



Seeing the Light: **Multi-Wavelength Optical Networks**

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**Optical Link Budgets
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Revision History



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Abstract



Many physical effects are manifest in the node-to-node transmission of multiple optical signals over a single fiber, all of which impair the reliability of data transmission. Some of these effects include linear chromatic dispersion, self- and cross-phase modulation, four wave mixing, stimulated scattering, and mid-span optical amplifier properties such as non-uniform signal amplification and the introduction of noise. Many strategies exist to compensate for these negative effects, and this report discusses several of the principal ones: dispersion compensation modules, fiber type, wavelength allocation plans, peak signal power control within the amplifiers, and transmitter launch power adjustment. To ensure reliable data transmission, some of these techniques must be specifically and procedurally employed by introducing additional mid-span equipment such as optical add/drop multiplexers, which extract and introduce new signals entirely at the optical level. An example of such a need involves adjusting the input signal power levels to compensate for amplifier-induced noise.

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Glossary



BER:	Bit Error Rate
DCM:	Dispersion Compensation Module
DSCM:	Dispersion Slope Compensation Module
DWDM:	Dense Wavelength Division Multiplexing
EDFA:	Erbium-Doped Fiber Amplifier
MOR:	Multi-wavelength Optical Repeater
NDSF:	Non-Dispersion Shifted Fiber
OADM:	Optical Add/Drop Multiplexer
OC:	Optical Carrier
OSA:	Optical Spectrum Analyzer
OSNR:	Optical Signal to Noise Ratio
STS:	Synchronous Transport Signal



1. Introduction to Optical Networks



1.1. Nortel Networks



Nortel Networks has grown to become a global Internet and communications leader, with 75,000 employees worldwide generating over 30 billion dollars in revenues. Though Nortel has a broad focus, spanning optical, wireless, and local Internet, a significant portion of its revenue can be attributed to its optical networks division; sales of Nortel optical networks alone are expected to exceed 14 billion dollars in the year 2000. Optical networks, the primary means of fast and large-volume data transfer, are evolving at an incredible speed. They boast ever faster data transfer rates, with 400 gigabits per second (Gb/s) capacity commercially available, and continually increased reliability. Nortel currently boasts a bit-error rate (BER) of 10^{-15} on many of its networks.

1.2. Dense Wavelength Division Multiplexing



One attractive advance in network technology involves the transmission of multiple signals simultaneously over a single optical fiber, called dense wavelength division multiplexing (DWDM). DWDM technology enables an upgraded system using existing fiber plant to multiply its capacity many times over. Nortel is currently working towards 160-wavelength DWDM systems.

1.3. Complications of DWDM

Advances in DWDM, however, bring with them associated difficulties involving the fundamental properties of light and the method of its transmission. As optical signals simultaneously propagate down a fiber, they experience many physical effects, including the following:

- Linear chromatic dispersion
- Four wave mixing
- Self- and cross-phase modulation
- Stimulated scattering

Because these effects hinder the correct interpretation of signals at their destinations, allowances must be made and counteracting procedures performed. Additionally, a signal can be optically amplified a number of times between its point of transmit and its final destination. This amplification further modifies the signals, and the relationships among them, through the following amplifier properties:

- Non-uniform signal amplification
- Noise introduction

A variety of techniques must be used together to minimize these effects.

1.4. Mid-Span Access Equipment

Transmitting data reliably is complicated even more by the introduction of additional optical equipment between transmit and receive locations. This equipment performs useful tasks, such as routing with the use of optical add/drop multiplexers (OADMs) that extract and introduce new signals entirely at the

optical level. However, it also unintentionally modifies signal relationships such as power levels and noise quantities that are relevant to the quality of the signals. Special consideration must be given to the overall node-to-node transmission when this equipment is included. Later sections of this report describe techniques that are effective in circumventing such performance decreasing factors.

2. DWDM Optical Networks

2.1. DWDM Links Defined

Dense wavelength division multiplexing (DWDM) is a powerful approach to increasing the bandwidth of existing networks without laying more fiber. It involves transmitting multiple signals simultaneously over a single optical fiber. This approach is possible because a property of light is that multiple photons can occupy the same space, as illustrated by the unimpeded crossing of two flashlight beams (Willner 1997, 35). Simultaneous transmission is accomplished by allocating certain signals to certain wavelengths of light, so that DWDM is analogous to the technique used to broadcast many different radio channels by placing them on carrier waves of different frequency. However, when many signals are concentrated in a narrow span of wavelengths, they must be spaced closely together, which leads to unwanted physical effects (see Section 3, Optical Layer Physical Effects).

An optical link is shown in Figure 1.

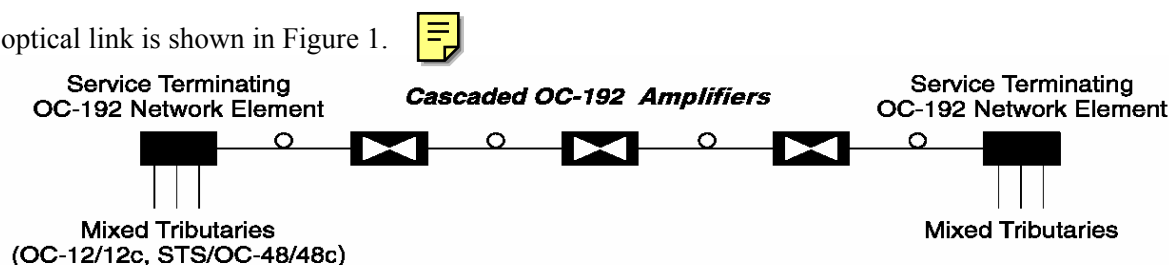


Figure 1: An Optical Link¹

An optical link begins when a network node transmits signals as light into a fiber span. These signals may be coming from many different sources and line-rates, called tributaries, with common sources including the Optical Carrier (OC) 12 and 48 levels (where the n in OC-n represents a capacity of $(n * 51.84)$ megabits per second capacity). The electrical analog to the OC standard is the Synchronous Transport Signal (STS). Signals are combined into an OC-192 signal (10 gigabits per second per channel), and the light can travel long distances through optical fiber because it is optically regenerated at line amplifier sites as needed to preserve signal levels while not degrading the signal quality past a certain threshold. When the signal arrives at its destination, a network node receiver converts the light back into an electrical signal and further routes it. This conversion terminates the link.

As indicated in Figure 2, in DWDM, multiple transmitters operate at different wavelengths, sending optical signals into a multiplexer which combines onto one fiber the signals that were previously traveling separately. These signals then travel together and, for the most part, are amplified together. For reasons discussed in Sections 3 and 4, some wavelength groups are amplified separately. Often a link will be bi-directional, with many wavelengths travelling in different directions to reduce the interaction among signals. Some wavelengths may be routed away from the link and others added at special mid-span sites using optical add/drop multiplexers (OADMs). Once the signals are near their destination, they go

¹ All figures, except Figure 3, are from "S/DMS TransportNode: Advanced Optical Networking Solutions for Global High-Capacity Transport Applications", courtesy of Nortel Networks.

through a demultiplexer and are again separated into their individual fibers, after which they may be received. The Multi-Wavelength Optical Repeater (MOR) and MOR Plus series of optical regenerators support up to 16 and 32 wavelengths, respectively. A full MOR Plus DWDM link is shown in Figure 2.

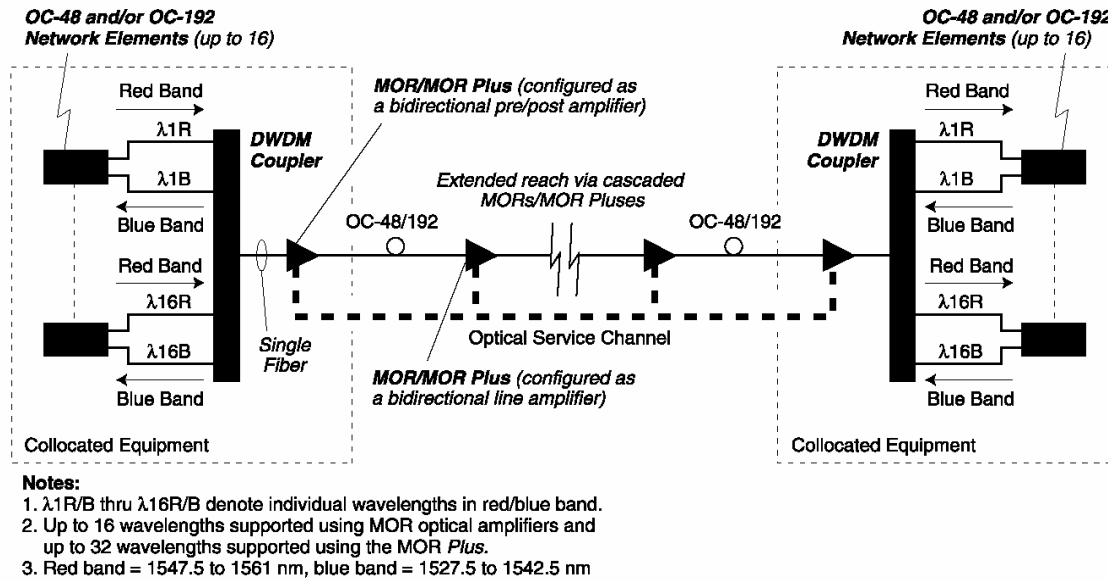


Figure 2: A DWDM Link

2.2. DWDM Systems

Two of Nortel's DWDM systems are the Multi-Wavelength Optical Repeater (MOR) Plus system capable of supporting 32 wavelengths and the OPTera 1600G series of amplifiers that commercially support 40 wavelengths (uni-directional), with plans for extensions up to 160 wavelengths. Both systems involve specific hardware used to reliably and consistently amplify multiple wavelengths, and follow specific standards, including which wavelength signals may be assigned to OADM sites and which may be added or dropped at these sites. For example, the MOR Plus standard allocates sixteen wavelengths between 1547.5 nm and 1561 nm to the red band, which propagates in the opposite direction to the sixteen wavelengths between 1527.5 nm and 1542.5 nm in the blue band. An extra wavelength is allocated for a spare and another for service.

Table 1 lists the wavelength allocation plans on the International Telecommunications Union Grid for the MOR and MOR Plus standards, which are valid on the fiber type known as non-dispersion shifted fiber (NDSF). Symbol X represents a valid channel, and OADM represents a valid channel that may be optically added or dropped, mid-span.



Table 1: MOR/MOR Plus ITU Grid

ITU-T λ Grid 100-GHz Spacing (nm)	Number of Wavelengths in Application			
	Up to 32	Up to 24	Up to 16	Up to 8
1560.60	SPARE	SPARE	SPARE	SPARE
1559.79	OADM			
1558.98	OADM	OADM	OADM	
1558.17	X			
1557.36	OADM	OADM	OADM	OADM
1556.55	OADM			
1555.75	OADM	OADM	OADM	OADM
1554.94	OADM			
1554.13	X	X	X	
1553.33	X			
1552.52	X	X	X	X
1551.72	X	X		
1550.92	X	X	X	X
1550.12	OADM	OADM		
1549.32	OADM	OADM	OADM	
1548.51	X	X		
1547.72	X	X	X	
1541.30	SPARE	SPARE	SPARE	SPARE
1540.56	OADM			
1539.77	OADM	OADM	OADM	
1538.98	X			
1538.19	X	X	X	
1537.40	OADM			
1536.61	OADM	OADM	OADM	
1535.82	X			
1535.04	OADM	OADM	OADM	OADM
1534.25	OADM	OADM		
1533.47	OADM	OADM	OADM	OADM
1532.68	OADM	OADM		
1531.90	X	X	X	
1531.12	X	X		
1530.33	X	X	X	X
1529.55	X	X		
1528.77	X	X	X	X
	MOR Plus Applications Only		MOR and MOR Plus Applications	

2.3. Link Performance Measurement

To assess how well our system (link) is performing, and to know how we must modify it to enhance its performance, we need techniques of predicting how many errors will result over some length of time while transmitting our data. Two popular methods for predicting this bit-error rate (BER) involve the optical signal to noise ratio (OSNR) and system Q.

2.3.1. Optical Signal to Noise Ratio

OSNR is obtained by taking the optical signal power and dividing it by the noise power in a certain bandwidth, which can be easily observed through the use of an optical spectrum analyzer (OSA). Most demultiplexers include a monitor tap that the OSA can be connected to in order to obtain the OSNRs of all channels just before they reach their receiver sites. Although we observe a signal of reduced power, the noise floor is reduced proportionally, yielding the same OSNR. This information tells us how easily the receiver will be able to interpret the signal without errors. We also use data on the channel OSNRs relative to each other in a process called equalization, where input transmitter power is adjusted to obtain roughly equal OSNRs over all the channels.

2.3.2. System Quality

Another measurement technique involves obtaining system Q. Using this number in connection with an understanding of how an optical receiver makes optimizing decisions in the resolution of signals allows us to determine channel BER performance.

System Q is defined as in Equation 1

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}, \quad (1)$$

where I_1 is the signal level for the 1 bit and I_0 the signal level for the 0 bit, with σ_1 and σ_2 the respective root mean square noise variances in a 1 and a 0 bit respectively, at the receiver (Verreault, 1999, 599). For more information on system Q, see *Fiber-Optic Communications Systems* (Agrawal 1997, 170-172).

3. Optical Layer Physical Effects

3.1. Effect Descriptions

Optical layer physical effects such as fiber loss, linear chromatic dispersion, four wave mixing, self- and cross-phase modulation, and stimulated scattering all contribute to the degradation of optical signals as they travel through an optical fiber.

3.1.1. Fiber Loss

Every type of fiber has an associated amount of attenuation per length of fiber and is wavelength dependent. As the signal propagates down the fiber, it is progressively attenuated. As an example, Nortel Network's "S/DMS TransportNode: 200 GHz, MOR/MOR Plus, 2 to 16-lambda Optical Layer Applications Guide" lists a 0.21 to 0.25 dB/km loss over NDSF fiber. Optical amplifiers are necessary to amplify the attenuated signal if system reach is to be extended.

3.1.2. Chromatic Dispersion

In most current DWDM systems, chromatic linear dispersion is the largest factor in signal distortion (Verreault, 1999, 600). This effect occurs because silica fiber has the innate property that its index of

refraction is a function of wavelength. But the speed of a lightwave is dependent on the refractive index of its medium, meaning that different wavelengths propagate down a fiber at different speeds. A signal experiences no dispersion at a particular wavelength, λ_0 , which is dependent on the type of fiber being used (see Section 3.2.1). A wavelength pulse is made from a number of spectral components that travel at different speeds down the fiber. Consequently, the transmission pulse spreads, with slower energy components lagging and faster components proceeding the main energy group. These variations create intersymbol interference and a higher BER.

3.1.3. Four Wave Mixing

Four wave mixing involves the transfer of power between wavelengths. The fiber's physical properties cause signals centered at optical frequencies $\omega_1, \dots, \omega_n$ to interact and create new frequencies at combinations and multiples of the parents. For example, we may find lower power signals at $\omega_i - 2\omega_j$ and $\omega_i - \omega_j + \omega_k$.

3.1.4. Self-Phase Modulation

Self-phase modulation occurs in high-speed optical systems due to fiber non-linearity. Specifically, the refractive index varies with light intensity. Because the rise and fall times of a bit are finite, the intensity variations induce a phase change (Willner 1997, 39), thereby creating new frequencies that then travel at different speeds down the fiber, resulting in either time compression or spreading of the bit.

3.1.5. Cross-Phase Modulation

Two pulses overlapping in a fiber cause a local power increase that changes the refractive index and causes another phase change in the same manner as that caused by self-phase modulation. The intensity at one wavelength modifies the refractive index at its own wavelength as well as the refractive index experienced by neighboring wavelengths. In this case, dispersion is beneficial because it spaces out the signals, reducing overlap.

3.1.6. Stimulated Scattering

The nonlinear effects of stimulated scattering have a variety of sources. Stimulated Rayleigh scattering is a loss mechanism involving light scattering from small-scale differences in the internal refractive index of the fiber. These differences are caused by microscopic density fluctuations introduced during the manufacturing process. Stimulated Brillouin scattering and stimulated Raman scattering both involve inelastic scattering of light with phonons, causing the wavelength of the scattered light to shift upwards (Agrawal 1997, 59-62). These effects reduce signal power and cause degradations.

3.2. Solutions

Some strategies that are employed to compensate for these negative physical effects include the use of specific fiber types, dispersion compensation modules, pre-distortion, and wavelength allocation plans, as described below.

3.2.1. Fiber type

Dispersion can be partially reduced by carefully selecting the fiber type to be used in the optical system. The following is a list of typical fiber types and their center frequency λ_0 , as described in Nortel Network's "S/DMS TransportNode: 200 GHz, MOR/MOR Plus, 2 to 16-lambda Optical Layer Applications Guide" (1999):

- Non dispersion shifted fiber (NDSF): λ_0 near 1310 nm, meaning positive dispersion for the typical wavelengths, in the 1550 nm range
- TrueWave Classic: $\lambda_0 < 1530$ nm
- TrueWave RS: $\lambda_0 < 1452$ nm
- LEAF: $\lambda_0 < 1513$ nm
- E-LEAF: $\lambda_0 < 1500$ nm



3.2.2. Dispersion (Slope) Compensation Modules

Because different wavelength channels travel at different speeds, we can observe their dispersion relative to one another to determine how much dispersion compensation is required. We can also determine polarity, which is positive if the shorter wavelengths travel faster than the longer ones, and negative if the shorter wavelengths travel slower than the longer ones (Willner 1997, 39).

One main method of dispersion compensation involves the use of dispersion compensation modules (DCMs), which are modules that introduce dispersions with opposite signs to the transmission fiber. As the wavelengths used become more numerous and over a greater range, the difference in dispersion experienced by each channel is no longer minor, and a dispersion slope compensation module (DSCM) must be used that provides wavelength dependent dispersion compensation.

Alternating between allowing the signals to disperse and correcting them as they travel along the fiber is useful because dispersion along the line helps to decrease nonlinear effects such as cross-phase modulation.

3.2.3. Pre-distortion

Most transmitters can be adjusted to pre-compensate signals with either a positive or negative chirp (which should be set to the opposite of the expected dispersion of the fiber). A chirp affects a pulse's spectral contents over a bit period such that the signal experiences compression rather than expansion over its propagation distance, which counteracts the fiber dispersion.

3.2.4. Wavelength Grids and Spacing

Standards are set for the wavelength distribution with three main points in mind.

1. We want as many wavelengths as possible, with as small a spacing between them as possible.
2. The larger the spacing between wavelengths, the more dispersion issues, but the less inter-channel cross talk, such as four-wave mixing.
3. Channels moving in opposite directions experience less inter-channel interactions.

See Section 2.2 for an example of four wavelength plans for the MOR/MOR Plus systems.

4. Amplifier Effects

4.1. Effect Descriptions

Similar to the optical layer physical effects treated above, mid-span optical amplifiers possess properties that degrade signal performance, including non-uniform signal amplification and the introduction of noise.

4.1.1. Non-uniform Signal Amplification

Doped fiber amplifiers are currently the most popular amplifier technology sold commercially (Verreault 1999, 600), with erbium-doped fiber amplifier (EDFA) technology leading the way. EDFA modules are capable of amplifying signals over the massive spectrum of 180 nm in the 1550 nm range. One drawback, however, is that the gain profile of the modules is not flat over this wavelength range, causing discrepancies in the amount of amplification each channel experiences. If these amplifiers are cascaded, this effect is significantly more pronounced.

4.1.2. Amplifier-Induced Noise

EDFA modules consist of silica glass fiber doped with erbium ions. The erbium ions are then excited to a higher and metastable energy state from which photons can cause them to fall, releasing a photon with the same phase and wavelength as the initial photon in the process and thus amplifying the signal (Willner, 1997, 33-34). This process is called stimulated emission. However, if not stimulated by a photon, excited erbium ions have only several micro- to milliseconds to live before decaying. This natural decay emits a photon with a random phase that adds noise to the system. Again, cascaded amplifiers greatly increase this effect.

4.1.3. OSNR Differences

We have achieved an equalized system when all of our channels have the same OSNR. We strive toward this goal, but it is hindered strongly by the two effects listed above. Because both contribute to channels at the receiver end of a link with unequal OSNRs, these effects must be countered.

4.2. Solutions

Tilt control, peak power control, grid amplification, and transmitter power adjustment can be used together to minimize many negative amplifier effects.

4.2.1. Tilt Control

Tilt control is an amplifier setting that helps to minimize the effects of EDFA non-uniform gain.

4.2.2. Peak Power Control

By putting the amplifiers in peak power mode and giving them a peak power goal, the amplifiers will attempt to ramp up their entire gain envelope to set the peak channel's power to that of the goal. If the total output hits an upper limit (also software-provisionable) before the peak power goal is reached, gain increases are stopped. This technique allows maximum amplification, while making sure a particular signal power (and thus OSNR) does not become too large in relation to the other signals – which would degrade them – and limits the extent of nonlinear effects experience by the channel.

4.2.3. Grid Amplification

In effect, we amplify each group of wavelengths independently of the other groups, which allows us additional control over amplification strategies such as the peak power setting. For example, in the MOR Plus system, we amplify the blue band in one direction and the red band in the other.

4.2.4. Equalization through Transmitter Power Adjustment

OSNR values can be adjusted by changing the link input (transmitter output) powers. A popular iterative approach to equalization involves repetitive calculation of average OSNR at the receiver site and adjusting all of the transmitters in steps toward this average. Slowly the OSNRs converge. Another method of transmitter adjustment involves gathering channel power information from each amplifier along the link. The following equation (Chraplyvy 1993, 428) indicates the output power of the i th transmitter should be set to an n span link:

$$P_{\text{new}}^i = P_{\text{TOT}} \left[\frac{P^i / (S/N)_i}{\sum_{j=1}^n P^j / (S/N)_j} \right], \quad (2)$$

where $(S/N)_i$ is the OSNR of the i th channel. This equation allows us to perform transmitter adjustments remotely without any manual measurements. In large systems, this option is very attractive.

5. A MOR Plus with OADM System

5.1. System Diagram

Figure 3 shows a link that was setup in the lab to test the effects of mid-span OADM equipment.

The symbols S1...S6 represent six 100 km spans over E-LEAF fiber. NX represents a blue Pre-(MSA) amplifier and a red Post-(MSA) amplifier, and PX represents a red Pre-(MSA) amplifier and a blue Post-(MSA) amplifier. MLs are optical attenuators.

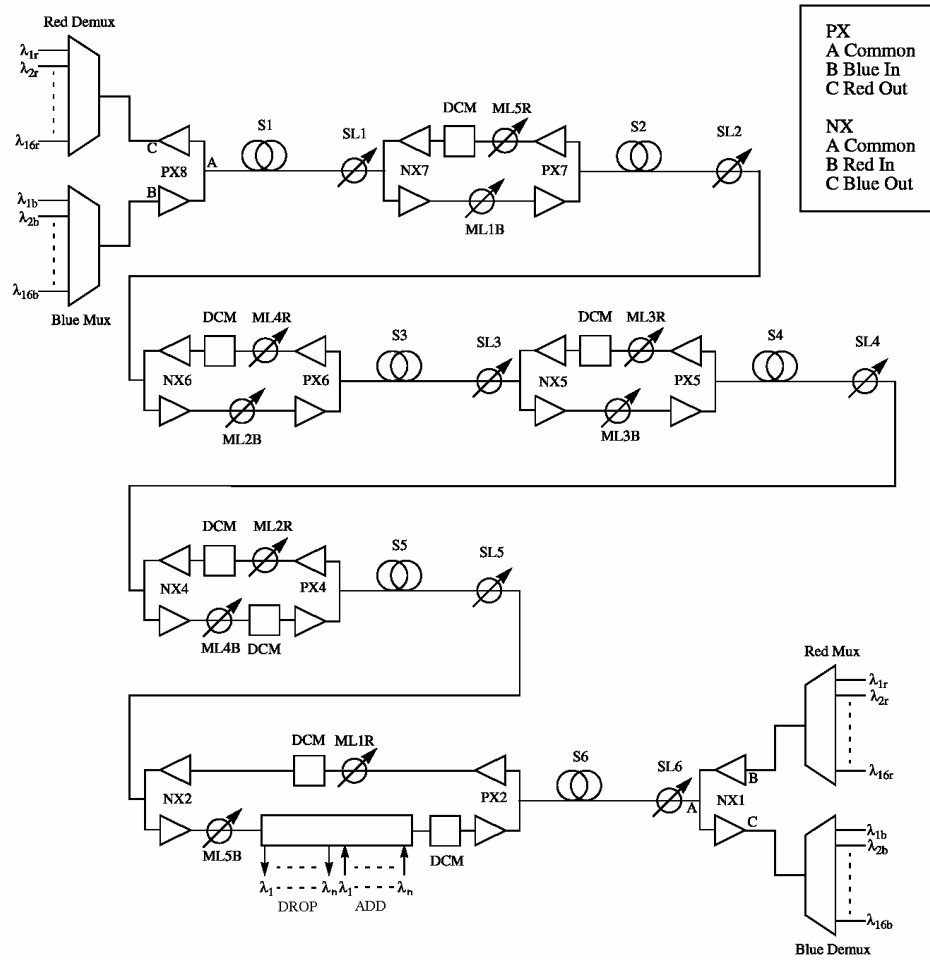


Figure 3: OADM System Diagram²

A typical one-wavelength (per direction) OADM site is shown in Figure 4. The above OADM site would look similar if expanded.

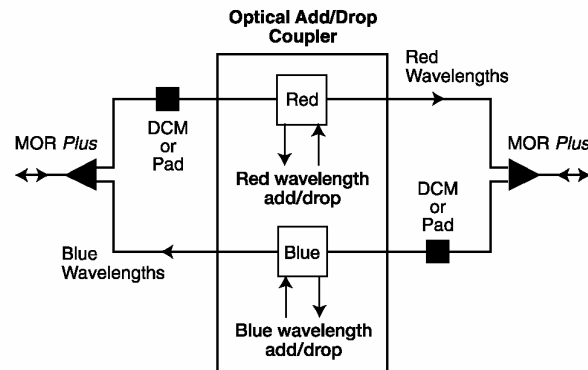


Figure 4: A Typical OADM Site

² Figure from "Level3 MOR+ OADM Equalization Test Plan," 2000, courtesy of Nortel Networks.

5.2. OADM Explained

The purpose of OADM is to route (re-direct) signals not just from node to node, but also in between nodes at the optical level. This routing saves time and effort because the signal does not need to be converted back into electricity, broken down, examined, re-built, routed, and converted back into light.

Figure 5 shows three typical applications of OADM equipment.

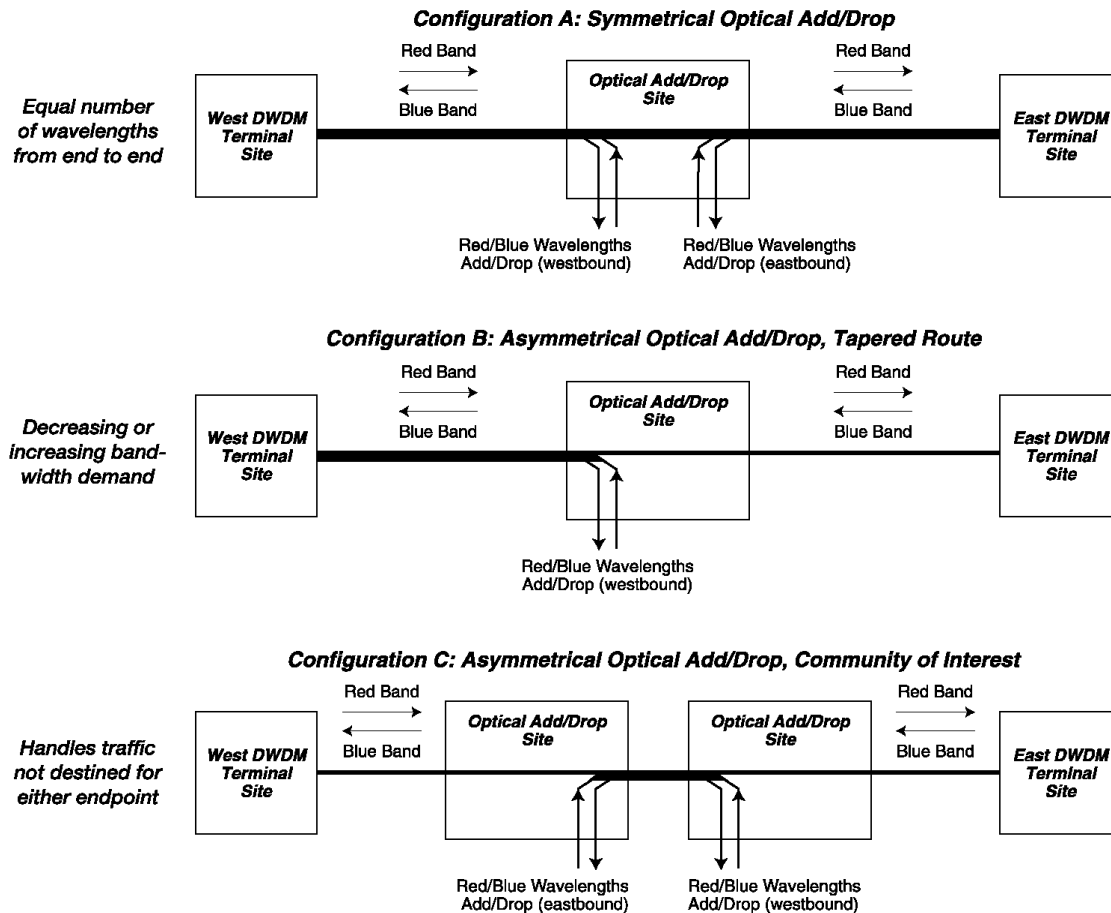


Figure 5: OADM Applications

6. OADM Performance Considerations

6.1. OADM Effects on Performance

OADM systems must be designed with concern for the physical and amplifier non-idealities discussed above. One of these considerations involves amplifier-induced noise.

6.1.1. Non-Equal Amplifier Noise

The channels being added have not necessarily passed through the same number of amplifiers as those channels from the west-to-east or east-to-west DWDM terminal sites, known as express channels. This discrepancy is a problem because, as noted in Section 4.1.2, amplifiers introduce noise onto the channels. If all channels pass through the same number of amplifiers, the amount of noise they have accumulated is constant, resulting in a roughly horizontal noise floor, neglecting the effects of tilt. Added channels may contain significantly different amounts of noise, yielding largely varying OSNRs, which put the system out of equalization.

6.2. OADM Performance Solutions

The problem with amplifier-induced noise encountered in OADM systems can be compensated by adjusting the added signal power.

6.2.1. Adjust Add Channel Power

A large signal OSNR existing on an added channel can be reduced by attenuating the signal at the time it is added to bring it into an acceptable range. Ideally, the signal power should be appropriately set at its transmitter site. When installing an OADM site in a link, this strategy must be kept in mind.

7. Conclusion

Optical networks are growing; they are becoming faster, larger, and more reliable. DWDM technology is a prime player in increasing network bandwidth. Increasing bandwidths and speeds, however, create an increased number of complications that must be taken into account in the design of optical network equipment and systems. Some performance-degrading effects to be aware of include linear chromatic dispersion, four wave mixing, self- and cross-phase modulation, stimulated scattering, and mid-span optical amplifier properties such as non-uniform signal amplification and the introduction of noise. To counter these effects, we can tailor systems with a combination of dispersion compensation modules, fiber type, wavelength allocation plans, peak signal power control within the amplifiers, and transmitter launch power adjustment. OADM systems, in particular, must account for the effects of amplifier-induced noise, which can be corrected through the dampening of signal power on the added channels.

As further advances are made in the field of optical networks, the effects discussed in this report will become increasingly significant. Fortunately, a strong base of knowledge and many effective counter techniques already exist to serve as guides to future solutions.

I thank Mike Moyer and Sik Heng Foo for their support in the writing of this report and for readily providing helpful technical assistance throughout the work term.



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