WHITE PAPER

Optical Dynamic Core Networks

Design, Implementation and Engineering Considerations

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Introduction

Developments in optical component technologies, specifically the Reconfigurable Optical Add/Drop Multiplexer (ROADM) used for wavelength steering, have enabled more complex reconfigurable optical networks. Traditional Dense Wavelength Division Multiplexing (DWDM) networks, typically based on banded filter architectures, provide static routes in which the majority of wavelength lightpaths generally share a common “A” and “Z” location. The design of these networks can be done fairly easily and allow for the optimization of known lightpaths from day one, but they do not provide flexible reconfiguration and present significant network design challenges when new or unforeseen A-to-Z lightpaths are required.

Multi-degree ROADM technology addresses DWDM shortcomings by enabling networks to be designed with an optical dynamic core, offering network flexibility and reconfigurable lightpaths. The goal in the design of these networks is to provide true any-to-any lightpaths for all data rates, up to and including 40 Gbps. To achieve the full benefits of an optical dynamic core, various engineering considerations must be taken into account during network design.

This paper discusses the issues and solutions associated with the design and implementation of multi-degree ROADM-based ring and mesh optical networks. It will outline the steps in the design of a complex mesh network using a combination of two-degree and multi-degree ROADMs, Erbium Doped Fiber Amplifiers (EDFA), Raman amplifiers, Polarization Mode Dispersion (PMD) compensators and chromatic dispersion compensators. Compensation methods used to combat the effects of chromatic dispersion, PMD and Amplified Spontaneous Emission (ASE) noise will also be covered in reference to both 10 Gbps and 40 Gbps systems.

Optical Dynamic Core

The major advantage of an optical dynamic core is that it offers the ability to create mesh networks by connecting ROADM base network elements to form a universal optical infrastructure that can simultaneously support multiple network topologies, as shown in Figure 1. Once the optical dynamic core is implemented, the optical infrastructure provides virtual networks that overlay on top of the optical infrastructure, as shown in Figure 2.

Network planning and service activation also benefit from the use of an optical dynamic core. In traditional Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) transport networks, planning and deployment is handled on a ring-by-ring basis and handoff between rings requires

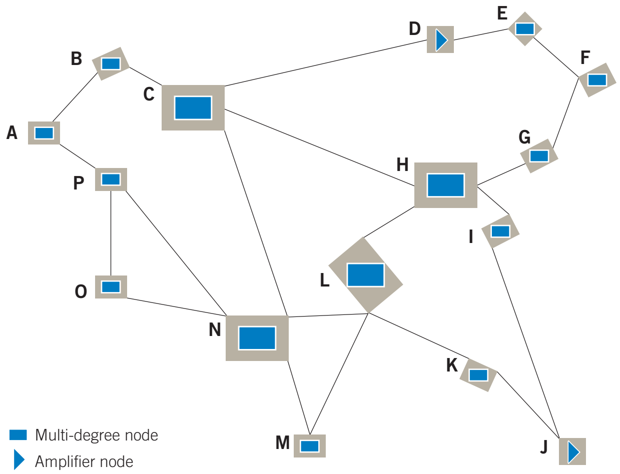

Figure 1. Multi-degree ROADM-based network

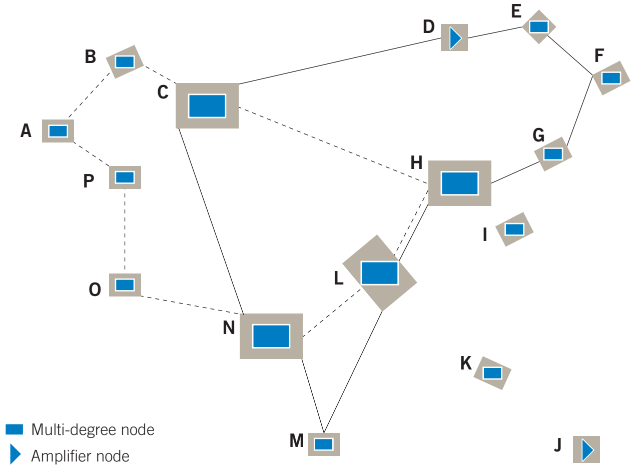

Figure 2. Virtual rings overlaid on optical dynamic core infrastructure

Optical-to-Electrical-to-Optical (OEO) or tributary regeneration. In addition, moving traffic between rings requires technician visits to more sites and adjustments to more equipment. An optical dynamic core removes the need to deploy equipment at intermediate locations when adding new services between two locations. Design and deployment activities are concentrated at the end location and software in any intermediate locations is configured remotely. This changes the approach to the network design from “ring-to-ring” to “end-to-end.”

An optical dynamic core provides significant capital equipment and operations savings, but to fully capitalize on its benefits, its design must correctly accommodate all possible lightpaths and factor in all relevant engineering considerations.

Setting up an Optical Dynamic Core

Today’s fiber provides greater performance than vintage fiber. However, fiber acquisition and its varied installation quality require that fiber spans be fully qualified or characterized. Obtaining fiber data through fiber characterization testing is the starting point for any network design. The minimum set of fiber characterization tests recommended include Optical Time Domain Reflectometer (OTDR), chromatic dispersion, PMD and overall span loss. This test data is critical for the design of an optical dynamic core.

An optical dynamic core set-up begins with the installation of optical nodes in the field. The optical nodes are fitted with multi-degree ROADMs to achieve wavelength steering between fiber spans. Various ROADM degree sizes are available; however, practical studies of networks show that four-degree ROADMs adequately meet the needs for a high majority of nodes. Higher-degree ROADMs come at a higher price and have higher insertion loss, which impact systems capability. These reasons and others support restricting the use of higher-degree ROADMs to only those node locations that truly require them.

The next step is the choice of amplifiers. The input amplifier choice is determined by the fiber span loss between two network elements. For every degree into a node there is a fiber span and an associated amplifier. Variable gain amplifiers provide the largest flexibility and ensure that common and predictable power levels are available throughout the network. In general, the output or booster amplifier in every node is the same, as its primary function is to compensate for internal losses within the node.

The final stage in an optical dynamic core set-up is to establish optical connections. Fiber spans are connected between network elements and fiber interconnections are made between multi-degree ROADMs.

40 Gbps on a Optical Dynamic Core

The demand for 40 Gbps in networks other than long haul, particularly within metro networks, is increasing very quickly. There are various drivers for the increase in demand, including Internet Protocol Television (IPTV) services and more common 40 Gbps interfaces on data equipment.

As 40 Gbps has not been targeted for use in metro DWDM networks until recently, many currently installed DWDM networks were designed and implemented with 10 Gbps engineering rules. In an ideal scenario, any 40 Gbps modules should work on these earlier networks as well as with newer, multi-degree-based ROADM networks.

The approach to supporting 40 Gbps transmission over an optical dynamic core mesh-based network is to continue to design and engineer the networks to 10 Gbps specifications. Additional specifications required by 40 Gbps beyond 10 Gbps requirements can be absorbed on the 40 Gbps transponder. Transmission impairments such as chromatic dispersion and PMD can be addressed by placing compensators on the 40 Gbps transponder module. This approach eliminates the need to modify existing 10 Gbps networks for 40 Gbps, enabling the most cost-effective and efficient network capacity expansion.

In-Line Amplifier Node

An In-Line Amplifier (ILA) node provides optical amplification without dropping or adding any wavelengths. In most cases, the ILA will be converted to provide wavelength ROADM capability at a future date. Variations in optical performance can exist between an all-amplifier node versus an amplifier node with ROADM capability. ILA nodes should be treated as a low-degree ROADM node in any network calculations.

Managing Chromatic Dispersion and Dispersion Maps

One of the greatest advantages of an optical dynamic core is its ability to provide true “any-to-any” lightpaths and to create and change lightpaths dynamically. Typically, each lightpath is independent and can traverse through completely different paths relative to each other. Therefore, trying to find commonality in lightpaths for chromatic dispersion compensation is normally difficult and does not provide adequate chromatic dispersion compensation for future lightpaths whose beginning and end locations are not yet known.

The solution to managing chromatic dispersion and the dispersion map in an ROADM-based optical dynamic core is to null out the affects of chromatic dispersion from node to node. Doing this provides low overall chromatic dispersion for any possible lightpath, relaxing transponder chromatic dispersion tolerance requirements and providing a more compatible DWDM artery to support future data rates.

Truly nulling out chromatic dispersion between nodes for all wavelengths on a DWDM platform can be achieved, but would require custom chromatic dispersion compensation modules per fiber span. This requirement would add significant cost and time delay and is impractical from a deployment perspective. Consider the optical mesh network as shown in Figure 3. Span distances are shown in Table 1. The network is comprised of 16 nodes and 20 lightpaths.

There are many lightpath possibilities within this network, but it is clear that a path on the outer ring would travel a long distance and pass through a high number of nodes, as shown in Figure 4.

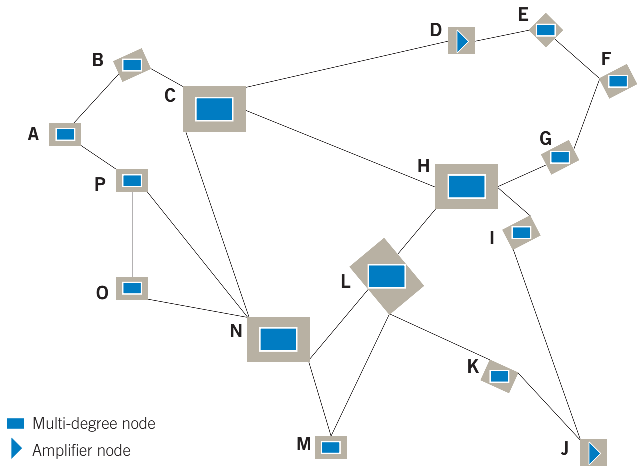

Figure 3. Multi-degree ROADM-based network

Span	Distance (Km)	Nodes	
1	22	A	B
2	18	B	C
3	93	C	D
4	21	D	E
5	11	E	F
6	23	F	G
7	37	G	H
8	12	H	I
9	110	I	J
10	55	J	K
11	39	K	L
12	26	L	H
13	37	L	M
14	12	M	N
15	9	N	L
16	34	N	O
17	33	O	P
18	42	P	N
19	21	P	A
20	58	C	H

Table 1. Span distances

Chromatic dispersion compensation is placed between every node. The chromatic dispersion compensation modules are in steps of 10 km. Consider the chromatic dispersion map of the lightpath travelling from node A to node P through the outer ring. The dispersion values of a set of dispersion compensation modules at 10 km increments are shown in Table 2, featuring a nominal dispersion value (Typ) and minimum and maximum dispersion values associated with each wavelength of each compensation module. The compensation module slopes are matched to within +/- 2.5% of the slope of SMF28 fiber with a zero dispersion wavelength of 1310 nm.

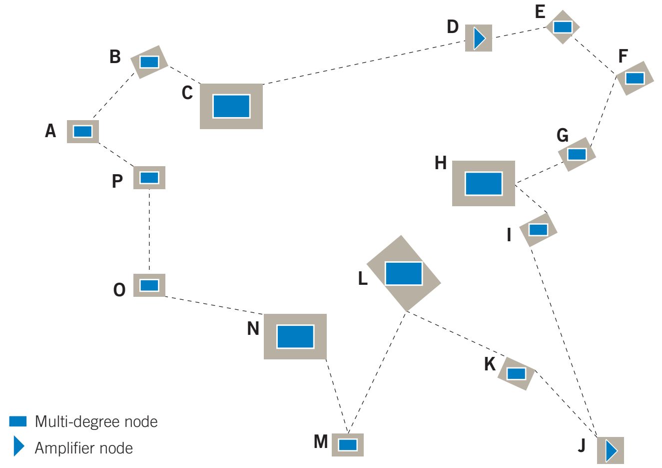

Figure 4. Outer lightpath

	Dispersion (ps/nm)								
	1525			1545			1565		
DCM (Km)	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max
10	-164	-160	-156	-176	-172	-168	-188	-183	-178
20	-328	-320	-312	-352	-343	-334	-375	-366	-357
30	-491	-479	-467	-528	-515	-502	-564	-550	-536
40	-655	-639	-623	-704	-687	-670	-751	-733	-715
50	-819	-799	-779	-880	-859	-838	-939	-916	-893
60	-983	-959	-935	-1056	-1030	-1004	-1126	-1099	-1072
70	-1147	-1119	-1091	-1232	-1202	-1172	-1314	-1282	-1250
80	-1310	-1278	-1246	-1408	-1374	-1340	-1503	-1466	-1429
90	-1474	-1438	-1402	-1584	-1545	-1506	-1690	-1649	-1608
100	-1638	-1598	-1558	-1760	-1717	-1674	-1878	-1832	-1786
110	-1802	-1758	-1714	-1936	-1889	-1842	-2065	-2015	-1965

Table 2. Chromatic dispersion compensation values

Assuming the use of SMF28 fiber with a zero dispersion wavelength of 1310 nm and a zero dispersion slope of 0.092 ps/(nm2km), Figure 5 illustrates the “worst case” accumulated uncorrected dispersion at the end of each of the 15 spans around the outermost ring shown in Figure 4.

For instance, the maximum positive accumulated uncorrected dispersion over the path from A to P (clockwise) for wavelength 1565 nm is 168 ps/nm. Similarly, the maximum negative accumulated uncorrected dispersion over the same path for wavelength 1565 nm is -158 ps/nm. Other clockwise paths along the ring displayed in Figure 4 can also be obtained from Table 2. For example, the maximum positive accumulated uncorrected dispersion over the path from A to E for wavelength 1565 nm is 102 ps/nm.

Figure 5 shows that the maximum accumulated dispersion for all wavelengths is still within typical chromatic dispersion specifications for both 10 Gbps and 40 Gbps transponders. This illustrates that all connections from node A to all other nodes along the path can be successfully compensated for chromatic dispersion.

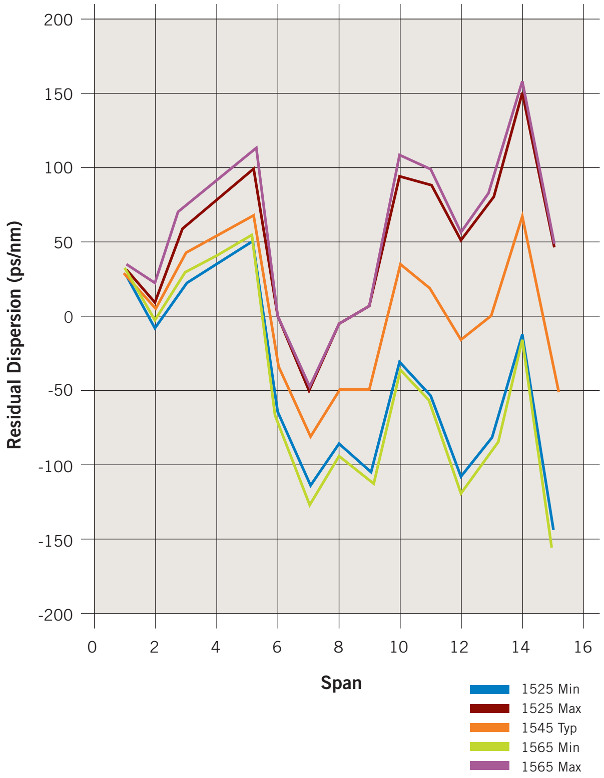

Figure 5. Chromatic dispersion map and walk off for large outer ring

Polarization Mode Dispersion

Polarization Mode Dispersion (PMD), like chromatic dispersion, limits the maximum data rate that the network can support. The goal in designing an optical dynamic core is to validate that the maximum PMD for any lightpath does not exceed the given specification.

PMD values used in network design should be obtained from actual field measurements. Fiber manufacturers’ PMD specifications are accurate for the fiber itself, but do not incorporate PMD incurred as a result of installation, which in many cases can be many orders of magnitude larger.

The first approach is to validate the maximum PMD value for all possible lightpaths. A network simulation tool or a planning tool can be used to identify all the possible lightpaths. Then the total PMD can be calculated, using the following equation:

$$\text{Total PMD} = \sqrt{(PMD\_Span1)^2 + (PMD\_Span2)^2 + \ldots\ldots + (PDM\_SpanN)^2}$$

Note: In practice this equation has shown 5–10 % inaccuracy. It is recommended that 10% be added to the total PMD calculated using this formula.

Optical node PMD must be added to the span PMD calculation to provide an overall PMD value for the lightpath. Ideally, the "worst case" PMD value will be lower than the system specification. In typical 10 Gbps-designed networks, the specification is set to 10 Gps, which provides adequate safeguards against Differential Group Delay (DGD) fluctuations. Additionally, software with re-routing algorithms can be developed to avoid spans with high PMD for higher data rate signals.

In situations where span PMD is high and no other fiber paths are available, PMD compensators can be used. A few options currently exist for PMD compensation. One option is the use of optical compensation whereby a variable DGD element is placed before the input of the optical receiver on a transponder module. Another option for PMD compensation is done electrically after the optical receiver by the use of Maximum-Likelihood Sequential Estimation (MLSE) techniques.

Optical Signal Noise Ratio and Noise

Optical Signal Noise Ratio (OSNR) and noise are accumulated as a signal travels through each network element. Fiber span loss and ROADM insertion loss represent the majority loss throughout the network. This loss must be compensated with amplifier units, introducing noise and lowering lightpath OSNR.

It is critical to understand and fully characterize each amplifier's Noise Figure (NF) relative to gain and the insertion loss of the node. Once fiber span losses are incorporated, end-of-line OSNR can be accurately calculated. When designing an optical dynamic core, the "worst case" OSNR can be calculated by performing end-of-line OSNR calculations on all possible lightpaths.

By its nature and capabilities, an optical dynamic core can present lightpaths that travel through many nodes and potentially long distances. Today's EDFA-based amplifiers provide the best compromise between cost and performance, yet they add considerable noise due to Amplified Spontaneous Emission (ASE).

The following solution to overcome the noise situations that arise when end-of-line OSNR has been exceeded assumes the following;

- EFEC on transponder modules
- SMF-28 fiber
- 0.3 dB/km fiber loss
- 2 dB connector loss and end points
- Transmission rate of 10.7 Gbps
- All add/drop nodes are ROADM-based
- All ROADM nodes are multi-degree
- All ROADM nodes incorporate two EDFA-based amplifiers, one output booster and one input amplifier

Based on the path from A to P shown in Figure 4, Table 3 illustrates the total OSNR at each node for a signal starting at node A and ending at node P. The second to the last column shows the OSNR values using only EDFA amplifiers in each node. In the example network outlined above, error-free traffic results when OSNR values are above 16 dB. As shown in Table 3, only the first eight spans can be traversed in the case in which only EDFA amplifiers are deployed — all traffic originating at node A and terminating at or beyond node K requires regeneration at node J.

If a Raman amplifier is placed at node J (along with an EDFA of lower gain), the resulting OSNR values are illustrated in the last column in Table 3. No regeneration is required as all OSNR values are above 16 dB.

Span	**Node Pair**	**IL**	**Span Length (Km)**	**Total OSNR (dB) (no Raman)**	**Total OSNR (dB) (Raman at Node J)**
1	AB	8.6	22	31.4	31.4
2	BC	7.4	18	28.4	28.4
3	CD	29.9	93	20.5	20.5
4	DE	8.3	21	20.1	20.1
5	EF	5.3	11	19.8	19.8
6	FG	8.9	23	19.5	19.5
7	GH	13.1	37	19.2	19.2
8	HI	5.6	12	19.0	19.0
9	IJ	35	110	14.7	17.5
10	JK	18.5	55	14.5	17.2
11	KL	13.7	39	14.4	17.0
13	LM	13.1	37	14.3	16.8
14	MN	5.6	12	14.2	16.6
16	NO	12.2	34	14.1	16.5
17	OP	11.9	33	14.0	16.3

Table 3. Network OSNR performance with and without Raman amplifier assist

The analysis portion of the tool should support the following functions for all possible lightpaths:

- General optical validation
- Chromatic dispersion map
- "Worst case" PMD
- OSNR

Network design and its actual implementation can be different. The planning tool should also have the capability to retrieve actual network operating conditions to ensure that analysis results are accurate and the tool provides maximum value.

Conclusion

Fuelled by the potential profit opportunities associated with video, voice and data triple play, demands on metro transport networks are increasing dramatically. The power of DWDM multi-degree ROADM nodes is being used to create optical dynamic cores capable of supporting more sophisticated network architectures including mesh. The shift in DWDM networks from fixed static style to dynamic is ideally suited to meet changing and dynamic traffic demands.

The shift to a dynamic optical core requires certain engineering considerations and techniques to maximize the capability. Most engineering considerations are common practice; however, some are subtle and nonintuitive. Transmission impairments such as chromatic dispersion, PMD, ROADM Filter narrowing affect and EDFA ASE noise are the major issues to consider.

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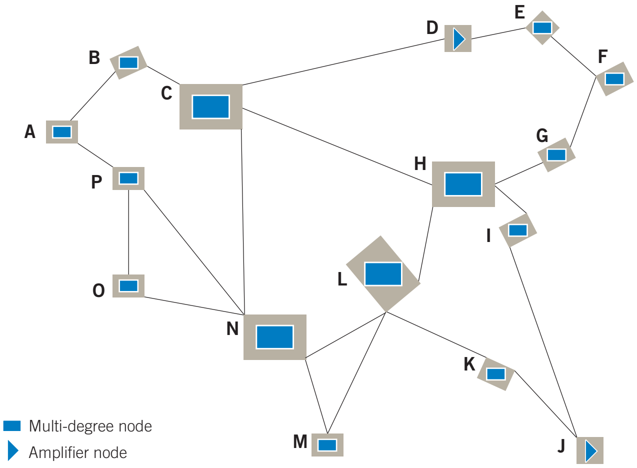

Figure 8. Multi-degree ROADM-based network

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