Environmental Effects on Chromatic and Polarization Mode Dispersion

By Kevin R. Lefebvre, Ph.D

TABLE OF CONTENTS:

With optical networks moving from 2.5 Gbps to 10 Gbps and onto 40 Gbps, the dispersion tolerance drastically reduces.

ABSTRACT

Tight requirements of high speed optical networks require an understanding of all the effects that result in the degradation of the optical signal. This includes taking into account the environmental conditions that affect chromatic dispersion and polarization mode dispersion. This paper explains how environmental effects, such as variations in temperature, and pressure play a role in determining the refractive index of the optical fiber and quality of the signal.

1.0 Understanding the Cause and Effect

With optical networks moving from 2.5 Gbps to 10 Gbps and onto 40 Gbps, the acceptable tolerance of dispersion (the broadening of light pulses) drastically reduces. For instance, the amount of acceptable chromatic dispersion decreases by a factor of 16 when moving from 2.5 to 10 Gbps and an additional factor of 16 from 10 to 40 Gbps. The tight tolerances of high-speed networks mean that every possible source of pulse spreading should be addressed, such as the environmental effects on dispersion.

Table 1: Environmental conditions of aerial fiber

Location	Average Minimum Temperature	Average Maximum Temperature	Average Wind Speed
New York	-8° C	25° C	19 km/h
Arizona	5° C	39° C	9 km/h
Florida	10° C	30° C	13 km/h
Wisconsin	-33° C	39° C	15 km/h

Optical fibers are exposed to various environmental conditions such as temperature, humidity and wind depending if the fiber is underground aerial or within inner-city ducts. For instance, aerial fibers experience a wide variation of environmental conditions based on the fiber's location (see Table 1). Optical fiber in each of these locations will experience different levels of wind speed and temperature fluctuation, changing the chromatic dispersion and polarization mode dispersion of the fiber. In addition to natural elements, optical cable may experience temperature changes due to manmade elements. Cables routed through inner-city ducts can experience temperatures as high a 130°C, resulting from leaking steam pipes.

Both temperature and stress have a direct affect on the physical properties of the optical fiber thus determining the quality of the signal. To fully understand how the environmental effects play a role in determining the quality of the signal, both chromatic dispersion and polarization mode dispersion should be addressed in terms of environmental changes.

2.0 Refractive Index

Light within a medium travels at a slower speed than in a vacuum. The speed at which light travels in the medium is determined by its refractive index. In an ideal situation, the refractive index would not depend on the wavelength of the light. However, this is not the case which results in different wavelengths traveling at different speeds within an optical fiber.

Environmental conditions, such as variations in temperature (see Table 1) can change the refractive index of the optical fiber. As temperature increases, so will the refractive index, however, the increase is not uniform over all wavelengths resulting in differing wavelength speeds. In addition, stress, such as the pressure experienced by a submarine cable, can affect the refractive index of an optical fiber. When pressure is exerted on the optical fiber, the refractive index decreases. The amount of the decrease is also a function of the wavelength.

3.0 Chromatic Dispersion

When a series of pulses travel down an optical fiber, the pulses broaden or disperse making them indistinguishable, creating an effect called intersymbol interference. The source of intersymbol interference arises from the waveguide and material properties of the optical fiber. One of the dispersive effects caused by the properties of the waveguide and the material is called chromatic dispersion and is measured in units of ps/nm/km.

A pulse is not monochromatic, but is comprised of several wavelengths. The amount of broadening a pulse experiences is a function of the refractive index difference between the wavelengths contained within the pulse. The difference in the refractive index results in the wavelengths comprising the pulse to travel at different speeds, causing some wavelengths to travel faster than others. This phenomenon is known as material dispersion. The detrimental effects of material dispersion result in the slower wavelengths of one pulse intermixing with the faster wavelengths of an adjacent pulse, causing intersymbol interference.

Optical fiber is composed of a core and cladding layer where the refractive index of the core is greater than the refractive index of the cladding. The difference in the refractive index causes most of the light to be confined within the core of the fiber, however, some of the light propagates within the cladding. The difference in the refractive index causes the light in the core traveling slower than the light in the cladding , resulting in a spreading of the pulse. This phenomenon is known as waveguide dispersion. Waveguide dispersion is a function of the wavelength of light, the refractive index difference between the core and cladding layers and the diameter of the core. Changes in the core diameter, the wavelength or the refractive index of the core and cladding will result in a change in the waveguide dispersion.

The time between pulses, or bit rate, determines the amount of pulse broadening an optical system can handle. The chromatic dispersion limit, the amount of acceptable dispersion, is inversely proportional to the bit rate squared. This implies higher bit rates can tolerate smaller amounts of dispersion. For instance, a 2.5 Gbps system can experience 16 times more dispersion than a 10 Gbps system and 250 times more dispersion than a 40 Gbps system.

Changes in the refractive index due to temperature variations will result in modifying the amount of chromatic dispersion the pulse experiences. Varying the temperature results in a change in the zero dispersion wavelength, the wavelength of the least amount of dispersion, on the order of 0.025 nm/°C. Taking into account the temperature variations in Table 2, the zero dispersion wavelength can swing by as much as 1.8 nm, see Table 2. The change in the zero dispersion wavelength results in a shift of the dispersion curve by $\Delta\lambda_o$, either increasing or decreasing the amount of dispersion experienced by the pulse . This is demonstrated in Figure 3, where the shift in the zero dispersion wavelength results in a change in the dispersion at λ_1.

Table 2: Temperature and zero dispersion variations

	ΔT (°C)	$\Delta\lambda_O$ (NM)
New York	33	0.825
Arizona	34	0.85
Florida	20	0.5
Wisconsin	72	1.8

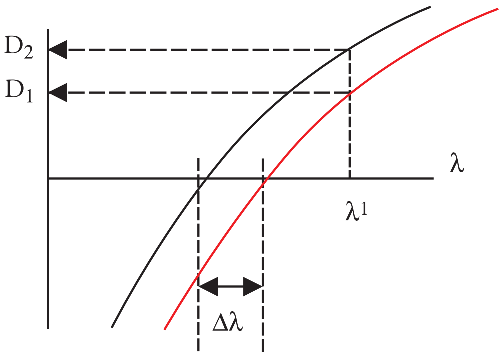

Figure 1: Chromatic dispersion as a function of wavelength with a shift in the zero dispersion wavelength

Not only does the temperature affect the zero dispersion wavelength, pressure and strain also shifts the zero dispersion wavelength. This results from changes in the waveguide properties of the fiber due to pressure or strain. The resultant strain and pressure related change in zero dispersion wavelength for unshifted fiber is 1.75nm/% strain and -0.007 nm/MPa, respectively.

4.0 Polarization Mode Dispersion

The refractive index of an optical fiber can have a different value across the horizontal and vertical axis of the fiber core. This difference in the refractive index results in the two orthogonal states of polarization (vertical and horizontal) traveling at different speeds through the fiber. The result is a Differential Group Delay, measured in ps/km 1/2, between the two states of polarization (vertical and horizontal axis) and possibly intersymbol interference. This effect is known as Polarization Mode Dispersion (PMD).

A typical design rule is that DGD should not exceed 10% of the bit rate for an NRZ signal. This implies that as the bit rate increases, the acceptable amount of DGD decreases. Meeting this design rule can be challenging since PMD is a result of geometric irregularities of the fiber core, temperature changes and stress placed on the fiber, making PMD unpredictable and statistical in nature.

The magnitude of polarization mode dispersion depends on the fiber's ambient temperature, as well as, the temperature's rate of change. Since the temperature changes over time, the time evolution of the DGD should be considered as shown in Figure 2. In general, DGD exhibits a rapidly oscillatory behavior in time. As the temperature gradually increases (decreases), the DGD oscillation stays approximately constant but increases (decreases) in amplitude (sections A and D of Figure 2). However, if there is a sudden change in temperature (sections B and C) the frequency of oscillations increases rapidly.

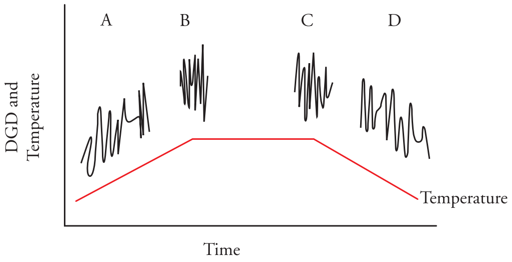

Figure 2: Time evolution of temperature and PMD

There are three main effects that cause the change in polarization as a function of temperature. An increase in the fiber's ambient temperature results in a change in the fiber length due to thermal expansion. This increase in length will allow the states of polarization (SOP) to separate for a longer time causing further spreading of the pulse. This effect, however, is small but will contribute to changes in dispersion. Another effect is the different thermal expansion of the various coating and buffer layers. This will result in internal stress on the fiber, resulting in DGD. Lastly, the birefringence (difference in the core and cladding refractive indexes resulting in a separation of the vertical and horizontal SOP) depends linearly on temperature which results in an internal stress within the fiber and a DGD.

5.0 Concluding Remarks

Tight requirements of high speed optical networks require an understanding of all the effects that result in the degradation of the optical signal. This includes taking into account the environmental conditions that affect chromatic dispersion and polarization mode dispersion.

To fully account for the environmental affects, both chromatic dispersion and polarization mode dispersion should be measured accurately. This would require measuring PMD over a long enough period of time to account for variation in temperature and stress and plotting the results as a histogram. This will give a baseline for a system where the design parameters above can be used to evaluate the amount of drift that can arise due to variations in the environmental conditions. The amount of drift can then be used to determine the quality of the signal over all environmental conditions.

NetTest
Center Green, Building 4
6 Rhoads Drive
Utica, NY 13502 USA
Toll Free: 1 800 233 3800
Tel: +1 315 266 5000
Fax: +1 315 798 4038
E-mail: info@nettest.com
web: www.nettest.com

NetTest Sales Offices

Australia	+61 039 890 6677	Italy	+39 02 95 12 621
Brazil	+55 11 5505 6688	Mexico	+52 5557 8249
Canada	+1 905 479 8090	Singapore	+65 220 9575
China	+86 10 6467 9888	Spain	+34 91 372 92 27
Denmark	+45 72 11 23 00	Sweden	+46 8 555 410 65
France	+33 1 30 08 88 88	UK	+44 1883 349 110
Germany	+49 89 99 89 01 0	USA	+1 978 983 3800

NetTest is a leading worldwide provider of testing, monitoring and management systems across both the optical and network layers of communications networks. NetTest provides network operators, network equipment manufacturers, component manufacturers and enterprise service providers with the network testing solutions they need.