Polarization Mode Dispersion

Definition

Polarization mode dispersion (PMD) occurs when different planes of light inside a fiber travel at slightly different speeds, making it impossible to transmit data reliably at high speeds.

Overview

PMD is the single biggest challenge facing system vendors and carriers as they attempt to deploy 40 Gbps optical networks. However, PMD is not just a problem at 40 Gbps; it is also evident in 10 Gbps optical networks as well.
This tutorial explains the nature of the PMD problem, what causes PMD, and how to compensate for this problem.

Topics

1. Introduction to PMD

Scientists and engineers for years have expressed the fear that as optical networking systems get faster and send signals longer distances, major physics-related problems would become a limiting force.

The technology for years had been given a free ride as it grew from 90 Mpbs to 270 Mbps to 435 Mbps to 2.5 Gbps. A problem began to manifest itself in 10 Gbps systems and threatens major dislocation at 40 Gbps networking. For the first time, the fiber-optics industry was faced with a networking killer.

The problem, which itself was not even discovered until the early 1990s, is PMD. It can distort signals, render bits inaccurate, and destroy the integrity of a network.

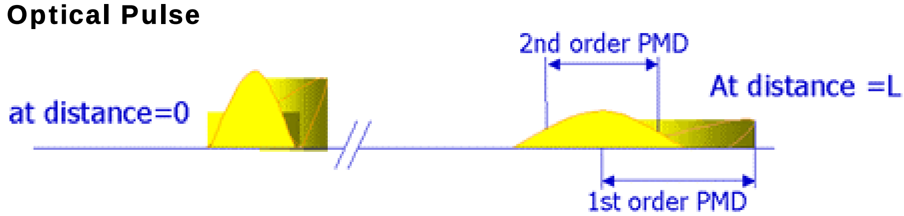
Approximately 20 percent to 30 percent of the single-mode fiber manufactured before the mid 1990s has a property that has become more problematic as bit rates and span lengths increase. The problem is that the core of this fiber is not perfectly round.

Of course, no fiber's core is perfectly symmetrical, but this fiber is off by enough that it causes dispersion to the degree that it renders signals unreadable.

When light travels down a single mode fiber toward the receiver, it has two polarization modes that follow the path of two axes. They move toward the receiver at right angles to each other.

When the core of the fiber that bounds the light is asymmetrical, the light traveling along one polarization axis moves slower or faster than the light polarized along the other axis. This effect can spread the pulse enough to make it overlap with other pulses or change its own shape enough to make it undetectable at the receiver (see *Figure 1*).

Figure 1. Graphical Representation of the Effect of PMD on an Optical Pulse

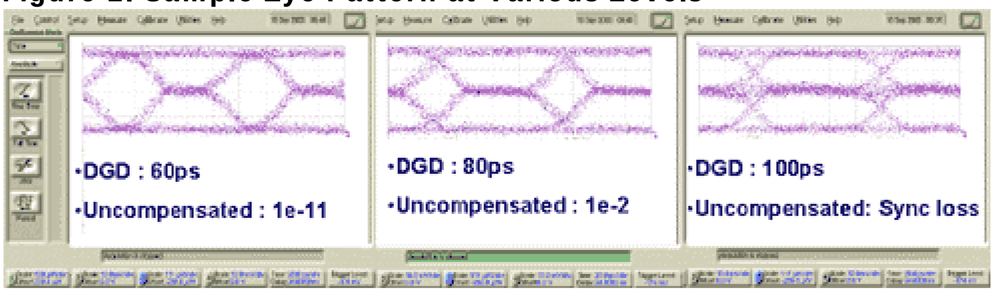


In *Figure 1*, the optical pulse and its constituent photons travel from the source, or transmitter, at distance =0, along the single-mode optical fiber. At some distance after PMD has affected the pulse, the polarized energy is separated by some time. This time is known as differential group delay (DGD). DGD is the fundamental measure of PMD and is measured in picoseconds (10^{-12} seconds). If

DGD is severe, the receiver at some distance L cannot accurately decode the optical pulse, and bit errors can result.

The optical eye pattern of a PMD–limited signal exhibits the effects of DGD by "closure" of the eye. The effect of the eye closure is caused by the separation of the polarized axes of photons, as the DGD becomes higher, separation becomes greater, and optical pulses start to interfere with each other, causing the eye to close (see *Figure 2*).

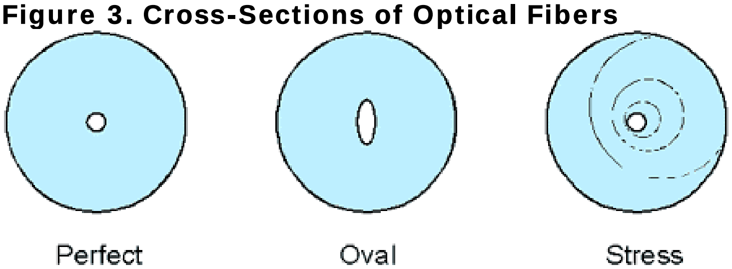
Figure 2. Sample Eye Pattern at Various Levels



2. Causes of PMD

The major cause of PMD is the asymmetry of the fiber-optic strand. Asymmetry is simply the fact that the fiber core is slightly out-of-round, or oval (see *Figure 3*). Fiber asymmetry may be inherent in the fiber from the manufacturing process, or it may be a result of mechanical stress on the deployed fiber. The inherent asymmetries of the fiber are fairly constant over time, while the mechanical stress due to movement of the fiber can vary, resulting in a dynamic aspect to PMD.

Figure 3. Cross-Sections of Optical Fibers

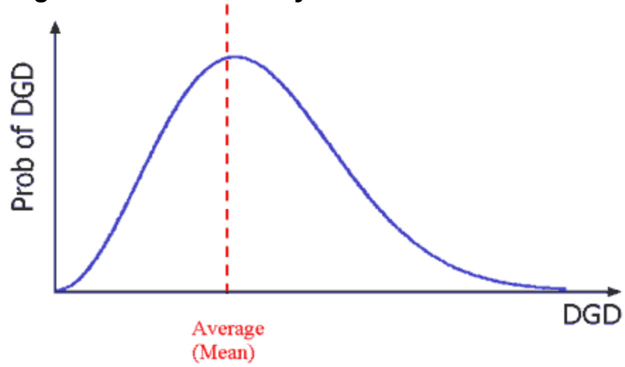


The mechanical stress on the optical fiber can originate from a variety of sources. One source that is very difficult to control is the diurnal (day/night) and seasonal heating and cooling of the optical fiber. Although much fiber is deployed in the ground and often within conduits, it is still subject to temperature variations and corresponding mechanical stress.

Another source of mechanical stress can originate from nearby sources of vibration. For example, much fiber is deployed alongside railroad tracks because of the ease of right-of-way and construction. However, vibration from passing trains can contribute to stress on the optical fiber. Fiber that is not buried next to railways and highways may be deployed aerially; in this scenario, wind can cause swaying of the fiber cable and can contribute to PMD.

Because of the combination of these effects, and the random way these effects add up over a section of fiber, PMD does not have a single value for a given section of fiber. Rather, it is described in terms of average DGD, and a fiber has a distribution of DGD values over time. The probability of the DGD of a fiber section being a certain value at any particular time follows a Maxwellian distribution (see *Figure 4*) As an approximation, the maximum instantaneous DGD is about 3.2 times the average DGD of a fiber.

Figure 4. Probability Distortion of DGD Levels in a Typical Fiber



3. Associated Effects of PMD

In the previous topic, we discussed the reasons for the variance of PMD over time. In addition to the time variance, PMD also varies over wavelengths. This variability over wavelength will be discussed again when we talk about PMD compensation, but here we will focus on the concept of second order PMD (SOPMD) (see *Figure 5*).

Figure 5. DGD Wavelength Spectrum

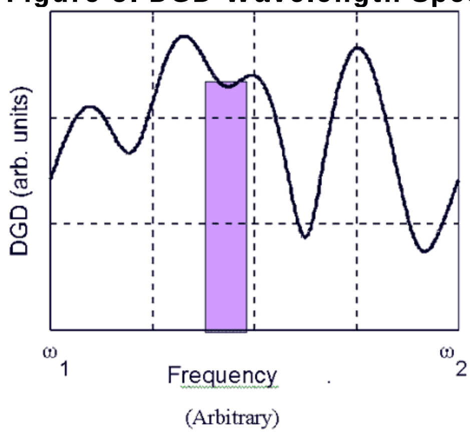
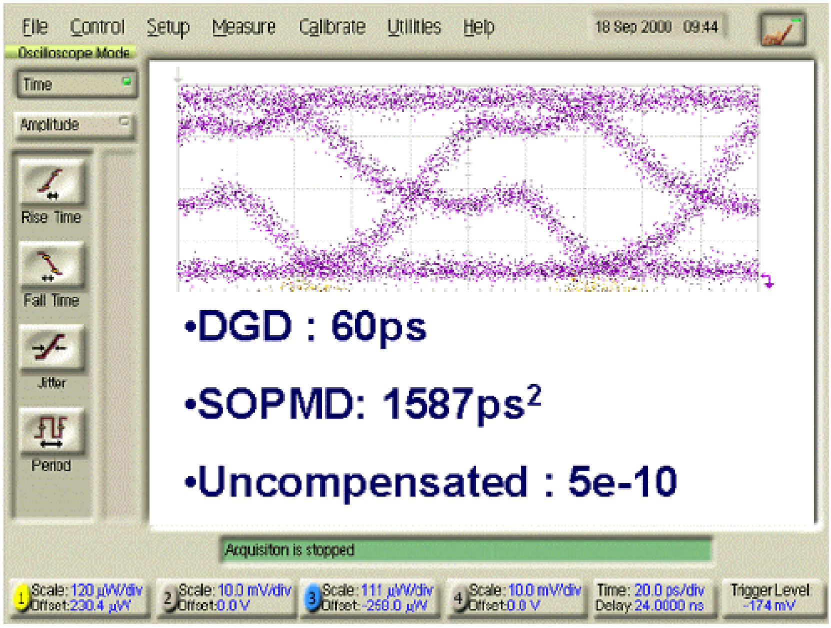


Figure 5 shows a typical variance of PMD over some select wavelengths from ω_1 to ω_2. This variance results in an optical dispersion that is a function of both the channel bandwidth and the value of DGD over that bandwidth.

The effects of this optical dispersion are evidenced in an optical pulse as a ragged edge of an optical eye.

SOPMD can also cause problems during the decoding of optical pulses at the receiver (see *Figure 6*).

Figure 6. Example of an Eye Pattern Distorted by Second-Order PMD



4. Network Impact

In the previous sections, we covered how PMD, and specifically DGD, can disperse the transmitted optical bit and cause bit errors at the receiver. If there are relatively few bit errors at the receiver, then usually other mechanisms of the transmission system can satisfactorily recover the lost transmitted information. However, if the bit errors are too numerous, then the transmitted information is too corrupt to recover and the transmission link should be considered out of service.

The quantity of bit errors encountered at the receiver are directly influenced by the amount of PMD in a fiber optic transmission span. In *Topic 1*, we covered how the DGD component of PMD was measured in the time separation of the polarized pulses of the optical bit. This separation is measured in picoseconds (ps, equal to 10^{-12} seconds). The average separation can be calculated from the

PMD coefficient of the fiber. PMD coefficients are in units of ps per √ km, or ps/(√ of km). Some fibers installed before the mid 1990's have coefficients of about 1–2ps/(√ of km). We can look at some example calculations to be expected with fibers of this quality for a fiber route about the distance from San Francisco to Los Angeles:

DGD = (PMD coefficient) x (√ of distance)

DGD = (1–2ps/(√ of km))((√ of 500 km))

DGD = 22–44 ps

DGD of this magnitude, in an OC–192/STM–64 transmission system, can be expected to result in a bit-error rate that is severe enough to cause service problems. Some general rules on limitations of distances caused by PMD are given in *Figure 7*.

Figure 7. Distance Chart for PMD

Maximum Optical Transmission Distance (km)

Without a Polarization Mode Dispersion Compensator (PMDC)

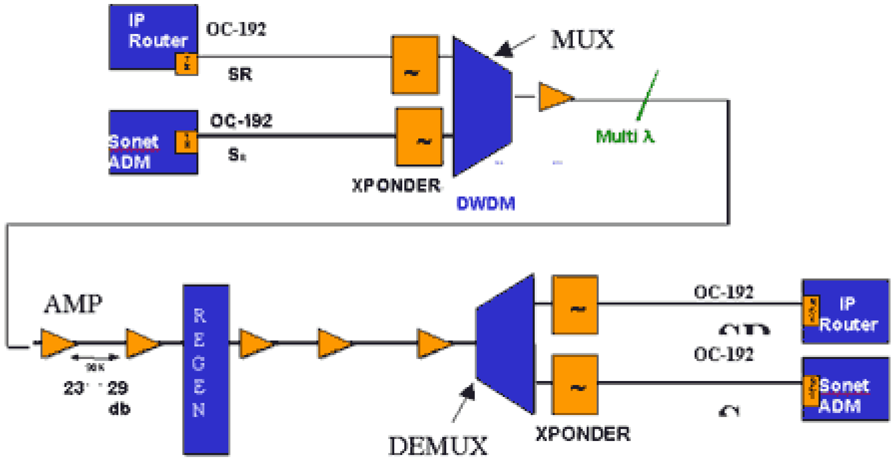
	Fiber PMD (ps per √km)		
Data Speed (Gbps)	Deployed Yesterday 1.00	Deployed Today .50	Deployed Tomorrow .25
10	60	230	781
40	4	14	49

Table based on published data for typical fiber estimates of effects of cable construction and installation process; includes effects of amplifies and other typical elements of a system.

5. Potential Solutions

PMD–induced problems can be reduced simply by shortening the optical transmission distance of a system. For example, in the San Francisco to Los Angeles route, an optical-electronic receiver function could be placed about halfway between the two cities (see *Figure 8*).

Figure 8. Transmission System with Mid-Span Regeneration Block Diagram

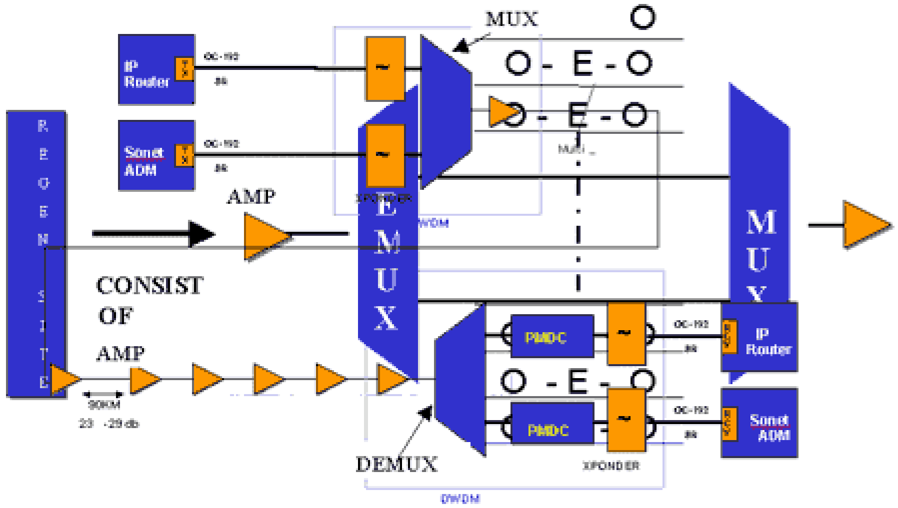


The sole purpose of the receiver at this mid-span site is to decode the optical signals before they are corrupted by dispersion. After the bits are decoded, the electronic signals are then merely retransmitted by another optical transmitter, continuing their journey to their final destination where they will be decoded again and routed or switched electronically.

This method of a mid-span receiver/transmitter function, typically known as regeneration, has been widely used in fiber-optic transmission since its inception. However, regeneration has always been considered a poor alternative because the only reason the transmitted bits are converted to electronic signals at the regeneration site is because of the dispersion of the optical bits; the electronic bits are not routed, switched, multiplexed, or, in most cases, even monitored: they are merely regenerated. Therefore, from a network point of view, a regeneration site is an inefficient and costly optical-electronic conversion site.

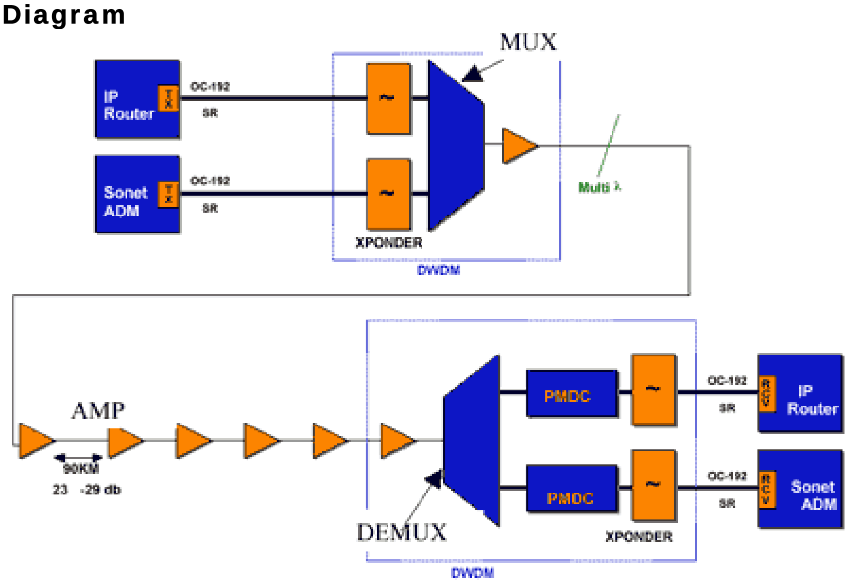
Adding to the expense and inefficiency of a regeneration site is the fact that most long-haul transmission systems are now multiwavelength, dense wavelength division multiplexing (DWDM) systems. In this application, the transmission link must first be demultiplexed, then regenerated, then multiplexed again (see *Figure 9*). This is a very costly operation compared to the preferred alternative of a multiwavelength amplifier.

Figure 9. Detail of the Regeneration Site



From a network and cost perspective, a more efficient method of addressing the PMD problem is to fix the effects of PMD while the transmission is in an optical state, before a receiver tries to decode the bits. This method is known as PMD compensation, and it is shown in *Figure 10*.

Figure 10. Transmission System with a PMD Compensator Block Diagram



A PMD compensator (PMDC), deployed at the destination of the transmission system, can reduce the effects of the dispersion in the fiber and ensure that the optical bits are correctly decoded by the receiver before they are to be routed and switched.

6. The PMD Compensator

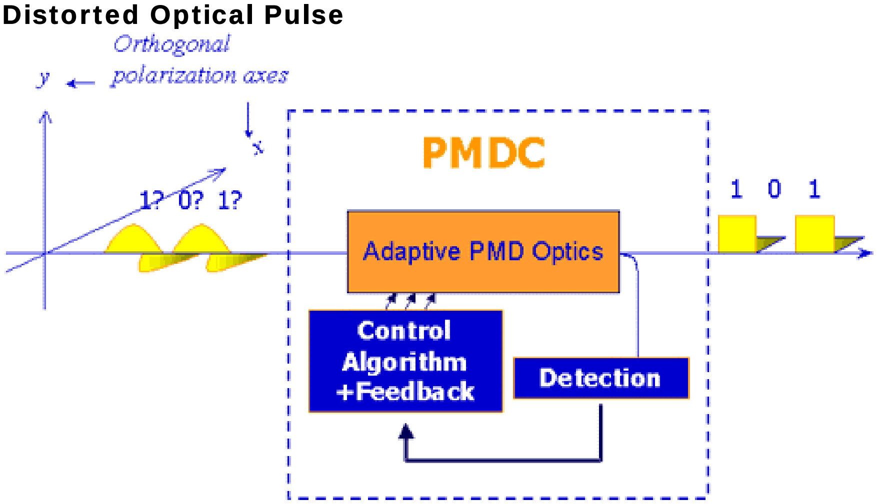
There are several technologies that can be utilized to compensate for the effects of PMD. These technologies have included the following:

- Mechanical devices that actually squeeze a portion of the fiber in order to realign the polarization pulses of the optical bit. In other words, a mechanical PMDC "counter-stresses" the fiber. The primary drawback of this method is that mechanical devices are more prone to failure over long durations; e.g., the original mechanical "step" switches of early voice networks, a technology of the early 20th century, demanded frequent maintenance and were prone to problems.

- Electronic devices that work after the receiver decoder, manipulating electrons in order to reduce bit errors. The primary drawback to this method is the difficulty in correcting an optical problem at the electronic layer.

The most reliable and efficient PMDC technology is the use of adaptive optics to realign and correct the pulses of dispersed optical bits. The high-level concept of adaptive optic technology is shown in *Figure 11*.

Figure 11. Graphical Representation of PMD Compensation on a Distorted Optical Pulse

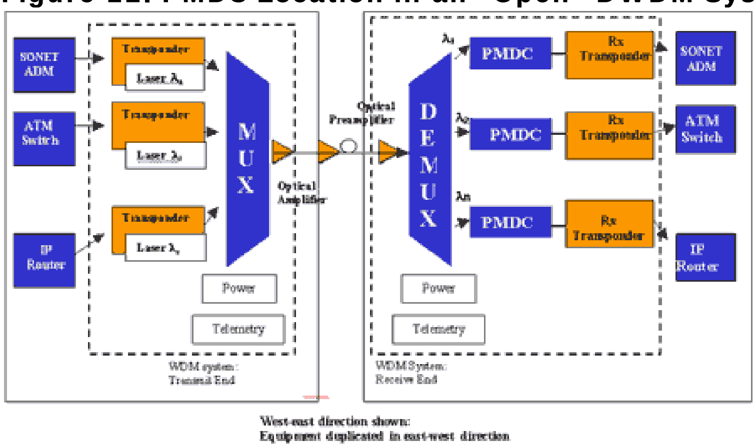


The figure shows how dispersed optical bits from the fiber network are corrected by the PMDC. Before correction, the polarized pulses of the bits have been separated and dispersed by PMD. The PMDC realigns and reshapes the optical bits before they are decoded by the receiver (Rx). The adaptive optics of the PMDC are controlled by an intelligent algorithm that is driven by analysis of the optical bit.

7. Compensator's Place in Optical Networks

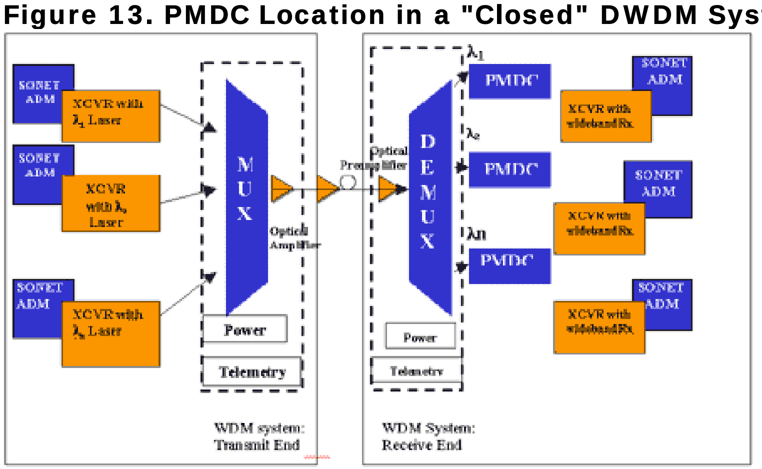
The optimal placement of a PMDC in a network is directly prior to the receiver function of a transmission system. In long-haul and ultra long-haul multichannel optical systems, the receiver is usually located within the DWDM optical transmission equipment at the central office or point-of-presence (POP) site. There are two general types of DWDM transmission systems. Systems where the receiver function is within the DWDM network element are known as “open” DWDM systems (see *Figure 12*). In this example, the PMDC subsystem is located after the optical demultiplexing but before the receive transponders. Since the adaptive optic PMDC is an all-optical device, locating within the DWDM system is easy and straightforward.

Figure 12. PMDC Location in an "Open" DWDM System



Some older multichannel optical systems do not utilize transponders for the DWDM function; these systems are known as “closed” systems (see *Figure 13*).

Figure 13. PMDC Location in a "Closed" DWDM System



In these types of systems, the receiver function is located not within the DWDM network element but in a synchronous optical network (SONET) or synchronous digital hierarchy (SDH) network element, whose receiver mates up with the transmitter's wavelength. In order to mate exactly, the DWDM network element and the SONET/SDH network elements must be manufactured by the same vendor, hence the term "closed." In this example, the PMDC subsystem is located between the optical demultiplex stage of the DWDM system and the SONET/SDH element; again, since an adaptive optic PMDC is all-optical, it can also operate within a "closed" system.

8. Economic Considerations

To understand the cost issue, we can examine the typical regenerator system shown in *Figure 8* of *Topic 5* of this tutorial. Because the equipment at each regenerator site is essentially a duplicate of the equipment at both endpoints of the 10 Gbps system, each regenerator site adds about 100 percent to the cost of an end-to-end system without regenerators. Therefore, a 600 km end-to-end system with 2 regenerator sites would be about 3 times the cost of a system without regeneration.

As stated above, regeneration provides other benefits in addition to eliminating concerns about PMD; primary among those is the boosting of the optical signal. However, because regeneration, and therefore the cost of regeneration, is wavelength specific, the economics of regeneration get worse as more channels are added on each fiber. For this reason, end-to-end systems that do not exhibit PMD problems utilize optical amplifiers instead of regenerators to boost the power of the optical signal.

PMD compensation, like regeneration, is performed on a per-wavelength basis. This is due to significant variability in PMD over wavelength within a transmission band. However, a single PMD compensator at the receive side of a 10 Gbps signal can mitigate the PMD effects that build up over an entire transmission span. Therefore, unlike the regeneration option that may require 2 separate sites to eliminate PMD on a 600 km span, a single PMD compensator located at the destination or receive side of the optical signal can improve the end-to-end performance of the transmission path.

PMD compensation can be accomplished for a fraction of the cost of a single regenerator site's equipment costs. In addition to the equipment costs associated with regenerating optical signals, there is also the issue of the costs of the regenerator sites themselves. Since these regenerator sites must be located within certain distance ranges along the optical transmission path in order to operate most effectively, the required placement for these sites may often be in difficult geographic locations. The buildings to accommodate these sites are often more costly to construct and maintain than equivalent real-estate space in the most desirable urban locations, simply because the site is so remote.

Self-Test

1. Polarization mode dispersion ______________________________.

    a. distorts signals

    b. destroys the integrity of the network

    c. occurs when light travels down fiber at varying speeds

    d. all of the above

2. Differential group delay is the fundamental measure of PMD.

    a. true

    b. false

3. Asymmetry, a major cause for PMD, is simply the fact that the fiber core is diamond-shaped.

    a. true

    b. false

4. One cause of polarization mode dispersion is ______________________.

    a. vibrations of the fiber

    b. Internet traffic overload

    c. electromagnetic interference

    d. all of the above

5. In today's networks, about how far can a signal travel at 40 Gbps before being affected by PMD?

    a. Across a small city

    b. Across a typical metropolitan region

    c. Across a region

d. Across the United States

6. Regeneration is an economical way to combat polarization mode dispersion in DWDM systems.

   a. true

   b. false

7. A polarization mode dispersion compensator (PMDC) can reduce the effects of dispersion in the fiber to ensure that the optical bits are correctly decoded by the receiver before they are to be routed and switched.

   a. true

   b. false

8. Polarization mode dispersion compensation is an example of ________________________.

   a. adaptive optics

   b. regeneration

   c. amplification

   d. switching and routing

9. Where is the optimal placement of a PMDC in a network?

   a. directly after the transmitter

   b. directly after the receiver

   c. directly prior to the receiver

   d. directly prior to the transmitter

Correct Answers

1. Polarization mode dispersion __________________________________.

   a. distorts signals

   b. destroys the integrity of the network

   c. occurs when light travels down fiber at varying speeds

d. all of the above

See Topic 1.

2. Differential group delay is the fundamental measure of PMD.

   a. true

   b. false

   See Topic 1.

3. Asymmetry, a major cause for PMD, is simply the fact that the fiber core is diamond-shaped.

   a. true

   b. false

   See Topic 2.

4. One cause of polarization mode dispersion is ________________________.

   a. vibrations of the fiber

   b. Internet traffic overload

   c. electromagnetic interference

   d. all of the above

   See Topic 2.

5. In today's networks, about how far can a signal travel at 40 Gbps before being affected by PMD?

   a. Across a small city

   b. Across a typical metropolitan region

   c. Across a region

   d. Across the United States

   See Topic 4.

6. Regeneration is an economical way to combat polarization mode dispersion in DWDM systems.

    a. true

    b. false

    See Topic 5.

7. A polarization mode dispersion compensator (PMDC) can reduce the effects of dispersion in the fiber to ensure that the optical bits are correctly decoded by the receiver before they are to be routed and switched.

    a. true

    b. false

    See Topic 5.

8. Polarization mode dispersion compensation is an example of ________________________.

    a. adaptive optics

    b. regeneration

    c. amplification

    d. switching and routing

    See Topic 6.

9. Where is the optimal placement of a PMDC in a network?

    a. directly after the transmitter

    b. directly after the receiver

    c. directly prior to the receiver

    d. directly prior to the transmitter

    See Topic 7.

Glossary

ATM
asynchronous transfer mode

DGD
differential group delay

DWDM
dense wave division multiplexing

IP
Internet Protocol

O-E-O
optical-electrical-optical

PMD
polarization mode dispersion

PMDC
polarization mode dispersion compensator

POP
point of presence

ps
picosecond, equal to 10^{-12} seconds

Rx
receiver

SDH
synchronous digital hierarchy

SONET
synchronous optical network

SOPMD
second-order PMD

WDM
wavelength division multiplexing