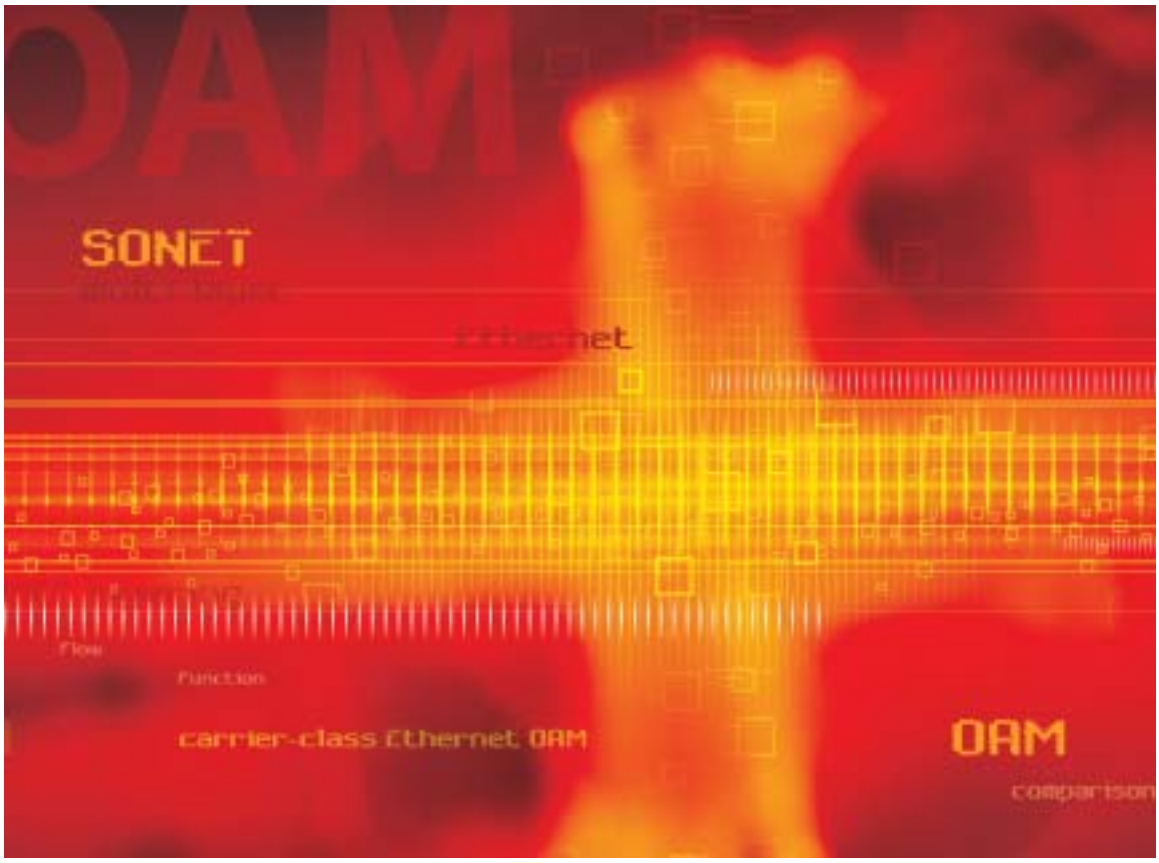
THE POSSIBILITIES ARE INFINITE FUJITSU

Optical Design Consideration for Transparent Reconfigurable Metro DWDM Networks



In recent years, deployment of WDM technology in metro and access networks has been increasing. The traffic pattern for these networks tends to be more dynamic, with an increased number of add/drop nodes as compared to long-haul networks. To reduce cost, the number of O-E-O conversions in the network must be minimized and signals must pass transparently at each of the OADM nodes. This process is accomplished by using an optical MDX, optical amplifier and optical switch matrix as shown schematically in Figure. 1

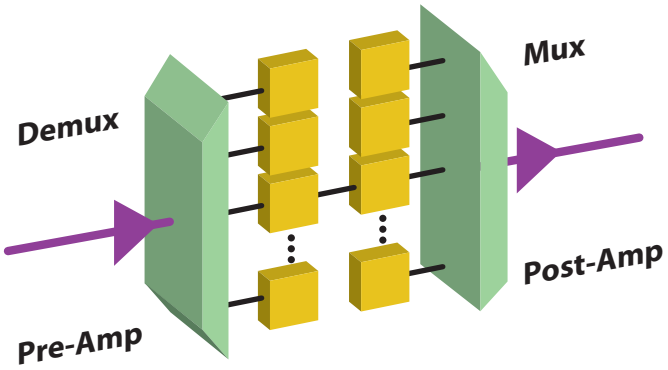


Figure 1: O-E-O Conversion

Fundamental to any optical design in metro and long-haul networks is the consideration of per-channel optical power levels and power level management [1], as well as waveform distortion factors and their necessary compensation schemes.

Amplifiers are used to compensate for optical power losses due to losses in the fibers, connectors and optical components (mux/demux, optical switches, etc). In addition, for certain power levels, power loss (depletion) can occur due to nonlinear effects such as SRS and SBS. These losses tend to fluctuate due to fiber temperature or variation of nonlinear effects at different power levels. Additionally, per-channel power variations, which cannot be compensated for by optical amplifiers, also exist. These per-channel power variations (statistical component loss variations) are a result of the manufacturing processes of different components. The loss variations, coupled with the optical amplifier gain spectrum shape (λ-dependent) and the transmitter output power variations (λ-independent), introduce optical power level tilt issues that must be addressed. Two power level management schemes have been proposed. The first is module-level power level management, where only optical mux/demux and amplifier tilt are considered, and coordination and signaling between different nodes is required. The second approach is per-node power compensation, which is based solely on the local node power level information and requires per-channel band power level equalization. The above mentioned power level variation factors and the proposed power level management schemes are extensively discussed by K. Peddanarappagari et. al. [1] and will not be emphasized in this paper. Instead, the focus will be on the characterization of waveform distortions and dispersion compensation schemes in transparent full wavelength access add/drop DWDM ring networks.

In addition to fiber dispersion, fiber non-linearities and mux/demux filter shape [2] can cause waveform distortions that affect the propagation of an optical pulse along any dispersive media, including fiber. Controlled intentional modulator chirp can be used to tailor the dispersion map to the system requirement [3]. Waveform distortion also occurs due to the bandwidth limitation and the non-uniform filter shape of the mux/demux filters. This impact becomes more significant in metro networks as signals tend to pass through multiple OADM nodes.

Waveform Distortion Factors

In transparent reconfigurable optical add/drop DWDM rings, several factors cause waveform distortion. Because of the short distances involved, and the small power levels required for metro applications, waveform distortions due to non-linear effects are minimal.

Dispersion Tolerance Window

As the result of fiber dispersion, the different frequency components of a signal suffer different propagation delays, resulting in signal quality degradation through distortion. The richer the frequency content of a signal, the more severe the degradation. A dispersion window can be determined where the penalty to the system due to waveform distortion is confined to a certain tolerable limit. Typically, the vertical scale of the eye diagram, the eye opening and the eye width (known as phase margin), measures the system penalty. The phase margin is defined as the ratio of the opening remaining in the eye width, compared with the opening in a back-to-back configuration.

Pre-chirping also affects the propagation of an optical pulse along any dispersive medium. Chirp adds a frequency slope to each pulse so that from leading to trailing edges of a pulse, the frequency content is shifted positive to negative or vice versa as appropriate. Properly used chirp is a form of pre-compensation that can compensate for some effects of dispersive degradation. Chirp can be used to provide either both negative or positive shifts in the dispersion window as compared to a null chirp case. Specifically, for a negative chirped signal, the minimum dispersion is limited by eye closure, while the maximum dispersion is limited by RMS eye power, whereas the opposite is true for a positively chirped signal. The combined effect on the allowable dispersion window is then limited by the eye penalty and the eye power.

Passband Narrowing and Loss Ripple

Unlike linear point-to-point DWDM optical network applications where wavelength channels are added and dropped at the terminal points only, wavelengths in optical add/drop DWDM systems may be multiplexed and demultiplexed multiple times. This process occurs more often for unbanded systems than for banded systems. Unbanded OADM systems, by definition, allow access to all wavelength channels at each node, which means that each wavelength is effectively multiplexed and demultiplexed at each node. Banded OADM systems drop or pass through a single band or multiple bands of wavelengths at each node. Thus, for banded systems the effects tend to be significantly better for wavelengths nearer the center of the band but suffer the same problems at the band edges.

Since mux/demux modules have limited bandwidth, an optical signal with rich frequency content passing through will have the spectral content of the affected signal. The impact is worsened when the signal is passed through cascaded mux/demux modules. This process is known as passband narrowing effect as shown in Figure 2.

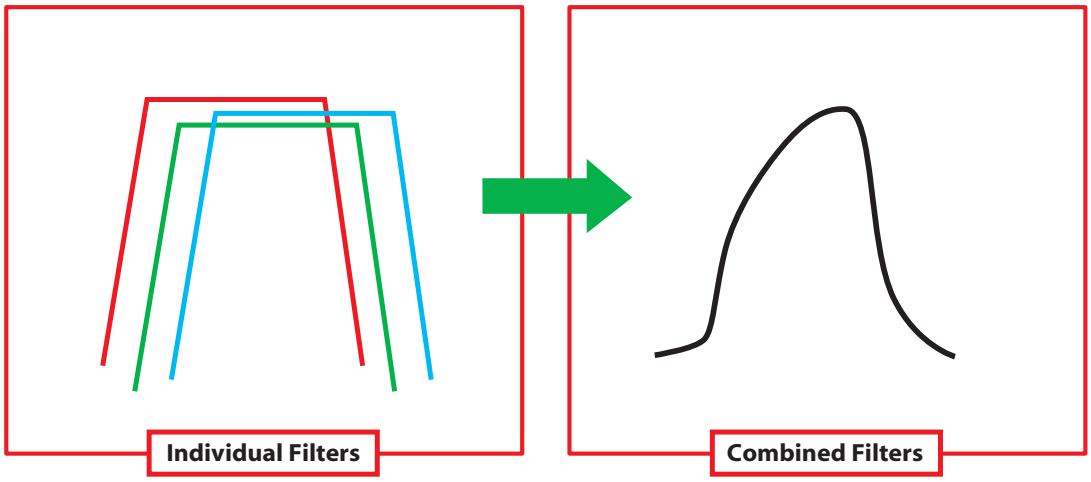


Figure 2: Passband Narrowing Effect

Insertion loss also varies across each passband of a mux/demux module and can also impact the shape of waveform. This loss ripple is defined as a function of the filter flatness. Multiple passes through the filter can be simulated by standard convolution techniques. However, since this filter flatness is different for each filter and each band, this calculation must include both constant and random filter fluctuations. The overall effect of this passband shaping is shown in Figure 3.

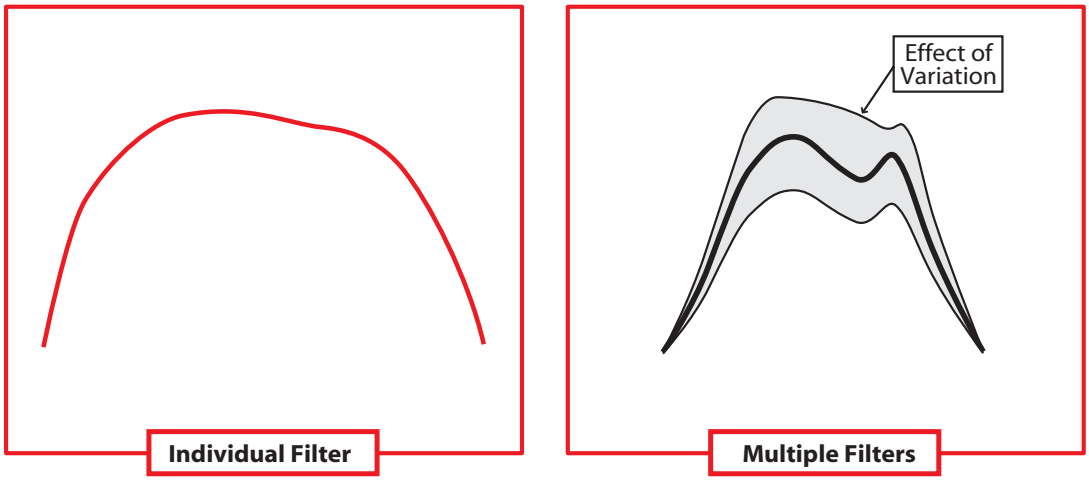


Figure 3: Passband Shape with Multiple Cascaded Filter Elements

Channel Source Accuracy

Channel wavelength accuracy plays as significant a role as any other factor in affecting the total waveform distortion related to system penalty. As the center of the signal source wavelength is shifted, the rich frequency content of the signal is filtered differently, depending on the individual filter shapes and the cumulative effect of the cascaded optical filters a signal may encounter. Figure 4 shows the eye closure penalty with a well-centered and an off-centered source channel.

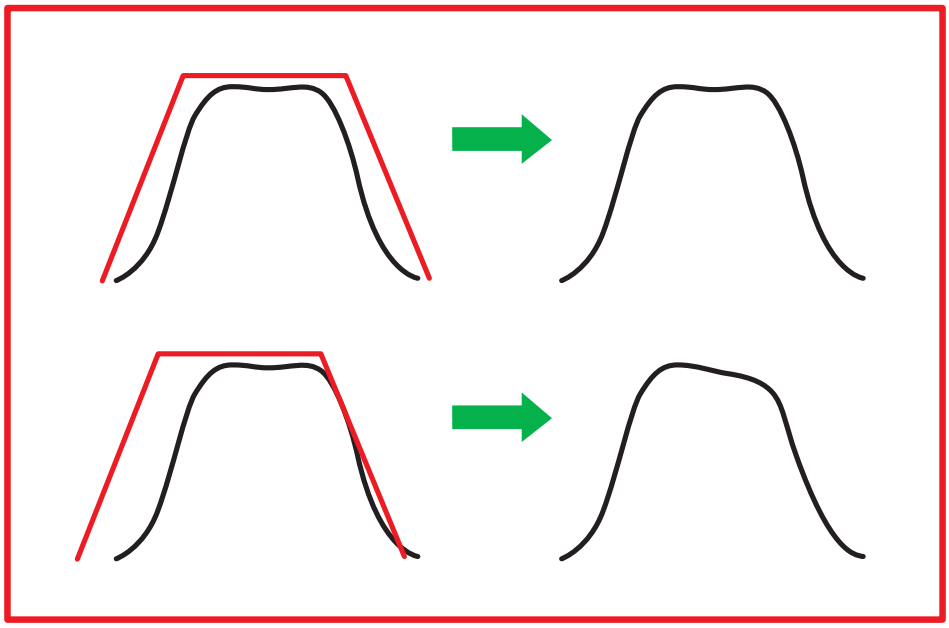


Figure 4: Eye Distortion with Wavelength Centered and Off Center to Filter

Dispersion Compensation Strategy

Once all the factors that affect waveform distortion are appropriately characterized, the necessary dispersion compensation scheme must be employed to bring the system within the allowable dispersion window. Again, unlike the point-to-point DWDM application, where dispersion consideration is given only to the one path between the two terminal points (Tx-Rx), for the transparent optical add/drop DWDM application, dispersion compensation must be carefully tailored to accommodate all possible optical paths of each signal wavelength. In this section, we will discuss how to determine the correct DCF modules for the ring using the dispersion properties and dispersion windows of each of the possible paths.

Linear Dispersion Variation

Dispersion Slope

Transmission fiber and DCF modules have different dispersion values at different wavelengths. This wavelength dependence is known as dispersion slope. A measure of the dispersion compensation ability of DCF modules over a wide range of wavelengths is characterized by the slope-compensating ratio, R, defined as follows:

$$R = \frac{RDS_{Tran}}{RDS_{DCF}}; \quad RDS_{Tran} = {D_{Tran}}/{S_{Tran}}; \quad RDS_{DCF} = {D_{DCF}}/{S_{DCF}} \tag{1}$$

where S_{Tran}, S_{DCF} are the dispersion slope per unit length of the transmission fiber and the DCF fiber respectively, and D_{Tran} and D_{DCF} are the dispersion amount per unit length parameters. RDS is the relative dispersion slope for each fiber type.

The residual dispersion (R_{dis}) due to dispersion slope is then:

$$R_{dis} = S_{Trans} l_{Trans} \times \frac{(1 - R) \times \Delta\lambda}{2}$$
$$\Delta\lambda = (\lambda_{max} - \lambda_{min}) \tag{2}$$

where R is the dispersion compensation ratio, l_{trans} is the transmission fiber length, and $\Delta\lambda$ is the range of wavelength channels of interest in the specific DWDM application.

Unpredictable Mux/Demux Errors

Different wavelengths undergo different amounts of dispersion in a typical MDX unit, which varies from D^{MDX}_{max} to D^{MDX}_{min} (ps/nm). When a signal goes through *N* nodes, as is the case for transparent reconfigurable OADM applications, the maximum dispersion due to MDX is $2 \times N \times D^{MDX}_{max}$ and minimum dispersion is $2 \times N \times D^{MDX}_{min}$. For *N* nodes, these unpredictable errors could be added statistically or linearly.

Statistical Errors

Transmission Fiber Dispersion Error
Typical transmission fiber is made up of smaller segments. The dispersion of these segments is random with variance of σ_{XmFib}. The dispersion variations of these segments adds up to contribute to the overall dispersion variation.

Transmission Fiber Length Error
Typically, the exact length of the transmission fiber is not known. Some systematic error always exists in the fiber length measurement. This error, in turn, introduces dispersion variation. Because the error is a function of the fiber span length, for the same ring size, the dispersion fluctuation is smaller for networks with a larger number of spans because the variances are added statistically.

DCF Error
DCF modules never exactly match their nominal value. The amount of error can be described as a percentage or as a statistical function. The greater the number of DCF modules, the more there is averaging of DCF error. Therefore, the worst case DCF error occurs when there are fewest DCF modules.

Other Optical Component Dispersion Error
Each component used in the ring has some random dispersion, which is different at different channels and for different individual parts. The variation is generally relatively small but has a potential to accumulate with an increased number of nodes.

Path Dispersion Calculations

For transparent per-channel optical add/drop DWDM ring applications, a wavelength path starts at a node and terminates at one of the *N-1* nodes (for an *N* node OADM ring). The DCF module deployment strategy in the ring is determined through an iterative process by considering all possible paths of the available l_i, i=1,2,K (N–1) span lengths. The dispersion window for each path, which must take into account the aforementioned dispersion factors and their variations, as well as the DCF module granularity, must be within the allocated system margin. Ring compensation and span compensation are two dispersion compensation schemes that can be deployed in a ring based system to adjust for these variations.

Ring Compensation

In ring compensation, the placement and value of dispersion compensation is calculated to limit the number of compensation modules, and therefore, the cost of deployment. In this method, a map is created of dispersion requirements and then DCUs are deployed around the ring, roughly dividing the residual dispersion so that dispersion accumulation never exceeds the maximum dispersion margin of the receivers. See Figure 5 for an example of how ring compensation can correct for residual dispersion.

This deployment scheme allows for the minimum number of DCF modules to be deployed and applies mainly to customers who have knowledge of the ring configuration and do not plan for future in-service ring length modifications.

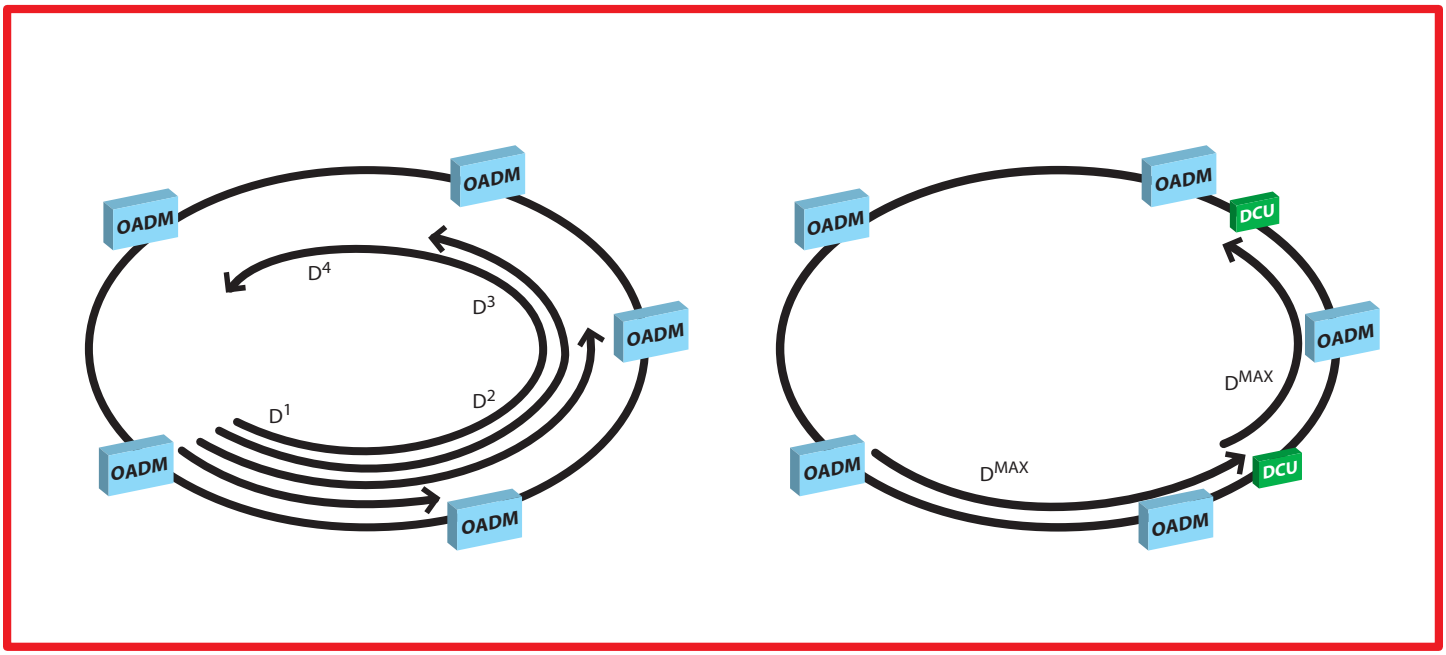


Figure 5: Ring Compensation

Span Compensation

In span compensation, the value of the dispersion compensation and the placement is calculated for maximum flexibility. In this method, a map is created of dispersion requirements and then DCUs are deployed around the ring (as shown in Figure 6) to match the dispersion on each span. Since the number of DCF modules required will increase with each span added in the ring, this compensation scheme is not as cost effective.

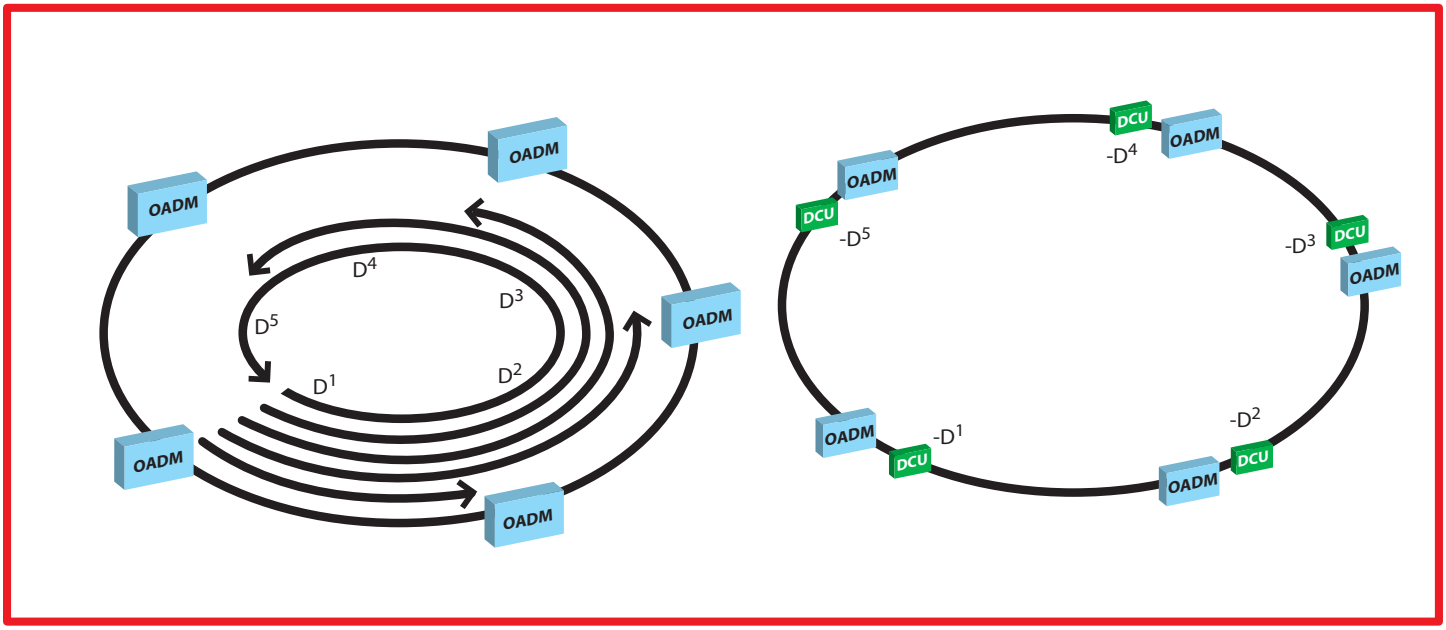


Figure 6: Span Compensation

Conclusion

In metro networks, signal path characterization is complicated by ring topologies that have multiple possible paths from each node. These paths need to be considered and the appropriate penalties taken or properly compensated.

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Acronym	Descriptor
DCF	Dispersion Compensation Fiber
DCU	Dispersion Compensation Unit
DWDM	Dense Wavelength Division Multiplexing
OADM	Optical Add/Drop Multiplexer
MDX	Mux/Demux
O-E-O	Optical to Electrical to Optical
RMS	Root Mean Square
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
WDM	Wavelength Division Multiplexing

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