Syracuse University

Department of Electrical Engineering

Technical Report

Optical and Electronic Mitigation of Transmission Impairments

Sanil Prabhakar
Sayuj Haridas
Dr. K. LaViolette

Spring 2004

ABSTRACT

Modern day fiber optic communication systems are characterized by a variety of sources of system degradation. The most important degradation mechanisms that can be identified are as follows:

- Linear signal Distortion
- Non-linear signal distortion
- Crosstalk
- Noise

The Non-linearities and noise distortions are governed by the power considerations. Fortunately there is enough margin for power, so that systems with more than Terabits/sec and trans-oceanic spans can be built from the point of view of power level consideration.

The linear signal distortions like Chromatic dispersion, Polarization mode dispersion, non-ideal filter characteristics etc. however belong to the category of fiber impairments that primarily limit the capacity of optical transmission. Easy to operate and efficient ways to manage power, dispersion and mitigate Polarization Mode dispersion (PMD) are decisive for the development of higher bit rate systems (40 Gbits/sec) and above. Each of these linear distortions manifests itself as the limiting factor, depending on the type of application. While PMD limits are important in long haul communication networks, chromatic dispersion is an important issue in metro networks.

Modern day systems have incorporated various techniques to compensate the limits due to distortions. Among the various compensation techniques, two primarily important techniques presently being considered are Optical Domain Mitigation and Electronic Equalization Techniques.

This paper investigates the feasibility of these two techniques. Cost-Performance analysis to compare these techniques based on the application will also be discussed.

TABLE OF CONTENTS

INTRODUCTION

Fiber optic technology has evolved dramatically over the years and has initiated some of the most impressive developments in the field of communication technology. The transmission capacity of commercial systems doubles every six months. Fiber optics support today’s information based explosion. Backbones of communication networks, transoceanic communication and even large Local Area Network (LAN) employ optical communication system.

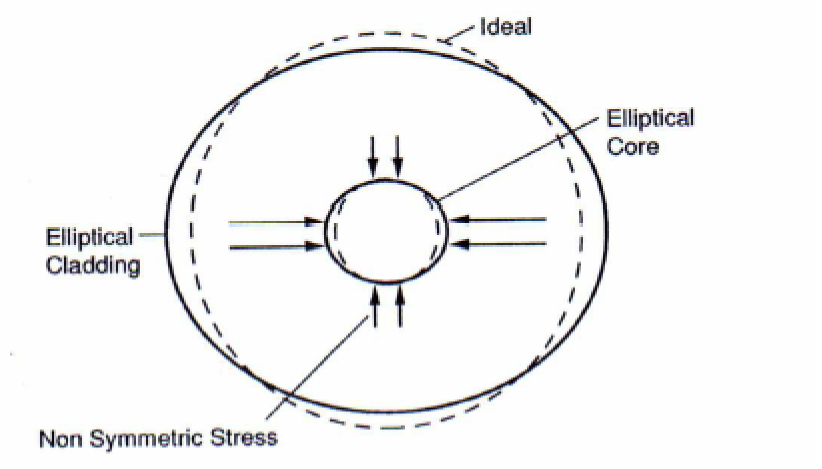
Indeed fiber optic technology created the first communication systems able to support Terabit/s transmission that some of the aforementioned systems require. Many advancements have allowed this achievement. First, manufacturing processes dropped fiber loss down to 0.2 dB/km. Then chromatic dispersion was ameliorated using dispersion compensation techniques. Non-Linearities were reduced using dispersion map management. Finally, the cost effective development of Wavelength Division Multiplexing (WDM) was allowed by the creation of optical amplifiers. However, Polarization Mode Dispersion (PMD) limits the design of high-speed fiber optic systems.

PMD is the manifestation of the remaining birefringence (anisotropy) of the fiber. Because of the imperfect circular symmetry of the fiber, there exist, in the propagation medium, preferential wave orientations. A lightwave, depending on the direction of its electric field, called polarization, has different propagation speed. This polarization dependence of the propagation constant induces dispersion of the pulses. Its main approximate effect is to duplicate the pulse into two copies propagating at different speed. This dual imaging affects systems so strongly that a 40 Gb/s system requires very low PMD fiber. Consequently, PMD has become one of the main topics of the fiber optic research, in recent years.

In order to understand why PMD plays an important role in the design of high-speed fiber optic communication systems we first need to know the origin, characteristics and effects of PMD. After a brief discussion of these topics we move into the mitigation techniques employed. PMD is a time-varying, frequency dependent phenomenon. The statistical time-varying behavior calls for adaptive techniques. Further, PMD being approximately a Maxwellian distribution, the compensation should also handle large value of Differential Group Delay (DGD). Amelioration of PMD in the optical domain would be discussed. The increasing number of WDM channels makes electronic compensation techniques a cheaper option. Finally and more importantly a cost-performance comparison of the two techniques is done. In contrast to chromatic dispersion, a perfect compensation is not possible for PMD (PMD of higher order). Therefore one usually uses the term PMD mitigator instead of compensator. The PMD mitigators reduce the outage probability for a certain average amount of PMD. They reduce the time to a low, acceptable value at points where PMD becomes disastrous.

POLARISATION MODE DISPERSION (PMD)

Light propagating in birefringent materials is subject to different propagation velocities. If the incident light is polarized along one of the birefringence axes of the medium it will take longer to pass the medium than if it were aligned with another axis. Silica fibers used in optical communication networks should be negligibly birefringent, but due to several reasons there is a certain birefringence, varying along the fiber. A set of orthogonal axes and a differential group delay (DGD) between them result, which describe the PMD of the fiber. An optical pulse, polarized along one of these so-called principal axes will be delayed by the corresponding group delay. For an arbitrary input polarization a pulse with sufficiently low bandwidth will be split in two pulses at the output, delayed against each other by the differential group delay. Such a pulse separation may lead to transmission impairments, especially at bit rates of 40Gbit/s and above. In a higher order approach, allowing for pulses with higher bandwidth, the direction of these axes and the magnitude of the differential group delay become frequency dependent, leading to additional pulse distortion.



Stresses in a single mode fiber

The reasons for birefringence in single mode fiber can be broadly classified as intrinsic and extrinsic. Intrinsic factors are those that are present in the fiber right from the manufacturing stage. When specialized methods had not evolved, the fiber drawing process induced some asymmetry that caused birefringence. Fibers thus manufactured (sometimes referred to as legacy fibers) can have rather high levels of PMD (0.5 ps/√km or greater). Present day fibers are manufactured with extra care and thus minimal asymmetry results. PMD levels are typically < 0.1ps/√km for such fibers. Extrinsic factors are those, which induce birefringence in a fiber after it's manufacture. Cabling of fiber after its manufacture can cause stresses that induce birefringence. External pressure can also induce birefringence in a fiber (e.g. bending, twisting etc.). There have been reports about the influence of temperature on fiber's birefringence.

The polarization states and delay depend on the birefringence of the fiber. On a real fiber the birefringence varies locally and the local birefringence may fluctuate in time, due to the variety of effects inducing the birefringence. The statistical nature of PMD makes it almost negligible for nearly all times, but disastrous for some small time. The output pulse of a long fiber will therefore be the result of a very complex superposition of all these local birefringence effects. Newer fibers have in general lower PMD. So for 10 Gbit/s systems, PMD compensation is not necessary for these fibers. For long haul systems with 40 Gbit/s and above, some compensation of PMD is necessary.

It has been shown, that for a small enough optical bandwidth the overall effect can (as for the short fiber) be described as split up of the input pulse in two output pulses with distinct polarization states (principal states). This effect is called first order PMD. The principle states and the delay (the differential group delay (DGD)) will vary statistically in time. The mean value of the DGD is taken as a measure of the PMD. All more complex effects are called higher order PMD.

The effect of birefringence and PMD are considered differently for short single mode fiber spans and long single mode fiber spans. All long haul systems use the latter category. But still, understanding the PMD mechanism in short fibers would help explain the mechanisms in the long haul systems.

In a short fiber segment, the stresses can be considered to be acting uniformly along the length. The single mode fiber segment becomes bi-modal due to the birefringence induced by these stresses. The propagation constants along the two (propagating) modes are slightly different. Therefore, a differential delay develops in the fiber segment, which is capable of broadening an input pulse. Mathematically, this broadening can be described as below:

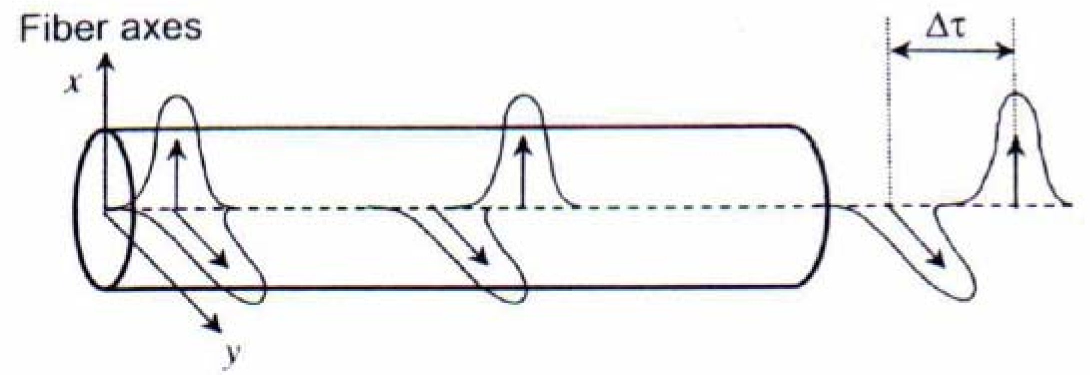
If β_s and β_f are the propagation constants along the slow and fast propagation modes respectively and if n_s and n_f are their effective refractive indices, then:

$$\beta_s - \beta_f \quad = \quad (\omega\, n_s - \omega\, n_f) / c \; = \; \omega\, \Delta n / c$$

where, ω and c are the angular frequency of the light signal and free-space velocity of light, respectively. The differential group velocity, expressed as group delay per unit length is obtained by taking the frequency derivative of the propagation constants

$$\frac{\Delta\tau}{L} = \frac{d}{d\omega}(\beta_s - \beta_f) = \frac{\Delta n}{c} - \frac{\omega\, d\Delta n}{c\, d\omega}$$

The group delay per unit length term $\Delta\tau/L$ is commonly known as the PMD coefficient of a fiber. Its unit is ps/km. Figure below illustrates the effect of birefringence on a pulse input into a short fiber segment.



A pulse launched with equal power on the two birefringent axes x and y of a short fiber segment gets separated by the DGD at the output

The relation between PMD induced delay and fiber length is no longer linear in the case of long haul fibers. This is because of the phenomenon called mode coupling that is taking place in all fibers longer than a certain statistical length called correlation length or coupling length. Fibers that are shorter than the correlation length are considered to belong to the short fiber category and other fibers in the long fiber category. As a lightwave propagates down a fiber, there is a constant sharing of energies between the propagating modes. This random exchange of energies is due to the varying stresses or perturbations that are experienced by the fiber along its length.

The correlation length is a statistical quantity defined as the length at which the average power in the orthogonal polarization mode (the mode perpendicular to the input mode) is within $1/e^2$ of the power in the input mode. The correlation length can vary between a few meters to more than a kilometer depending on whether it is a spooled fiber or a cabled fiber.

The effect of mode coupling is that the DGD has a square root of length dependence rather than linear length dependence. However, in either case, PMD causes dispersion or broadening of the lightwave signal. Whereas this broadening is predictable in the case of short length fibers, it is probabilistic for long length fibers.

In digital fiber optic systems, estimating the power penalty incurred can assess the PMD effects. The expression for the PMD induced power penalty is

$$\varepsilon \cong [A\,\Delta\tau^2\ \gamma\,(1 - \gamma)] / T^2$$

Where is the power penalty in dB, $\Delta\tau$ is the DGD, γ is the power splitting ratio between the two component modes ($0< \gamma <1$), T is the full-width at half maximum of the lightwave pulse. The factor A is a dimensionless parameter determined by the pulse shape and receiver characteristics. Another relation that gives an estimate of the PMD induced limitation on the bit rate and the span of a digital fiber optic system is

$$B^2L \approx 0.02/(PMD)^2$$

Where, B and L are the bit-rate (Gb/s) and link length (km) respectively, and PMD has units of ps/√km. This relation was arrived at by considering the case that the PMD induced delay must be less than 14% of the bit period in order to avoid incurring PMD-induced power penalty of 1 dB or greater for a period of 30 min per year.

A GEOMETRICAL MODEL OF PMD

Fundamental cause of PMD is birefringence, which causes the SOP of light to change as it propagates. The SOP evolution is described most conveniently on the Poincare sphere: for SOP represented by S, the birefringence represented by W causes S to evolve as

$$\partial S/\partial z = W \times S \qquad (1)$$

Of more immediate system importance is the description of the SOP as a function of frequency at a fixed distance

$$\partial S/\partial \omega = \Omega \times S \qquad (2)$$

Ω → Dispersion vector, a consequence of Euler's theorem in classical mechanics.

The dynamic PMD equation derived from eq. (1) & eq. (2) would be

$$\partial \Omega/\partial z = \partial W/\partial \omega + W \times \Omega \qquad (3)$$

An interesting aspect of PMD is that generally W and hence Ω is known only in a statistical sense.

The fiber, in this geometric model, is viewed as a set of retarder plates, and uses eq. (1) to evolve two identical SOPs with distinct optical frequencies and tracks their evolution through a generic section. This evolution is natural, since it is simply the result of the fundamental birefringence equation. As a consequence, the evolution can be described by the following vector, which is a "primitive" differential PMD for the k^{th} section, having length Δz and birefringence W_k as

$$\Omega_k = (\partial W_k/\partial \omega)\Delta z \qquad (4)$$

The partial sum of these differential PMDs would be

$$\Omega_{k+1} = R_k\,(\Omega_k) + \Omega_{k+1} \qquad (5)$$

where R_k represents the rotation about the vector W_k through an angle $W_k\,\Delta z$ and the parenthesized subscripts signify partial sums. Thus, eq. (5) states that the partial sum approximation of the PMD vector after k+1 sections is found by rotating the previous partial sum (i.e. after k steps) through the same angle that an SOP would be rotated and adding the differential PMD for the next step. This equation is the discretized version of the dynamical equation (3). Casting PMD in this form permits several simplifications to analyses of PMD.

CHARACTERIZATION OF PMD

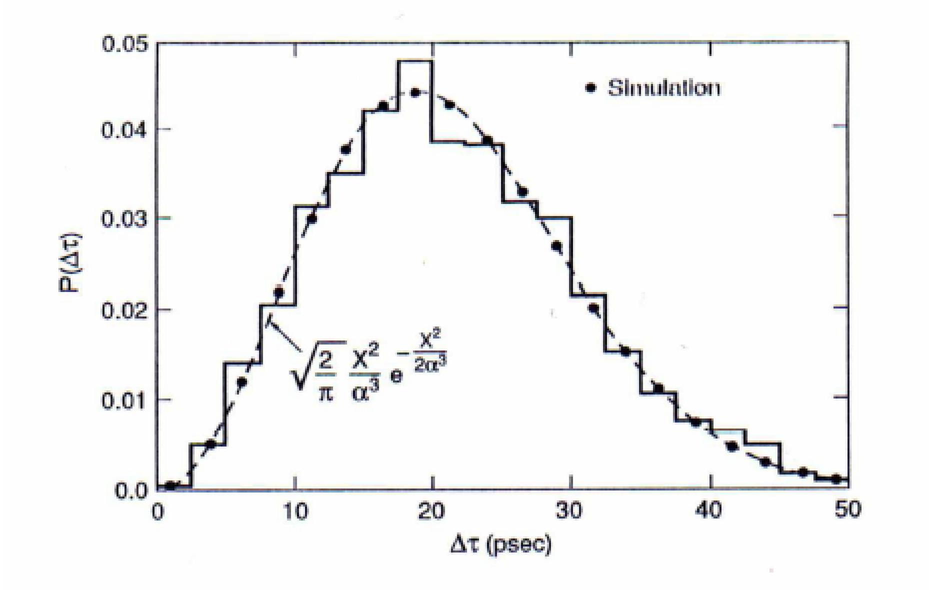
PMD in long haul fibers is a stochastic or random process. Therefore the penalties due to PMD are also random. In order to develop effective compensation techniques it is necessary to understand the nature and characteristics of PMD.

The PSP concept

In order to satisfactorily understand and explain the observed statistical effects associated with PMD, models have been proposed. One model is the coupled power model (low coherence model) for long fiber spans. This model was originally developed for multi-mode fibers. However, the most prominent among the models, which is best suited for modeling long single mode fibers, is the principal states model (high coherence model). According to the principal states model, a single-mode fiber can be thought to have a set of two orthogonal principal states of polarization (PSPs), which have certain properties as described below. A light pulse aligned with one of the fiber's two input PSPs will emerge out of the fiber end as a single pulse, unchanged in shape. Also, the emerging pulse will be polarized along the corresponding output PSP of the fiber. On the other hand, if the pulse's state of polarization (SOP) is aligned anywhere between the two input PSPs (but not aligned along either of them), the pulse will be split into two orthogonal components. Moreover, due to the differential group delay, or DGD, these components will arrive at the output at different times, resulting in pulse broadening. Based on this PSP concept, a long single-mode fiber may be modeled as a concatenation of randomly oriented, short sections of birefringent fiber. The frequency domain definition of PSP can be described as follows. For a length of fiber, at every frequency, there is a pair of input polarization states called the PSPs. A PSP is that input polarization state for which the output state of polarization is independent of frequency over a small frequency range.

PMD statistics

The PSP model has facilitated the investigation of the statistical properties of PMD. It is now a well-established fact that the average DGD has a square root of length dependence. The probability density function of DGD is Maxwellian over time and over wavelength.



The measured probability density function of DGD and the Maxwellian fit (dotted line)

Higher order PMD

Among all the higher orders, it is the second-order PMD that has been attached the most significance and thereby there is considerable amount of literature existing on it. The PMD vector, owing to its dependence on the angular frequency ω, can be expanded as a Taylor's series with ω as the independent variable. The second order term in the expansion corresponds to second order PMD.

The physical significance of second-order PMD is that it causes a polarization- dependent pulse broadening or compression (termed as polarization dependent chromatic dispersion or PCD) and a depolarization of PSPs or the rotation of the PSPs with frequency.

PMD MITIGATION

To enable high speed transmission in PMD impaired systems, mitigation measures have to be taken and due to the statistical nature of the fiber's PMD characteristics adaptive compensation is required. The undesirable effects of PMD are not limited to digital communication systems but affect analog communication systems as well. Either electronic circuitry can be used to reduce signal distortions after detection or optical devices in front of the receiver can be used to compensate for the actual fiber characteristics.

With the evolution of specialized manufacturing methods, PMD in present day, long haul fibers is kept very low (< 0.1ps/√km). Still, no matter how good the fiber maybe, at some bit-rate-length product, PMD will be an issue. Hence, there is need to investigate strategies for PMD mitigation.

Over the years, research groups from around the globe have proposed and/or demonstrated different strategies for PMD compensation. Their relative merits and demerits will be considered. The methods to increase the tolerance of a fiber-optic communication system to PMD will also be discussed.

PMD compensation can be broadly divided into two categories depending upon the domain in which the mitigation process is performed. These are

1) Optical PMD Compensation Techniques
2) Electronic Compensation Techniques

Optical PMD compensators typically comprise of a polarization-controlling device, an optical delay element (fixed or variable) and allied electronics, which provide control signals to the optical components, based on feedback information abt the link's PMD.

Electronic Compensation techniques consist of equalization using digital filters, which reduces the inter-symbol interference (ISI). When applied to digital fiber-optic communication systems, such methods can be adopted after the receiver, to reduce ISI due to impairments. Since they are used in the post detection stages, the phase of the optical signals will not be available. Such electronic PMD equalizers can be integrated into the receiver, thus saving installation costs. The goal of electronic equalizers is minimization of ISI at the receiving ends (regardless of the phenomenon that is causing it, be it PMD or chromatic dispersion or any other).

OPTICAL MITIGATION TECHNIQUES

The signal processing demands for electronic mitigation increase with higher transmission rates, thus ultimately limiting the mitigation capabilities, it is then that we concentrate on optical solutions. Integrated electronic solutions have the advantage that they consist of small and fast circuits that can be incorporated in the receiver, and which also can compensate for other types of distortions, for example chromatic dispersion. However, when the bit rate is increased to 40 Gb/s per channel and beyond, where the electronics still is immature, it will in practice be very difficult and expensive to implement such solutions. Even though the components in the electrical domain are generally faster and more flexible than bulk optics, the phase information is lost after detection, and therefore, the optical PMD compensators may have larger potential as the PMD (in theory) can be completely compensated in the optical domain. However, the complexity, or the number of DOFs, in such a broadband compensator would be very large. Launching the signal into a principal state of polarization (PSP) is a straightforward first-order method to optically reduce the effects of PMD.

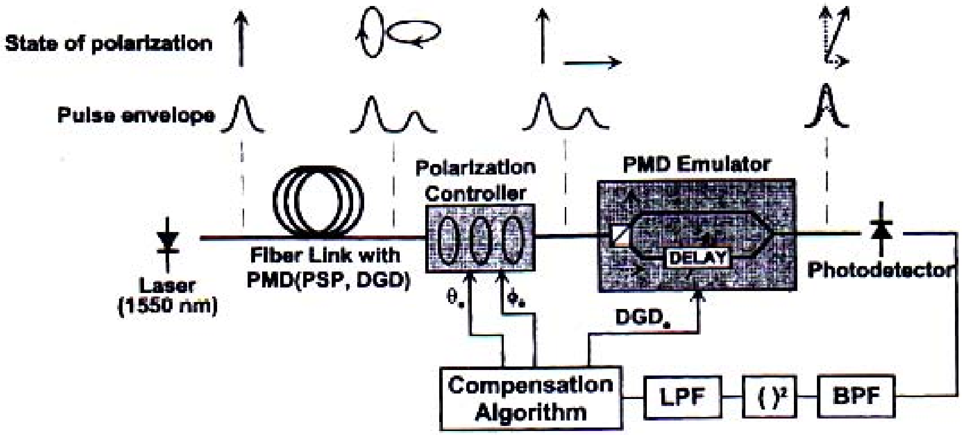
Optical post transmission compensation is currently an intense research field where both first- and higher order compensators have been proposed. It is practical to use a compensator with just a few control parameters as this limits the complexity and speeds up the response. However, a properly designed compensator with a large number of control parameters (or DOF) is more flexible and able to compensate also for higher orders of PMD.

An optical PMD compensator consists of a PMD equalizer, a polarization controller and a feedback loop, using a suitable monitor signal. Several stages made of equalizer and polarization controller may be concatenated to compensate for higher order PMD. The PMD equalizer is a birefringent element of either fixed or variable DGD, while the polarization controller is used to match the axes of the equalizer with the principal axes of the fiber. A suitable monitor signal, basically independent of bit rate and modulation format, is the degree of polarization (DOP), which is measured using a polarimeter. The power ratio of polarized light to total incident light decreases with increasing DGD of the fiber.

PMD compensators can be classified as half-order, first-order and second-order Compensators. A **half-order** compensator comprises of a polarization controller and a fixed optical delay element. In addition, there is a feedback control mechanism to provide appropriate control signals to the polarization controller. The principle of operation is that the polarization controller is adjusted so as to minimize the combined DGD of the link and the compensator. The delay element is fixed. Since this compensator can only compensate for a fixed amount of DGD, rather than varying delays, it is sometimes referred to as a half-order compensator.

A **first-order** PMD compensator is slightly more complex than a half-order compensator since it has a variable delay element instead of a fixed delay element. A feedback mechanism provides control signals for adjusting both the polarization controller and the delay element. The first-order compensator can be employed to counter different amounts of DGD values. The first-order configuration uses a polarization controller and a variable delay element. Based on the feedback signal, polarization and delay adjustments are executed so as to minimize the PMD effects.

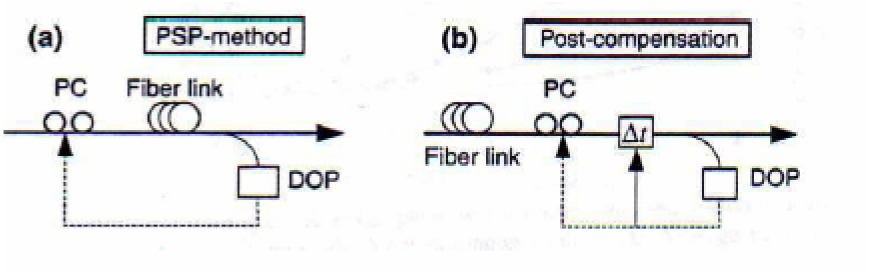
In order to increase the accuracy of the PMD compensation, the SOP of the optical signal may be scrambled before the signal is launched into the fiber link. as shown in the fig below.



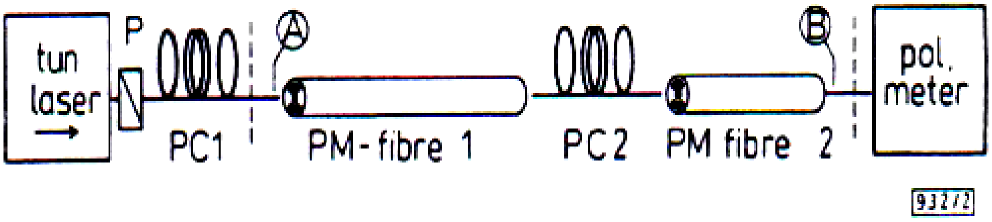
First-order adaptive PMD compensator functional block diagram (LPF and BPF: low- pass and band-pass Filters, ( )2 - square-law Detector)

A first-order compensator, using the DOP (Degree of polarization) of the received signal as the feedback parameter, is used to compensate for PMD at data rates of 40 Gb/s and 80 Gb/s. An advantage of using the DOP as the feedback parameter is that compensation can be made bit-rate independent.

Another approach for first-order PMD compensation is called the PSP transmission method. The PSP transmission method is a pre-compensation method in which a polarization controller is used to align the SOP of the optical signal with a PSP of the fiber link. The fig below shows the block diagram of a first-order PMD compensator based on the PSP transmission method.



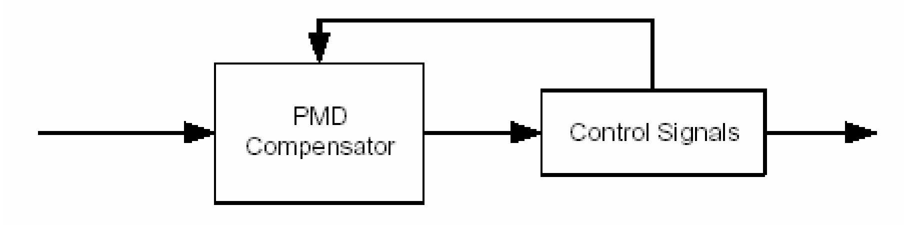
Given the increasing data-rates and the expanding bandwidth, importance has been attached to **second-order** PMD compensation also. One proposed configuration uses two polarization controllers and two pieces of high birefringence fiber. The compensator's PSPs are made to vary linearly with frequency so as to compensate for PMD over a larger bandwidth. The figure of a 2^{nd} order compensator is as shown below



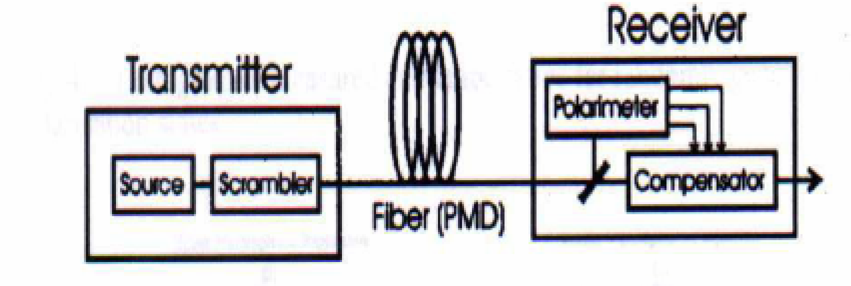
ELECTRONIC EQUALISATION TECHNIQUES

The goal of Electronic equalizers is to minimize the ISI (Inter symbol Interference) at the receiving end. This can be achieved in 2 ways.

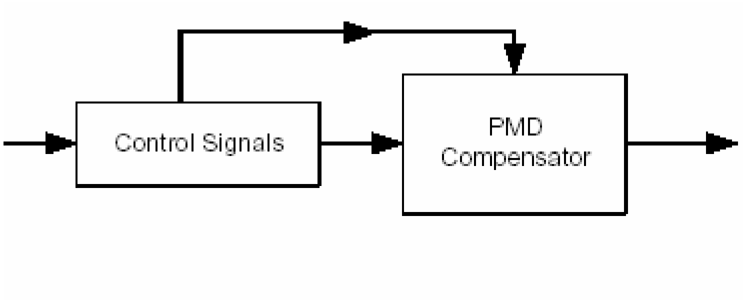
FEED FORWARD METHOD OF PMD COMPENSATION



A feed-forward technique uses a fixed delay element. The adjustments to the polarization controller are made based on real time PSP characterization using measurements from a polarimeter. A scrambler is used to rapidly change the SOP of the transmitted optical signal in order to hasten the collection of a large number of distinct polarimetric measurements. Figure below is a block diagram representation of this technique.



FEED-BACK METHOD OF PMD COMPENSATION



Some of the electronic filters using the feedback technique are the transversal filter (TF), decision feedback equalizer (DFE) and the maximum likelihood sequence detection scheme (MLSE).

The **TF** divides the signal into two copies, delays the copies by constant delay stages, and superimposes the differentially delayed signals at the output port. The tap weights are adjusted to minimize ISI in the received signal.

The **DFE** is a non-linear filter. Non-linear filters are advantageous in the sense that they can improve signal quality even if the received eye-diagram is poor (severe ISI condition), unlike TF, which requires an "open" eye-diagram. However, DFE requires high-speed signal processors.

The **MLSE** scheme is based on the correlation between an undistorted signal sequence and an estimate of the received signal sequence, over many bits. The selection of the sequence and the maximization of the correlation are the factors based on which the decision for each individual bit is made .The MLD scheme provides the best possible performance.

ADAPTIVE PMD COMPENSATION

To be efficient an equalizer should be adaptive. The early version of the adaptive PMD compensator was similar to the PMD feedback technique. It consisted of a polarization controller (HP 11896A) and a PMD emulator (JDS FITEL PE3). The control signals for the polarization controller and the PMD emulator were generated based on the power level of the tone corresponding to half the data rate, in the received base band spectrum (e.g. 5 GHz tone was considered for 10 Gb/s data rate).

Several enhancements were then made to the compensator, which included the addition of a high-speed, liquid-crystal based polarization controller in place of the HP 11896A, a variable delay line and a fixed length of polarization maintaining fiber, instead of the PMD emulator, and a microcontroller to control these two devices. This helped to enhance the overall speed and efficiency of the PMD compensator.

The feedback technique was then changed from the one based on the RF tones to the one using the received signal’s Degree of Polarization (DOP), to make the PMD compensator bit-rate independent and also to reduce the complexity of the hardware involved.

The present version of the PMD compensator uses a DOP-based feedback technique. The high-speed, liquid crystal, polarization controller, the variable delay line and the fixed length of polarization-maintaining fiber, and the microcontroller have been retained. An interface board, developed in the laboratory, is used to communicate the control signals from the microcontroller to the polarization controller and to the variable delay line.

Comparison of different electronic techniques is given below:

PARAMETER	FFE	FFE+DFE	MLSE
POWER	Lowest	Low	High
CD	Medium	Medium-High	Medium-High
PMD	Medium	Medium-High	Medium-High
DMD	Medium	High	High

CD – Chromatic Dispersion
DMD – Differential Mode Dispersion

COMPARISON OF OPTICAL DOMAIN AND ELECTRONIC DOMAIN MITIGATION

CONSIDERATIONS

1. Low cost of implementation: Any design criteria is driven by the cost factor. In the case of PMD mitigation, the cost is mainly influenced by the placement of the mitigation scheme within the optical communication system. The two options are:

   a.) Integrated design: The integration of PMD compensators in the transceivers involves mitigation in the electronic domain and impacts the per channel cost. The mitigation can be made adaptive with feedback with less complexity but it is not compatible with legacy solutions. On the other hand integration with optics would have an initial setup cost impact, but it has the potential to be share across channels. The feedback techniques however, involve difficulty of implementation.

   b.) Modular or Standalone design: The standalone option obviously has a first cost impact but since its use is only when needed, it brings with it the advantage of possible sharing across multiple channels. This in turn however, would require complicated control algorithms.

2. Market Space: The coverage and reach of the system also defines the type of the mitigation to a considerable amount. Depending on this consideration a system can be:

   a.) Long haul: In case of transoceanic communication, difference in standards would make optical mitigation, transparent to a lot of parameters (MAC, framing etc) a better alternative. It is also a better option for long haul systems involving optical amplifiers rather than repeaters.

   b.) Metro: MANs are characterized by large volumes rather than large distances, and therefore driven by lower cost considerations making electronic compensation a cheaper alternative.

3. Bit rate/Format dependence: The transparency of optical mitigation to bit rate/format makes it the first choice for high bit rate systems (40Gb/s) and also involving multiple formats. Electronic compensators depending heavily on these parameters provide satisfactory cost effective solutions only up to 10Gb/s systems.

The secondary considerations are as follow:

- ❑ Non-linearity independence: Reduction of ISI in the presence of a mix of effects generally non-linear in nature.

- ❑ Specific Physical effects: Correction budget not significantly influenced by related effects. Leads to ease of link budget contribution/measurement etc.
- ❑ Dynamic v/s Variable: Dynamic for fast-bit time systems and Variable for slow-seconds systems.

The overall mitigation consideration strategies i.e. Optical V/S Electronic has been summarized in the table below:

Strategies	**Optical**	**Electronic**
Cost	> $1000/channel	< $1000 potential
Bandwidth	Multiple channel	Per channel
Dynamic Range (e.g. Dispersion)	+/- 1000 ps/nm	+/- 800 ps/nm (linear operation)
Bit rate/Format	Independent	Dependent
Availability	Mainly Start-ups	Available soon
Strengths	Not channel specific Larger impact	Lower cost Low impact
Weaknesses	Space Cost	Lower benefit Linear operation required

(Courtesy: Ciena Corporation, Linthicum, MD 21090)

The industrial leaders in the field think differently about the future of mitigation techniques:

AMCC (Applied Micro Circuit Corporation) observes, “Electronic mitigation is now and will continue to be a part of the solution”. They believe that competitive pressures will continue to drive component suppliers to innovate. Advances in IC technology will further shift the balance towards electronic techniques and further decrease the cost of this approach.

Bell Labs, Lucent Technologies state that the cost advantage of sharing optical components in WDM systems is an important consideration in favor of optical compensation, making it superior than the Electronic equalizer, which is a “per-channel” device. The OEQ (optical equalizer) can handle multiple impairments and provide simultaneous compensation for WDM channels. Furthermore, optical equalization can make use of the optical field’s phase, which would be lost in the case of electronic equalization.

Cisco Systems hold that FEC and now E-FEC has successfully mitigated the OSNR limitation (introduced by EDFA ASE). Electronic mitigation of optical transport impairments is an important technology for improved, lower cost, multi-service Metro networks, which are currently scaling to 10G. They also feel that integration to pluggable optical modules is the most interesting combination for technology innovation.

Alcatel believes that Optical PMD compensation using PMF (Polarization Mitigated Fiber) would be the answer for bulk optics. PMD limit, blind adaptation to fluctuating distortion, ability to compensate additional distortions and adaptation speed would be important considerations in deciding the method of compensation.

CONCLUSION

This report studies the origin, effects and characteristics of Polarization Mode Dispersion and its compensation in the electronic as well as the optical domain. The causes and the mathematical model of PMD were discussed. The statistical time-varying and frequency dependent behavior of this phenomenon makes the perfect compensation almost impossible. However, mitigation techniques can provide considerable reduction of the effects of PMD to acceptable values. The discussion next shifted to the two domains of mitigation – Optical and Electronic. The compensation techniques used in both the categories were studied briefly. Following this a cost-performance comparison of the two techniques was discussed. The uses of these techniques are significantly influenced by the application and the major design considerations.

Both these techniques face a lot of challenges in the future. As for the electronic equalization techniques the major challenges would be providing integrated DSP based solutions for A/D conversion at a minimum of 10 G Samp/sec. Blind adaptive channel estimation with respect to acquisition without training sequence as well as tracking of unknown channel dynamics, clock recovery from heavily distorted and noisy signals, fast adaptive channel tracking are some of the other compelling challenges.

Optical mitigation techniques need to add adaptability to changing conditions for effective compensation of PMD. The techniques should be more cost efficient. Improvements in the performance of both these techniques hold the key for effective fiber optics communication at rates of 40Gbit/s or more over substantial distances at low bit error rates.

REFERENCES

[1] Arun-Prasad Chimata, Christopher Allen, “Development of Adaptive Polarization-mode Dispersion compensation system “, ITTC-FY2003-TR-18834-02, January 2003.

[2] Henrik Sunnerud, Magnus Karlsson, Chongjin Xie, Member, IEEE, and Peter A. Andrekson, Senior Member, IEEE, Member, OSA, “Polarization-Mode Dispersion in High-Speed Fiber-Optic Transmission Systems”, Journal of Lightwave technology, vol. 20, No 12, December 2002.

[3] Laura Adams, Big Bear Networks, “Optical and Electronic Mitigation of Impairments”, OFC 04 Workshop, Feb 2004.

[4] Loukas Paraschis, Cisco Systems, “Application of Electronic mitigation of optical transport impairments in metro networks”, OFC 04 Workshop, Feb 2004.

[5] Daniel Castagnozzi, Applied Micro Circuits Corporation, “Optical and Electronic Mitigation of Impairments”, OFC 2004, Feb 2004.

[6] Julien Porrier, “Electronic Mitigation of Polarization Mode Dispersion”, Thesis submitted at the Virginia Polytechnic Institute, Defended July 25th 2000.

[7] Peter.J.Winzer, C.R.Doerr, S.Chandrasekhar, D.Stahl, A.Bhardwaj,”Optical Equalization techniques”, Bell Labs, Lucent Technology, No 12,OFC 04, Feb 2004.

[8] Fred Buchali, Henning Bülow, Alcatel Research & Innovation, “Optical and Electronic Mitigation of Impairments,” OFC 04, No 6, Feb 2004.