. It achieves this ability by dispersing incoming light onto a switching engine that can uniquely address each part of the spectrum. Figure 3.1 shows a WSS that consists of a single common optical port and N opposing multi-wavelength ports where different wavelength channels from input fiber can be independently switched to different output ports.

Figure 3.1: A WSS with a single common optical port and N output ports



Adapted from: *The Seven Vectors of ROADM Evolution*. (n.d.). Retrieved from Infinera: https://www.infinera.com/wp-content/uploads/The-Seven-Vectors-of-ROADM-Evolution-0302-WP-RevA-1121.pdf

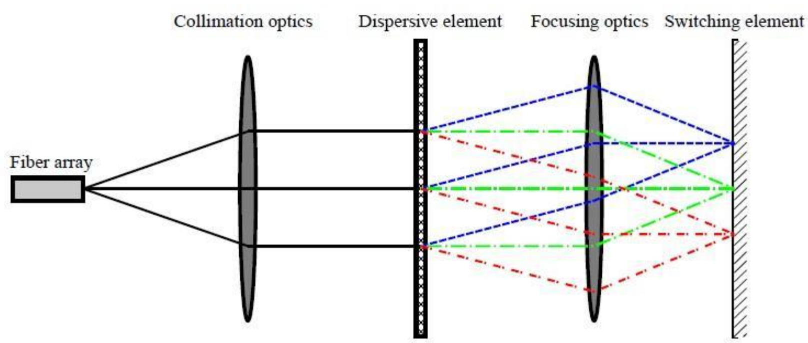
Initially, ROADMs used fixed-grid Wavelength Selective Switch (WSS) technology that can function on a specific channel plan and spacing. The most commercially available fixed-grid WSS supported a maximum of 9 ports on a 50/100 GHz fixed grid. These ROADMs were based on 50 GHz or 100 GHz fixed grid channel spacing. Each wavelength added to the network needs to fit within this rigid channel spacing so that it can pass through the ROADM. With the invention of coherent technology, higher baud signals with wider channel sizes were in demand, wavelengths began to require more channel spacing, and a fixed-grid system was unable to provide that channel space. Then flexible grid technology was introduced, and ROADMs evolved to support flexible grids, and individual channels can use different channel widths and spacing. The flex grid technology supports 50GHz to 200GHz channel spacing. For instance, transmitting a 400Gbps signal at 50GHz channel spacing is impossible. However, if two 50GHz channels are joined into a single 100GHz channel, a 400Gbps signal can be transmitted. The major advantage of flex grid technology is that it is operated by software, so it is possible to change the channel spacing according to specific requirements dynamically. Flex grid supports 6.25GHz or 12.5GHz granularity. It allows the channels to be tuned to specific bandwidth requirements. A 400Gbt/s signal format is expected to fit into a 75GHz wide channel, by tuning the 100GHz channel to a 75GHz channel to support a 400Gbit/s signal, the spare 25GHz space can be saved for other applications.

Numerous technologies can be used as a WSS switching engine. While early ROADMs were based on wavelength blocker and planar lightwave circuit (PLC) technologies, the current WSS technologies are based on micro-electromechanical systems (MEMS) mirrors, liquid crystal (LC), and liquid crystal on silicon (LCoS). The first ROADM-based networks using WSS were deployed in the early 2000s, using single WSS in a Broadcast and Select (B&S) architecture, and it was fixed-grid. It became necessary to meet various requirements to facilitate evolving network applications such as higher port count, premium port, and multiple common ports with the further development of ROADM. The huge number of micro mirrors in MEMS affects its performance stability. Also, it is hard for MEMS to support a high port count (>20) and flexible grid. LC has much better stability. However, the main disadvantage of LC technology is the thickness of the stacked switching elements. Also, it has a limited ability to high port count. Liquid Crystal on Silicon (LCoS) technology dominates current WSS installations as LCoS-based WSS can support Flex-grid technology-enabled networks, and high port counts with excellent performance. With the development of LCoS WSS, both twin WSS enabling Route and Select (R&S) architecture, and 20 port WSS were commercially available.

3.1.1 Generic WSS

One of the key benefits of LCoS is that there is no requirement to lock the spectrum of the switching to any predetermined channel plan. The LCoS WSS allows modern photonic line systems to increase spectral efficiency and reduce cost, power, and space per bit. Figure 3.2 shows the working principle of a generic WSS. Multiple wavelengths come from the input port, where the input port is part of the fiber array. The fiber array is perpendicular to the screen. The light from the input port is first extended and collimated by the collimation optics. Then the light is projected onto the dispersive element. In LCoS-based WSS, the dispersive element is a conventional grating element. The purpose of the dispersive element is to spatially separate the multiple wavelengths. With conventional grating, the wavelengths are separated into different angles. These lights are still collimated, and then they are focused by the focusing optics and projected under the switching element. The switching element directs different wavelengths to different output ports. In LCoS-based WSS, this switching element is the LCoS chip. The switching element directs lights to different perpendicular angles. The direction of the fiber array is perpendicular to the screen, so when the light twists back, they are focused into different output ports depending on the switched angle by the switching element.

Figure 3.2: Schematic of a generic WSS

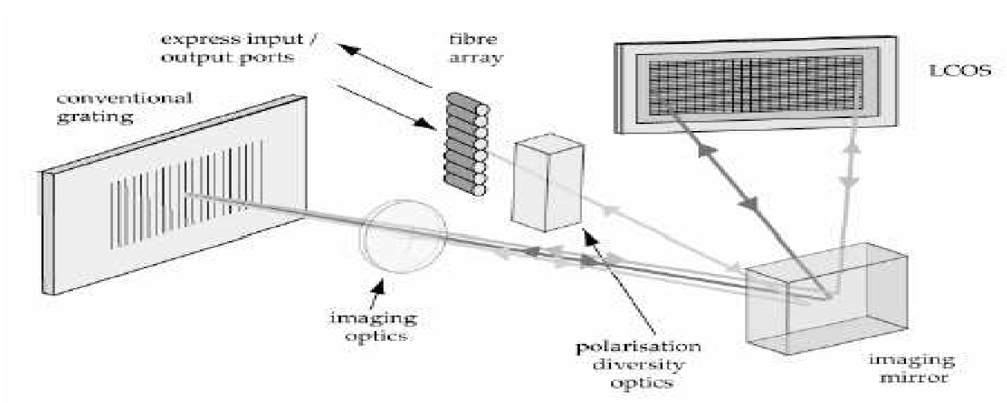


Adapted from**:** Hardy, S. (2017, November 7). *Open optical line system pros and cons at the Open Optical Conference*. Retrieved from Lightwave: https://www.lightwaveonline.com/optical-tech/transport/article/16673512/open-optical-line-system-pros-and-cons-at-the-open-optical-conference

3.1.2 LCoS-based WSS

Figure 3.3 shows the Schematic of the Optical Design of LCoS-based WSS. Multiple wavelengths of light pass through the fiber array from the input fiber. Since the fiber is single-mode fiber, the polarization of the light is random. However, the conventional grating is very sensitive to the polarization of light, so the polarization has to be controlled. The purpose of polarization diversity optics is to transform the polarization of the input light into linearly polarized. In addition, the polarization is transformed into S-polarization relative to the conventional grating because the conventional grating has maximum diffraction efficiency at S-polarization. The light passes through the first imaging optics and is reflected by the cylindrical mirror, and then it passes through the second imaging optics. Here the light is collimated and then projected and then projected onto the conventional grating, as discussed in the generic WSS design. After passing through the second imaging optics and then being reflected by the cylindrical mirror, the light is now focused on the liquid crystal on the silicon (LCoS) chip surface. However, different wavelengths are focused on different ports. The LCoS chip reflects light to different vertical angles, so when the light traces back through all the elements, it gets focused into a different output port depending on the reflecting angle.

Figure 3.3: The Schematic of Optical Design of LCOS-based WSS



Adapted from: Baxter, G., Frisken, S., Abakoumov, D., Zhou, H., Clarke, I., Bartos, A., et al. (2006). Highly programmable Wavelength Selective Switch based on Liquid Crystal on Silicon switching elements. *Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference.* Anaheim, CA.

ROADMs are based on two primary architectures: Broadcast and select (B&S), and Route-and-select (R&S) ROADMs. There are different types of ROADM based on WSS ports. The most common sizes of WSS are 1x2, 1x4, 1x9, 1x20, and 1x32, where the first digit refers to the line port and the second digit refers to the number of available ports for connecting to the other degrees or for add/drop.

The next-generation ROADM supports colorless, directionless, and contentionless functions. A reconfigurable optical add/drop multiplexer (ROADM) with colorless, directionless, and contentionless (CDC) function enables the connection of optical add/drop signals from/to any direction at any wavelength and local transponders without any signal contention.

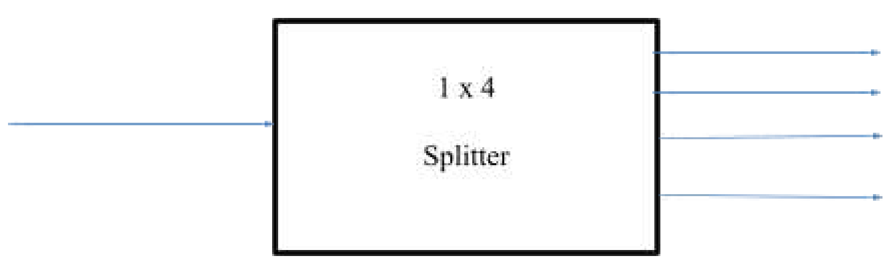
Colorless means that an add/drop port of a ROADM is not wavelength selective; therefore, any wavelength can be added/dropped at any add/drop port of a ROADM. Traditional ROADMs were limited by fixed add/drop transceivers and wavelength assignment. When a wavelength is selected, the transceiver is manually connected at add/drop site to the correct mux/demux port. So, to make a change, the add/drop site must be physically wired and rewired. But the colorless function automates the assignment of add/drop wavelength functionality. By software control and tunable transponders, any wavelength of any color can be assigned to any port. It eliminates the requirement for a technician on site.

Traditional ROADMs were also directionally dependent. The add/drop ports and the transponders connected to the ports are fixed in an outgoing direction. Changing the direction of a particular transponder needs site-visit and physical rewiring by a technician. Directionless means that each add/drop port of a ROADM is not nodal degree selective, and therefore any channel added on a port can be directed to any nodal degree, and vice versa. This function allows any wavelength to be routed in any direction by software control and without physical wiring.

The problem with colorless and directionless ROADM is that wavelength blocking can occur when two wavelengths of the same color converge at the same WSS structure at the same time, which causes network contention. Contentionless means that the same wavelength can be added/dropped at the same add/drop module. It allows multiple copies of the same wavelength on a single add/drop structure.

3.1.3 Optical Splitter

In recent optical network topologies, the fiber optic splitter helps users maximize optical network circuits performance. A fiber optic splitter can split a wavelength into two or multiple wavelengths, and vice versa. It contains multiple input and output ends. The passive optical splitter can split at a certain ratio. The configuration of (1x4) splitter, is the basic structure. It separates a wavelength in a single input fiber cable into four wavelengths and transmits them through four individual output fiber cables. For example, if the input fiber optic cable carries 2000 Mbps bandwidth, then four end users can use the network with 500 Mbps bandwidth.



The 2 x 64 optical splitter, is more complicated than the 1x4 splitter. The 2x64 splitter has two input terminals and sixty-four output terminals. Its function is to split wavelength from two individual input fiber cables into sixty-four wavelengths, and it can transmit them through sixty-four light individual output fiber cables. The requirement for larger splitters in networks has increased with the rapid growth of FTTx worldwide to serve mass subscribers. According to different transmission mediums, there are multimode optical splitter and single mode optical splitter. In multimode optical splitter, the fiber is used for 850nm and 1310nm operation, whereas in single mode the fiber is used for 1310nm and 1550nm operation. There are also FBT splitter (fused biconical taper splitter) and PLC splitter (planar lightwave circuit splitter). The maximum split ratio of FBT splitter is up to 1:32, and the split ratio of PLC splitter is up to 1:64. PLC splitter has several types such as bare PLC splitter, blockless PLC splitter, ABS splitter, LGX box splitter, fanout PLC splitter, mini plug-in type PLC splitter, etc.

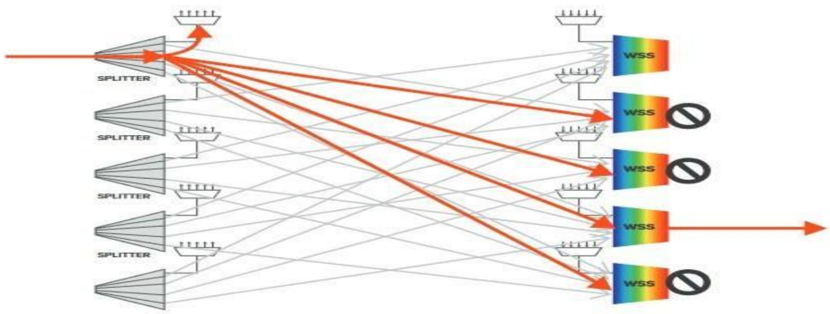
3.1.4 Optical couplers

Optical couplers are photonic devices that take an optical signal in one port and divide it to other ports. A commonly used coupler configuration has one input and two outputs (1x2). There are other configurations such as two inputs and two outputs (2x2), one input and four outputs (1x4), and two inputs and three outputs (2x3). The coupling ratio indicates ratio that the input optical signals are divided between the outputs. It depends on the configuration of the coupler. The commonly used coupling ratios are 50:50, 90:10, 80:20, and 70:30.

3.1.5 Broadcast and select (B&S) architecture

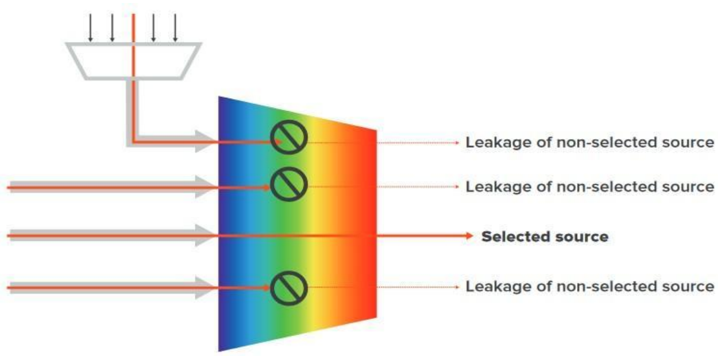
Broadcast and select (B&S) architecture works by taking all the wavelengths from each degree and broadcasting them to a splitter. The WSS, on the egress side, receives a copy of each active wavelength from every other degree and also from the add/drop units for that degree, if there are any. B&S ROADMs contain fewer WSSs. It is cost-effective and mostly deployed for network nodes with degrees less than nine due to the unacceptable insertion loss of the power splitter. At the same time, the splitting ratio is greater than 9. Therefore, single 1×9 WSS is mainly used in B&S nodes. However, if the number of ROADM degrees grows, there is a need for more splitting at the ingress, which causes more loss. It requires more amplification and ultimately results in more noise. And when the needed source is selected, some leakage of the non-selected sources for that wavelength may occur, as shown in Figure 3.5. Since the power splitter allows all spectrums that increase the noise level, a vital design focus of a single WSS is to increase the port isolation specification to at least 40dB for all port, channel, temperature, and attenuation combinations.

Figure 3.4: Broadcast and Select Architecture



Adapted from: John. (2021, December). *What Is a Fiber Optic Splitter?* . Retrieved 6, from FS Community: https://community.fs.com/blog/what-is-a-fiber-optic-splitter-2.html

Figure 3.5: Egress WSS in B&S ROADM



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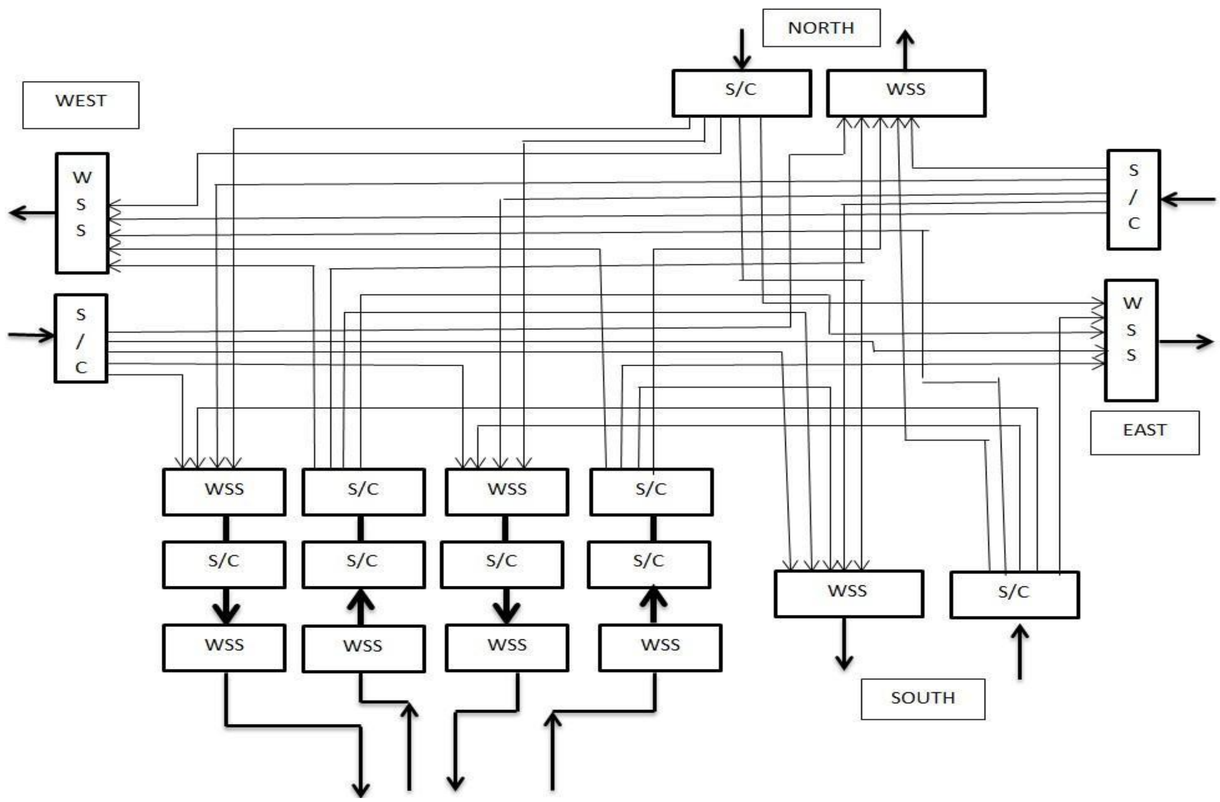
3.1.6 WSS-based Colorless and Directionless Architecture at a 4-degree node

Figure 3.6 shows the Colorless and Directionless architecture using 1x9 WSS modules and multi-port splitter combiners. The wavelengths from all four directions encounter a splitter providing a 1x8 power split. While three of the eight ports in the splitter are connected to the WSS along the other three directions, two ports are connected to the two WSSs to provide local drop at node A. The rest of the ports are reserved for scaling in the future. The WSS at the drop site consolidates the wavelengths from different directions. The wavelengths are then split using a 1x8 splitter. It provides an expansion facility since the number of wavelengths to be received may exceed the number of available ports on the WSS. Subsequently, a second WSS at the add/drop site provides a colorless add/drop across its ports.

Figure 3.6: WSS-based Colorless and Directionless Architecture at a 4-degree node



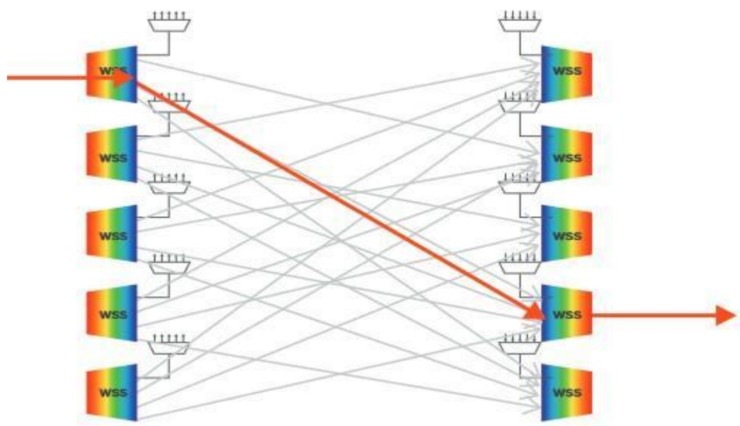
Adapted from: Ma, Y., Stewart, L., Armstrong, J., Clarke, I., & Baxter, G. (2021). Recent Progress of Wavelength Selective Switch. *Journal of Lightwave Technology, 39*(4).

To realize the colorless add feature, again, WSS is used to consolidate all the wavelengths that originate at node A. Since any wavelength can be added at any port of the WSS, it becomes a colorless addition. An 8x1 combiner then provides expansion similar to the splitter on the drop side. A splitter then splits it 8 ways, connecting all the directions. A WSS is present along each direction, which either blocks or allows a certain wavelength along that direction. Thus a wavelength added at A can be sent along any direction, realizing a directionless feature. The WSS is a better choice at the add site as it offers many intelligent functionalities. Since the WSS provides channel specific blocking feature, the drifting channel alone can be blocked. If a combiner were to be used instead, it cannot provide such functionality as it is a passive device. The WSS-based Colorless and Directionless ROADM architecture offers other valuable advantages too. All the wavelengths entering node A from any direction can be routed to any other direction using the splitter, while simultaneously making all of them available at the local drop of node A. Also, the wavelengths added at the local node A can be routed in any direction as a splitter is provided at the add site. Thus, any wavelength either coming in from any direction or originating at that node can be multicast to all directions.

3.1.7 Route & Select (R&S) architecture

By integrating two WSS, in a single module, the twin WSS modules by Finisar were optimized for the new generation of Route & Select (R&S) ROADMs. R&S ROADM architecture has a WSS on the ingress, so it can direct the wavelength to only the required egress ROADM degree, and there is no splitter. This makes them more scalable as there is no splitter, and the loss is independent of the number of WSS ports. Twin WSS are becoming increasingly popular in core networks since this enables R&S node designs at a reasonable cost. These systems share both optics and electronic control circuitry making them only incrementally more expensive to build than single systems. As the majority of node architecture, R&S is able to employ a higher port count WSS to support more degrees, and reduce Optical Signal to Noise Ratio (OSNR) penalty sourcing from noise accumulation.

Figure 3.7: Route and Select ROADM



Adapted from: John. (2021, December). *What Is a Fiber Optic Splitter?* . Retrieved 6, from FS Community: https://community.fs.com/blog/what-is-a-fiber-optic-splitter-2.html

3.1.8 Quad WSS

Dual WSS modules can be used to build 2xNxM Add/Drop modules with CD function, and further, four WSS integrated can create a single module new generation Quad WSS product without sacrificing optical performance. Quad WSS is four independent WSS units in a single module, which enables four degrees of B&S or two degrees of R&S functionality in a single low-profile line card. Each WSS can be configured independently of the others. Each WSS is bidirectional and can be used as Mux or Demux. Utilization of quad WSS may result in greater reliability and lower power consumption, for the overall ROADM system. In 2020, Finisar Australia releases the world's first Quad wavelength selective switch (4x1x9 WSS) with Flexgrid technology for use in next-generation reconfigurable optical add-drop multiplexer (ROADM) networks.

Figure 3.8: Finisar’s quad 4x1x9 wavelength selective switch

Adapted from: (n.d.). Retrieved from Finisar: https://finisarwss.com/

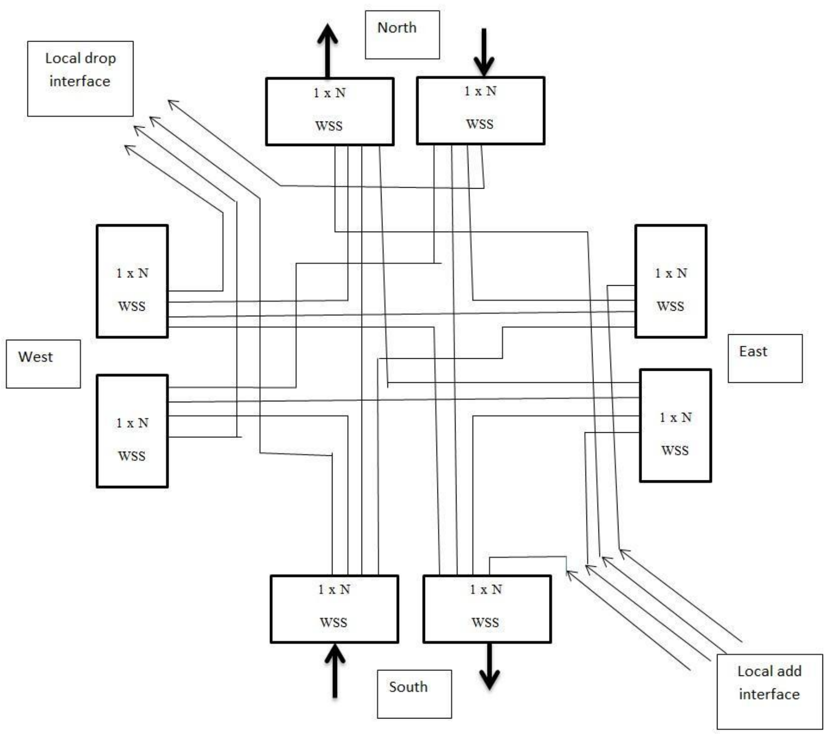
With the growing deployment of R&S ROADM by network operators, various requirements have been raised to facilitate evolving network applications. High port count requirement continues today since the first WSS was invented. The demand for ports comes from three sources: Firstly, regional data centers are more and more likely to be included in the transport network, further increasing the number of ROADM nodes. For the sake of low latency, which is crucial for 5G and other time-sensitive services nowadays, network flattening has become a trend in the evolution of network architecture. Therefore, full mesh connections are highly preferred, increasing the ROADM degree requirement. Secondly, optical line protection and pre-defined restoration requirements for some high-quality services need to reserve additional WSS ports and fiber paths for protection and restoration redundancy. Lastly, 400Gb/s and beyond transceivers using flexible baud rate and constellation mapping require Multiplexers and De-multiplexers (Mux/Demux) to support flexible grid, and high port count WSS can be extremely helpful acting as Mux/Demux to simplify the Mux/Demux architecture. One of the challenges for the design of high port count WSS devices is port isolation. This comes from both the size constraints placed on commercial WSS devices, and the increased switching angles for the LCoS. Simplistically, if more fibers are added to a WSS of the same size, then the fibers may need to be put closer together. This increases the leakage of light between adjacent fibers. Alternatively, if space is not a premium, then the LCoS needs to switch through larger angles, which can create more digitization and increase insertion loss. These issues had been overcome, and commercial high port count WSS was built with excellent port isolation, typically for R&S network architectures.

The performance of Broadcast & Select and Route & Select with a 1x9 or smaller port WSS is minimal. Above 1x9, such as 1x20 WSS or higher degree, R&S has a better performance rate. A 1x9 B&S WSS can provide a good solution for fixed add/drop ROADM, and colorless-directionless or CD function with up to four degrees. R&S is highly recommended for colorless-directional or CD function and colorless-directionless-contentionless function with five or more degrees. In addition to the standard common port, WSS can be designed to have multiple common ports. The evolution of multi-common port WSS is CDC WSS, which supports contentionless add/drop for CDC-ROADM. Colorless, Directionless, and Contentionless (CDC) ROADM architecture can be realized by combining the WSS with a multicast switch (MCS). The CDC add/drop solution for ROADM is based on the M × N multicasting switch, and the ROADM based on route and select WSS, and MCS provides colorless, directionless, and contentionless (CDC) feature.

3.1.9 Transit side of a 4-deg ROADM based on the route and select architecture

Figure 3.9 shows the transit side of a ROADM based on the route-and-select architecture, which interfaces the local add/drop side. The transit side of a ROADM is responsible for redirecting the WDM channels from one direction to another.

Figure 3.9: Transit side of a 4-deg ROADM based on the route and select architecture



Adapted from: Yang, H., Robertson, B., Wilkinson, P., & Chu, D. (2017, May). Low-Cost CDC ROADM Architecture Based on Stacked Wavelength Selective Switches. *Journal of Optical Communications and Networking, 9*(5), 375-384.

In this architecture, the incoming WDM channels from a network direction will pass through a couple of paired 1 × N WSSs. The first 1 × N WSS routes the signals to the destined direction, while the second WSS multiplexes the signals together with those from other directions for further transmission. Although it is possible to replace the 1 × N WSS (used in reverse) at the exit side of each direction with a 1 × N coupler to realize the same routing functions but the 1 × N WSSs provide better channel isolation and lower insertion loss, especially in a multi-degree ROADM. For an R-degree ROADM based on this architecture, each direction requires two 1 × N WSSs; therefore, 2R 1 × N WSSs are required in total. For each 1 × N WSS, the port count N needs to be at least R, i.e., (R − 1) ports to be connected with WSSs for other directions, while at least one port is reserved for the add/drop interfaces. For the example of a 4-degree, ROADM node eight 1 × N WSSs are required, where N needs to be at least 4.

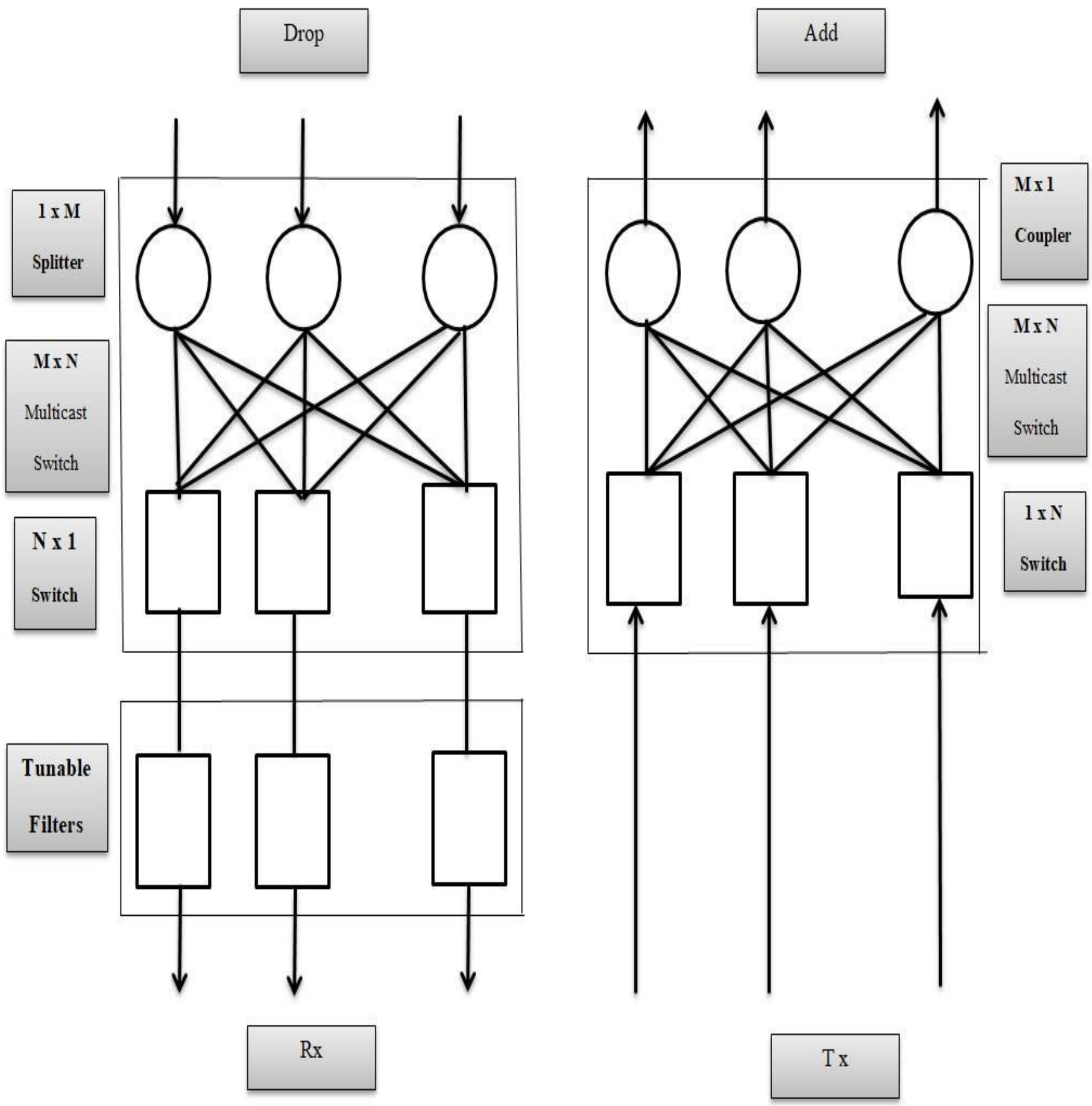
3.2 Multicast Switch:

To realize the Colorless, Directionless, and Contentionless function of ROADM, a transponder aggregator (TPA) is needed. It is an optical switch that can assign any wavelength and any direction to each transponder, and it must be employed between the add/drop ports and the transponders. An N × M TPA is required on both the drop and add sides; here, N is the number of input/output routes, and M is the number of transponders. In the TPA, WDM signals are incoming from or outgoing to the ROADM, while a single wavelength is received from or sent to the transponders. On the drop side, the capability to connect different wavelength signals from the same direction to different transponders is required, while on the add side, the capability to launch different wavelength signals from different transponders in the same direction is required.

The multicast switch offers a compact and cost-effective TPA among all TPA configurations. The architecture of an M × N multicast switch is shown in Figure 3.10. In a multicast switch, an array of M 1 × N splitters/couplers is paired with another array of N 1 × M optical switches. M × N multicasting switches are designed for an M-degree network node and are able to add N wavelength channels to the network node in a CDC fashion or vice versa. In a multicast switch on the drop side, WDM signals from each direction are broadcasted by a 1 × M splitter, and the signals from the desired incoming fiber are selected by an N × 1 optical switch. This architecture enables us to select an optical signal at any wavelength from any direction. The optical switch rejects the same wavelength signals from other input directions, eliminating any signal contention in the TPA. On the add side, the output signals from the transponders are routed to a desired outgoing fiber by a 1 × N switch array, combined with different wavelengths by an M × 1 coupler, and then launched into the add ports of the ROADM. This architecture enables to send an optical signal at any wavelength in any output direction.

In a typical node, each input fiber carries 80 wavelength channels, and 20% of them are dropped for local processing. As a result, Ndrop M × N multicasting switches are required for the CDC drop operation in an R-degree ROADM node, where $N_{drop} = R \times 80 \times 0.20 / N$. Accordingly, the port count of the 1 × N WSSs used in the transit side will be $R + N_{drop} - 1$. Considering that the same number of channels also needs to be added to the network node for further transmission, the equivalent number of M × N multicasting switches will be required for the CDC add operation. Due to the high loss of the M × N multicasting switches, an array of M amplifiers needs to be placed at the interface between each multicasting switch and the transit side of the ROADM. In total, two M × Ndrop amplifiers are required for the CDC add/drop operation.

Figure 3.10: The block diagram of an M × N Multicast Switch



Adapted from: Yang, H., Robertson, B., Wilkinson, P., & Chu, D. (2017, May). Low-Cost CDC ROADM Architecture Based on Stacked Wavelength Selective Switches. *Journal of Optical Communications and Networking, 9*(5), 375-384.

Tunable filters are also required by the transceivers at the drop side, if the transceivers do not have coherent detection capability, as the multicasting switch itself does not have a filtering function. A WDM signal at the desired wavelength is extracted by a tunable filter, and then the transponder receives the selected signal. Given the high cost of tunable filters, especially those compatible with the flexible spectrum standard, it would only be cost-effective to deploy CDC add/drop solutions based on the multicasting switches in conjunction with the transceivers with the coherent detection capability.

3.3 The optical network physical layer impairments

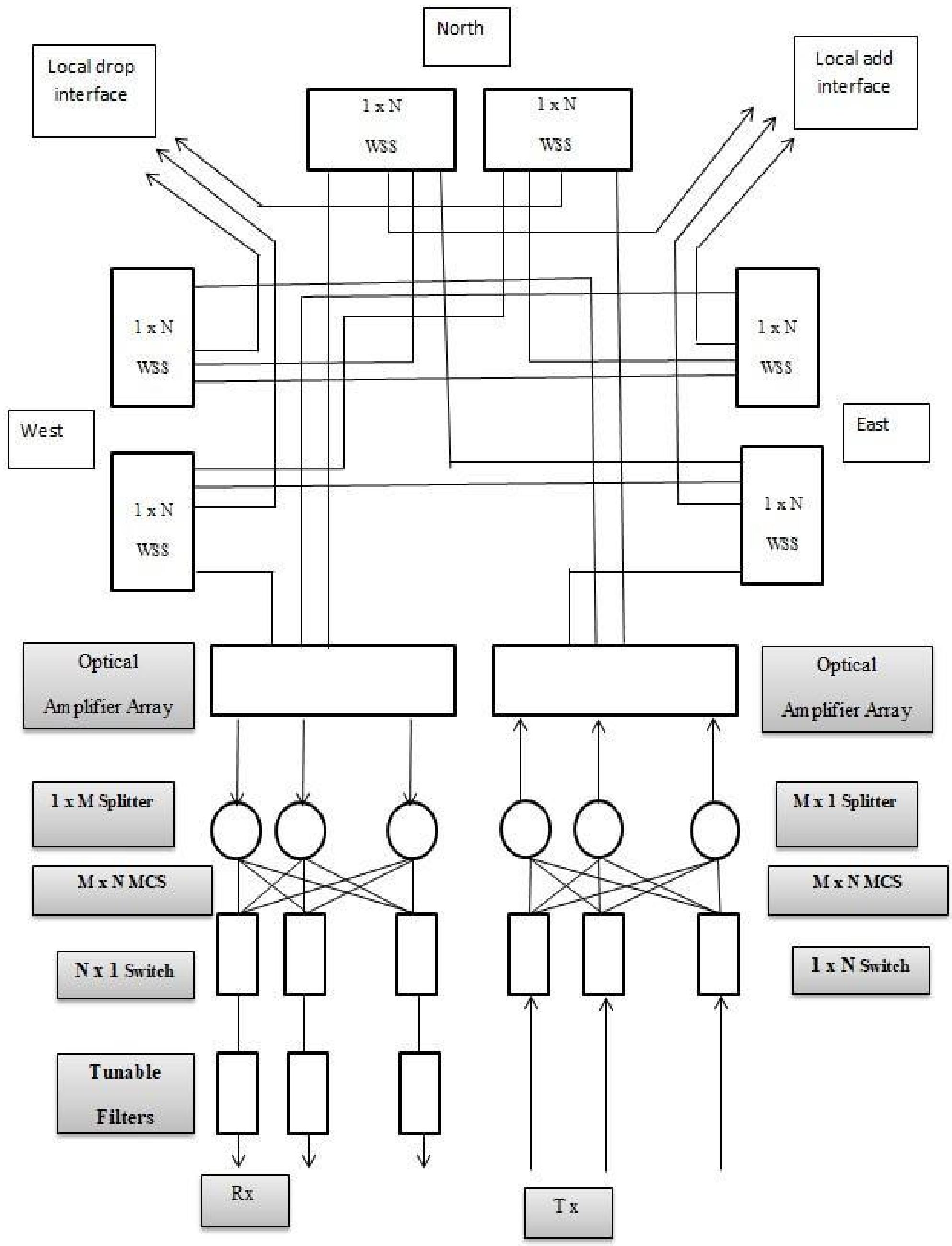
The optical network physical layer impairments (PLIs) have to be considered since the optical signal along its path, passes through optical fiber links as well as optical components inside the ROADMs, such as optical switches, Mux/DeMux and splitters/couplers. The losses, noises, and interferences generated in these links accumulate along the light-path degrading the optical signal transmission. In particular, the imperfect isolation of switches and filters inside the ROADMs leads to signal leakages that originate interfering signals known as crosstalk signals. One of the crosstalk types that become enhanced in an optical network and degrades the optical network performance is the in-band crosstalk. The in-band crosstalk occurs when the interfering signals have the same nominal wavelength as the primary signal but originated from different sources so this impairment cannot be removed by filtering. In ROADM-based optical network, the in-band crosstalk will accumulate over the ROADM cascade and can limit the number of nodes that the signal passes in the network. The R&S architecture is the most robust architecture in terms of the in-band crosstalk generated inside multi-degree CDC ROADMs. The impact of in-band crosstalk, optical filtering, and ASE noise in a cascade of multi-degree CDC ROADMs based on the R&S architecture, the architecture with MCSs and WSSs-based add/drop structures lower the generation of in-band crosstalk.

3.4 CDC ROADM

Figure 3.11 shows the architecture of Colorless, Directionless, and Contentionless (CDC) ROADM composed of Wavelength Selective Switch, Multicast Switch and an array of amplifier.

The Colorless, Directionless, and Contentionless (CDC) ROADM is composed of a 1×N port WSS and a multicast optical switch MCS. An M×N port MCS switch has M input ports and N output ports and is composed of M 1×N port optical splitters and N M×1 port optical switches. The optical signal is input from one of the input ports, and is first divided into N parts by the optical splitter, and broadcast to all N optical switches; then the optical switch corresponding to the target output port selects the received optical signal, and other optical switches ignore its signal. According to the 1×N port WSS and MCS functions, this ROADM structure can realize the CDC function. However, the optical splitter in the MCS generates too much loss when splitting and broadcasting, so an optical amplifier array is required to supplement the optical power.

Figure 3.11: The architecture of Colorless, Directionless, and Contentionless (CDC) ROADM



Adapted from: Yang, H., Robertson, B., Wilkinson, P., & Chu, D. (2017, May). Low-Cost CDC ROADM Architecture Based on Stacked Wavelength Selective Switches. *Journal of Optical Communications and Networking, 9*(5), 375-384.

4. Use Cases

800G Coherent Optical Technology

The demand for optical network systems that offer 800Gbps coherent optical channels is a use case for open line system. The commercial availability of this technology is relatively recent; there are still only a limited number of vendors offering 800G capable systems. However, because the primary 800G technology is based on transponders (rather than on optical line systems), an open optical line system would enable a service provider to select a transponder vendor that offered 800G even if it was a different vendor than the service provider's line system vendor.

Metro Point-to-point DCI

Data Center Interconnect (DCI) technology uses high-speed packet-optical connectivity to connect two or more data centers over short, medium, or long distances. Data Centers need to talk to each other to share data and content and provide back-ups for redundancy. DCI technology enables the transmission of critical assets over any distance. Data centers require compact products that meet data center requirements such as AC power, front-to-back airflow, and 600 mm depth. Point-to-point DCI over metro distances is an obvious starting point for OLS. In a point-to-point nature, a single vendor can provide both ends of the OLS, while a different vendor, or vendors, can provide the traffic-bearing functional blocks, also with data center form factors.

Metro Mesh

The metro mesh topologies comprise rings and mesh topologies with a much larger number of nodes. The complexity of a metro mesh topology with more nodes require a transport SDN controller to provide a layer of abstraction with open APIs on the controller rather than the network element itself. Relative to long-haul, with more limited reach requirements, interoperable FEC and ROADM degree interoperability become options in the metro, enabling multi-vendor scenarios both within functional blocks/layers as well as between functional blocks/layers.

Long-Haul

Long-haul differs from the metro use cases in terms of the optical performance required to support much longer distances. This requirement for performance cannot be met with lowest common denominator technology required for interoperability and requires vendor-specific innovations to achieve the maximum performance. In terms of WDM optical interface technology, these innovations include enhanced FEC, spectral shaping, impairment compensation, novel modulation, and increased baud rates. WDM line system innovations that impact reach include the link control and amplification technology. For these reasons, long-haul networks are likely to maintain a single vendor for the OLS layer, and while capable of supporting multiple vendors at the traffic bearing layers, equipment at both ends of each wavelength is likely to be from the same vendor. Like metro mesh, given the complexities of optimizing performance in a long-haul network, a transport SDN controller is required for abstraction.

Submarine

Using different vendors for the traffic-bearing functional block, typically referred to as Submarine Line Termination Equipment (SLTE), and WDM line system, typically called "wet plant," is not new in submarine networks. However, what is new is that while in the past, submarine, networks were initially deployed with a single vendor and then evolved to multi-vendor systems with new vendors introduced for SLTE, new submarine systems are starting to be deployed with different vendors for the SLTE and wet plant from day one. Wet plant and SLTE technology evolve at very different rates and the wet plant must be selected and deployed long before the SLTE. This approach lets the submarine cable operators select the best SLTE at the time it will be deployed rather than at the beginning of the wet plant deployment cycle.

Different possible ways of deploying OLS

There are many ways of deploying an OLS. An operator can choose how disaggregated their OLS solution they would like to be. OLS is not a "one size fits all," and it depends on the operators' environment. For deploying OLS, the WDM system is divided into functional blocks, the next thing to consider is the number of vendors for each functional block and the network software. After disaggregating the WDM system into an OLS and a traffic bearing functional block (transponder/muxponder and/or transport switching) with an SDN control layer, then there are many approaches to complete the network.

i. First approach could be to use different network elements for the OLS and the traffic block but with the same vendor providing both network elements and the SDN software.
ii. Second approach is a variation of the first approach using the same vendor for the OLS and traffic block but with in-house or third-party SDN.
iii. Third approach is to use one vendor for the OLS and a second vendor for the traffic block. In fact, this approach with alien muxponders and third-party SDN is already being deployed for data center interconnect (DCI).
iv. Fourth approach is to use a single vendor for the OLS where interoperability is most challenging, while using two or more vendors at the traffic bearing block with interoperability between WDM interface optics enabled by using the same modulation and common forward error correction (FEC).
v. Fifth approach encompasses using multiple vendors for each functional block with the addition of interoperability between OLSs from different vendors including the OSC and link control/power level setting.

5. Challenges

The key challenges of OLS are created with regard to the ownership and implementation of the network building blocks. These building blocks, such as network design, are fundamental and necessary to the deployment and operation of any network. However, the implementation of these building blocks must be carefully considered when deploying optical networks to ensure that one's implementation addresses the needs of all involved parties. Network planning will need to design and plan network capacity growth, and operations will need tools to analyze and operate the network. In addition, introducing multiple vendors' hardware into a common optical network creates new design and operations complexity, while also establishing a need to safeguard vendor intellectual property and competitive information.

Network Planning and Design

Some of the essential resources or services for network engineering and capacity management organizations are Network Planning and Design tools. Proprietary tools are available with most ROADM solutions today and accurately characterize the capabilities of supported systems. However, transitioning to an open, multi-vendor environment requires adapting or re-architecture these tools. In addition, the myriad combinations of vendor transponders and ROADM networks require new approaches. Some of these include: (1) an open network design solution that protects confidential information of vendors needed for network design purposes; (2) offline network characterization tools and services that prequalify or estimate optical performance over ROADM infrastructure; and (3) closed- loop learning algorithms and solutions that optimize network design based on performance criteria and risk tolerance.

Capacity Management

The issues that affect multivendor planning and design also impact Capacity Planning and Management systems. These systems leverage detailed knowledge of both the ROADMs and transponders, and require accurate estimation of optical reachability among all potential endpoints on a ROADM network. Organizations responsible for Capacity Management use this information to ensure on-time delivery of end-customer services. As with Planning and Design tools, transitioning to an open, multi-vendor environment requires an adaptation or re-architecture of Capacity Management solutions. The information obtained from network design tools and services can be utilized for capacity management purposes using APIs to upload to the Path Computation Engine (PCE) and offline capacity management tools. It is critical that the same information and network/service inventory is available to all systems to ensure accurate records management and seamless automation.

Service Design and Activation

Similar to Network Design and Capacity Management, the design and activation of services over a multi-vendor, open network requires careful consideration and integration into any production architecture. With proper capacity management, business process automation in this functional area will allow service providers to automate service creation to support use cases such as Dynamic Service Activation and Topology Automation. Service activation, reconfiguration, and optimization will require accurate network and service inventory, optical reach estimation, and real-time knowledge of network performance. Furthermore, as the network is deployed and additional performance statistics are available for analysis, the information available can be leveraged to further optimize network design and performance as well as mitigate network performance degradations.

Service Assurance

With traditional line systems and all of the other portions of the network, the operator had a huge weight lifted off of their shoulders, which involves reassurance. Vendors spend an incredible amount of research and development dollars assuring that their products will work within their contained system, if that means between the WDM line interfaces or the integration of transponders and muxponders within a chassis-based solution. Regardless of how far a vendor's solution reached, they always controlled that environment and would assure functionality. With disaggregation and OLS, this somewhat goes out the window. A vendor can comply with standards and agreements of openness, but the testing and functionality burden will fall mostly on the operator to ensure the systems operate as expected.

Complexity

For those who are used to doing things from a traditional transport system perspective, OLS may be a more complex task. In traditional systems, there is a simplistic method in which provisioning and monitoring happen. Again, OEMs spend a lot of R&D on being certain this works, and it is as easy to use as possible for their customers. There is a certain amount of open API "know-how" and experience that will be needed.

6. Conclusion

Reducing vendor lock-in is the greatest attraction of the OLS approach. OLS reduces vendor lock-in, reducing the barriers of introducing new vendors as and when needed, in accordance with the renewal cycle of each layer/functional block. New vendors with best-in-class technology for specific functional blocks can be introduced incrementally without the need for forklift upgrades, swapping out the entire optical network or building a parallel network. While the initial purchasing process for a traditional WDM network is typically highly competitive, once a vendor has been selected and the network has been deployed, the bargaining power of the network operator is severely diminished. The vendor gets stronger position regarding future pricing negotiations. By reducing vendor lock-in and enabling other vendors to compete for incremental upgrades based on the renewal cycle of each functional block, competitive pricing pressures can be maintained throughout the lifecycle of the network. Furthermore, by lowering barriers to entry, innovative smaller vendors can also compete without being able to offer a complete solution including the NMS. An increased number of competitors will also have a positive impact on the ability of network operators to drive attractive pricing.

Another key benefit of open line system is that it supports faster innovation cycles, which allows quicker adoption of technological advances. The concept of rapid innovation in optical networking is not merely hypothetical. The industry is currently experiencing the emergence of two advances that are greatly facilitated by open optical networking, 400G coherent optical pluggable modules and 800G coherent transponder technology. OLS can easily adapt to changing requirements with dynamic spectrum allocation, flexible add/drop structures, and optical mesh restoration. It supports for seamless growth, including C- and L-band expansion to handle even the most challenging network requirements. Also, 400ZR and 400ZR+ coherent optical pluggable modules promise to provide significant savings for the connections between routers, switches, and multiplexers. As 400ZR and 400ZR+ coherent optical pluggable modules will be sourced from the optical line system vendor, benefits provided by 400ZR and 400ZR+ are largely dependent on the use of open optical networking for these connections. Thus, widespread deployment of these coherent optical pluggable modules should drive deployment of open optical networking. Also, the service providers' optical networks are growing at a high rate which can enable the introduction of open optical networking without requiring the replacement of existing infrastructure.

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