Measuring and Compensating for PMD in High-Speed Optical Networks

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ABSTRACT

Polarization Mode Dispersion is a physical phenomenon in optical fiber that causes light pulses to spread in time. If the amount of spread (dispersion) is excessive, adjacent light pulses will overlap and interfere with each other. This interference will manifest itself as an increased Bit Error Rate as the receiver may be unable to discern adjacent bits from each other. As the bit spacing decreases, as in high data-rate transmissions such as 10 Gbps (OC-192, STM-64) or 40 Gbps (OC-768, STM-256), excessive PMD will severely impact network operation. This paper will explain how these negative effects can be minimized or eliminated through proper PMD measurement and compensation.

1.0 Understanding PMD

While the phenomenon of Polarization Mode Dispersion (PMD) has been known for years, it has only been recently that it has posed a serious, realistic problem for optical networks. PMD's negative effects result in a limitation of a networks bandwidth or length that is, of course, undesirable to say the least. It is important to understand however, that with proper measurement and management, the negative effects of PMD may be minimized or eliminated altogether. While this is important for today's 2.5 and 10 Gbps networks, it will become critical as we progress towards Ultra Long-Haul 10 G and 40 G networks.

Before PMD can be eliminated it must first be understood. As its name implies Polarization Mode Dispersion is based on the polarization of light. In essence, different polarizations of light travel at different velocities. You might ask yourself, "Shouldn't light travel at the speed of light regardless of its polarization state, it is still light after all?" While this is technically true, there is one more factor that must be considered, the medium in which the light is traveling. All things being equal, light will propagate at the same velocity regardless of its polarization state, however, in a silica-based optical fiber, all things are not equal.

As a result of a property of optical fibers called 'birefringence', different polarizations of light are propagated at different velocities through the fiber. As laser light is generally highly polarized, the digital bits that they emit contain light that is also highly polarized. Couple this with the birefringence present in the fiber and the result is that different components (polarizations) of the digital bits travel at different velocities. In other words some of the light in the bit travels faster and some of the light travels slower. This causes the digital bit to spread in time; this is termed dispersion.

2.0 Dispersion Limits

Excessive spreading, or dispersion, will cause bits to 'overflow' their intended time slots and overlap adjacent bits. When this occurs, the receiver may have difficulty discerning and properly interpreting adjacent bits, this manifests itself as an increased Bit Error Rate. Three last facts should be presented and understood before PMD can be truly managed and controlled. First, the amount of pulse spreading or dispersion will accumulate with distance, the longer the link, the more time the pulse has to disperse. Second, the more birefringence in an optical fiber (the greater the difference in the propagation rates of the different polarized components), the quicker the pulse will disperse. Third, the closer the transmitted bits are together (i.e. higher data rates) the less spreading or dispersion can be tolerated. See Table 1.

Table 1

SDH	SONET	Transmission Rate	Bit Time	PMD Limit [1]
	OC-1	51.84 Mb/s	19.29 ns	2 ns
STM-1	OC-3	155.52 Mb/s	6.43 ns	640 ps
STM-4	OC-12	622.08 Mb/s	1.61 ns	160 ps
	OC-24 (1.2 Gbps)	1,244.16 Mb/s	803.76 ps	80 ps
STM-16	OC-48 (2.5 Gbps)	2,488.32 Mb/s	401.88 ps	40 ps
STM-64	OC-192 (10 Gbps)	9,953.28 Mb/s	100.47 ps	10 ps
STM-256	OC-768 (40 Gbps)	39,318.12 Mb/s	25.12 ps	2.5 ps

[1] Dispersion is typically limited to 10% of the bit time

The information presented above might lead one to the intuitive conclusion that to avoid or limit the negative effects of PMD one could simply limit the length of the transmission link, or provide more time between bits (transmit at a lower data rate). While these are both logical and true, of course, neither is desirable. A more economical and lucrative approach would be to control PMD through other methods that would still allow for longer link lengths (read fewer costly repeaters) and higher data rates (read increased revenue generating potential). These other methods include PMD measurement and characterization and ultimately dynamic PMD compensation.

3.0 Controlling PMD

With proper PMD measurements, the PMD present in a link may be monitored and kept in check during an installation. Birefringence is affected by stress in a fiber and anything from rough handling, to fiber/cable quality, to environmental conditions can impact the stress on a fiber and thus its birefringence. As a result, the PMD will also change due to these characteristics. Monitoring PMD during an installation can provide verification of cable quality and validate handling and installation techniques to help minimize PMD in the network right from the start. In addition, when performing an upgrade from 2.5 Gbps to 10 Gbps the PMD must be verified to ensure that the system will operate properly once turned up.

The worst case imaginable would be to have engineering design a network configuration, have purchasing procure the required transmission gear, have operations install the upgraded system and to have sales promote increased capability and sell additional bandwidth only to find that the system doesn’t work properly once turned up due to excessive PMD. Not only will schedules be delayed and operational expenses increased dramatically, but customer satisfaction and loyalty will also be seriously compromised.

On an existing network, PMD measurements can help to optimize the bandwidth capabilities, and the revenue generating potential of each fiber. The bandwidth on a fiber is equal to the number of channels on the fiber multiplied by the data rate of each channel. This implies that if either the number of channels or their individual data rates are increased, so too will the bandwidth of the fiber be increased. By characterizing the PMD profile of each fiber in a cable, each fiber may be pushed to its individual limits and the total bandwidth and revenue generating capabilities of the cable can be maximized.

For example, if a 12-fiber cable, running at 2.5 Gbps and 16 channels per fiber, were tested and it was found that 3 fibers in the cable could actually support a 10 Gbps transmission rate, then the total capacity of the cable could be increased by 75% by running these fibers at their individual limits!

Table 2: Sample Calculation
12 fibers * 16 channels * 2.5 Gbps = 480 Gbps total cable capacity -or- (9 fibers * 16 channels * 2.5 Gbps) + (3 fibers * 16 channels * 10 Gbps) = 840 Gbps A 75% increase in the total cable capacity

In addition, for dark fiber providers, PMD measurements can help to minimize opportunity costs and increase efficiency. If the dispersion profile of each fiber in a cable is known, the fibers provided to each customer can be matched intelligently to their requirements. It would be inefficient, to say the least, to provide a fiber capable of supporting 10 Gbps data rates to a customer that only requires 2.5 Gbps. PMD measurements can provide the critical piece of information that can enable this type of intelligent fiber provisioning.

4.0 PMD Test Equipment Selection

When selecting a field portable PMD test set, several issues become key. First, as every fiber in a cable must be measured, test time becomes critical. Not just for small values of PMD, but for larger values as well. When selecting a PMD instrument it is important to understand its test times for all values of PMD, not just the small values that make the headlines on specification sheets. After all, what good is an instrument that can measure large amounts of PMD if it takes several minutes to complete a test? Second, with the increase of route length due to the deployment of Raman pre-amplifiers, dynamic range becomes key. A PMD test set should be capable of measuring links containing up to 55 dB of attenuation to ensure that the kit you invest in today will continue to meet your needs in the coming years. Also, ensure that the instrument will meet your durability and ruggedness needs at these performance levels, remembering that these instruments will be constantly deployed in the field. Finally, the PMD measurement range will also become a concern. If you measure PMD with the intent to deploy 10 Gbps service and find that the link is unacceptable, the next logical question is “Can the link at least handle 2.5 Gbps transmission?” With the addition of Return to Zero (RZ) modulation formats and Forward Error Correction (FEC) some of today’s 2.5 Gbps systems are capable of withstanding up to 60 - 70 ps of PMD. As a result, the PMD test set must be able to accurately and quickly measure such values.

Today, if the bandwidth of a cable was to be increased, one approach as indicated earlier, would entail increasing the data rate of some, or all of the fibers contained in the cable. If PMD measurements reveal that one fiber is unfit for a data rate upgrade, subsequent fibers are tested until one of sufficient quality is found. However, there comes a time when even this approach is no longer sufficient. Once the PMD profiles of all fibers are known, it may become evident that there no longer exist any fibers in the cable suitable for upgrade. Historically, this would have spelled the beginning of the end of life for such a cable. However, with the advent of new, innovative technologies, PMD compensation has become a reality and has breathed new life into these ailing networks.

5.0 PMD Compensation

Compensating for PMD in live networks has been a major challenge for two principal reasons: first, because PMD changes are statistical in nature and secondly because PMD varies over time and by wavelength. As a probabilistic effect, the level of PMD in an optical signal at any moment varies in an unpredictable fashion. In fact, the statistics of PMD over time and over wavelength can be characterized by a Maxwellian distribution. The long tail of the distribution means that much higher PMD states can be reached. It’s common to define the “maximum” level of PMD, approximately 3.1 times the mean, as significant for determining the outage of a network. The statistical nature of PMD over time is very different from most other impairments in a fiber, such as chromatic dispersion which follow fixed or deterministic behavior. PMD levels on a high-PMD fiber can be low for days at a time, but then can rise to high levels, causing severe errors and outages for sustained periods of time. A PMD compensator must therefore be able to change dynamically to compensate for the temporal fluctuations in PMD levels.

PMD also varies statistically by wavelength. Different wavelengths react differently to the birefringence within a fiber, leading to varying levels of PMD at the end of a link. It is common that one channel can be impaired by PMD but the neighboring wavelength channel can be fine. Therefore PMD must be compensated on a wavelength-by-wavelength basis.

A PMD compensator must therefore compensate PMD on an adaptive, real-time, per-wavelength basis. Each bit can be analyzed to determine the PMD in the signal. The polarization of the signal can then be altered to correct for the PMD, restoring the bit as close as possible to its original state. The compensation can be done in the optical domain, which maintains the quality and scalability of an all-optical solution.

It is critical for a compensator to have a wide range of compensation. Over the course of months, the PMD on a fiber in a live network can vary from minimal to 100 picoseconds or more. The compensator must perform in all these states. In addition, the compensator must be able to cope with both First Order PMD and Second Order PMD, the two principal components of PMD.

The fundamental cause of PMD is a deviation from circularity of either the optical fiber core or the cladding that surrounds it. Although as any high-school physics student knows, the speed of light in a vacuum is a constant c, the speed of light when passing through any medium with mass is a function of c, as well as, the refraction index of that medium. If the core or cladding of a fiber is even slightly oval, one polarization mode travels at a different speed than the other, and at the gigabit speeds of today's networks, that's enough to make a difference to the quality of the signal.

At the practical level, many things can lead to ovality of a fiber, and hence PMD. One can divide these causes into intrinsic and extrinsic factors. The most common intrinsic cause of PMD is ovality in the manufacture of the fiber. In fact, most single-mode fiber manufactured before about 1996 is prone to exhibit PMD because fiber manufacturers were not well aware of the problem and hence did not optimize their manufacturing processes to minimize PMD. Common extrinsic causes of PMD include stresses induced during cabling of the fiber, temperature change, or fiber movement. Often the day-to-night variation in temperature can be enough to induce significant levels of PMD in fiber, particularly fiber sections that are not buried underground. Fiber movement can be caused by many effects, including fiber vibration due to trains or trucks passing over buried fiber, or the impact of wind on aerial fiber.

6.0 PMD's Impact on the Network

How big a problem is PMD for 10 Gbps networks? Estimates from the US telecommunications research center Bellcore and individual carriers show that PMD is an issue in some 20%-30% of the fiber spans in long-haul networks. In other words, for a conventional long-haul span (say 300km in Europe and 500km in North America), PMD would on average exceed the tolerance of a 10G line system on some 20-30% of the fibers on any given span. The conventional solution for this problem is to use repeaters (regenerators) at mid-span to keep the PMD levels at tolerable levels. This is an expensive solution. Another solution is to re-route the traffic through other spans to avoid the high-PMD fiber. Ultimately, this is also an expensive solution, and one that can lead to even bigger problems as fiber exhaust is reached on those spans-a carrier can effectively paint itself into a corner where its best fiber is overloaded and it has fewer and fewer alternatives.

Table 3

	PMD Coefficient [ps/sqrt(km)]			
Bitrate [G/s]	**1.00**	**0.50**	**0.25**	**0.1**
2.5	2,690	10,606	40,111	181,44
10	168	661	2,500	11,309
40	10	40	149	676
80	2	8	32	144
160	0	1	3	11
	unrepeated transmission distance [km]			

100 Amp/DCM span spacing [km]
0.7 Amp/DCM PMD [ps]
13.0% Rcvr tolerance to PMD [% bit period]

Leading-edge carriers are striving to incorporate PMD compensation into their link design strategy. Typical strategies now include careful field measurement of all the fibers on any link that the carrier wishes to light at 10 Gbps. If the mean PMD levels are low enough, the link can be lit without PMD compensation, however, if high-PMD fibers must be lit, the use of PMD compensation will be required. This will facilitate economic deployment of larger amounts of bandwidth, as well as, increased flexibility in the network, including the ability to turn up more wavelengths or more links with greater efficiency and respond more quickly to customer demand, fulfilling revenue opportunities quicker and more cost-effectively.

7.0 The Future of PMD

While field PMD measurement techniques are quite mature, PMD compensation is still a new tool in the carrier's toolkit. But current trends in network design promise to make it more widespread. First is the growing popularity of 10 Gbps networks. This bit rate is fast becoming the new industry standard for backbone networks. Many industry analysts are forecasting 10 Gbps system growth over the next few years at double-digit rates-while some forecasts show 2.5 Gbps systems, at least in the long-haul, declining not only relatively but even in absolute terms. Most leading vendors are today shipping 10 Gbps systems. With Internet traffic growing at a rough 100% a year, most carriers are planning for growing demands on their backbone and 10 Gbps is the most cost-effective way to meet that demand. At first carriers, or at least the most careful planners among them, test their fiber and turn up the low- PMD fibers at 10 Gbps first. But as traffic demands grow and the need for 10 Gbps spreads, carriers are finding that they cannot afford to be that selective. Often the busiest routes in the network have some high-PMD fibers. The result is that more carriers are turning to compensation as the most costeffective solution.

Another trend boosting interest in PMD compensation is the growing popularity of ultra-long-haul or ULH networks. A number of vendor startups and even public companies have come into being in the last three years solely to design and offer ULH solutions. Since PMD levels rise with the distance the signal travels on fiber, PMD which might be negligible on a 300km or 500km link can become a major issue on a 1000km link. Figure 3 above shows the distance an optical signal can travel before electrical regeneration for various qualities of fiber. Fiber with a PMD coefficient of 0.5 is not uncommon in 1990s-era fiber plants, and as the chart shows, moving to ULH on such fiber would be impossible without PMD compensation. Even while planning long-haul networks, forward-thinking carriers now are often looking ahead to ULH architectures and trying to build in the flexibility of longer reach today.

Finally, the advent of 40 Gbps networks promises to make PMD compensation even more widely deployed. At 40 Gbps, the bit period is just 25 picoseconds, which means that the tolerance to PMD falls to just 2.5 ps, assuming the standard receiver tolerance of 10% of a bit period). As Figure 3 suggests, with 1990s-era fiber, it will be difficult to go more than a few dozen kilometers before encountering PMD issues at 40 Gbps. Estimates from carriers suggest that 80% or more of fiber links are likely to require PMD compensation for successful 40 Gbps deployment. At this rate, PMD becomes an even more critical issue. With such tight tolerances for PMD, the PMD level not only of the fiber, but also of the network elements and the components within the network elements become critical. Indeed, PMD analysis and compensation are likely to become standard requirements in many future networks.

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