POLARIZATION OTDR: LOCATING HIGH-PMD FIBERS

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APPLICATION NOTE

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PMD: The Ultimate Limitation to High-Bit-Rate System Deployment

It is generally accepted that the total maximum tolerable polarization-mode dispersion (PMD) of a link should not exceed ten percent of the length of a bit. For non-return-to-zero systems operating at 2.5 Gb/s, 10 Gb/s, and 40 Gb/s, this translates into less than 40 ps, 10 ps, and 2.5 ps, respectively. Moreover, to operate within acceptable PMD levels, the maximum distance between two regenerators decreases in proportion to the square of the increase of the transmission rate per channel.

Therefore, upgrading from 2.5 Gb/s systems to 10 Gb/s and 40 Gb/s systems implies a fall in the inter-regenerator distance by a factor of 16 and 256, respectively.

Increasing the number of regenerators on a given existing link is obviously not an option (roughly costs US$1 million each). Similarly, even though improvements in production techniques have considerably reduced the PMD of new singlemode fibers, laying down a complete network made of these new fibers considerably reduces the cost advantage of higher-speed transmission. PMD compensation or mitigation may eventually become part of the solution, but it is unlikely that such techniques can be applied to DWDM systems cost-effectively or that they will correct the highest PMD values found in the field. Moreover, most mitigation schemes do not account for second-order PMD, or compensate for the more recent PDL-PMD cocktail effect.

The first step in high-bit-rate system deployment, therefore, implies an upgrade of parts of the fiber network itself.

Polarization-OTDR for Fiber Network Upgrade

Major difficulties are often encountered when working with old fiber networks. As PMD was not always measured at the time of deployment, values as high as 80 ps or more are common, and fibers often exhibit considerable variation in PMD, even within a given cable. Consequently, PMD is very likely to change significantly along the length of any given fiber link consisting of a mixture of fibers. Up to 35% of existing networks are thought to be unsuitable for transmission rates above 2.5 Gb/s.

The cost of fiber network upgrades should obviously be kept to a minimum. The goal is, thus, to classify the fiber segments with respect to their PMD contributions, to replace the largest contributors, possibly one at a time, until the overall PMD is brought down to an acceptable level, and then to proceed with the system hardware upgrade.

Locating the largest PMD contributors imposes few but stringent requirements. Any practical instrument dedicated to such a task must be able to measure in presence of high birefringence (for instance between 1 and 10 ps/km), with a dynamic range sufficient to cover the entire length of the transmission system, and should include relatively simple hardware, since it is a field application.

A solution based on a polarization optical time-domain reflectometer (P-OTDR) has recently been successfully integrated into the EXFO FTB-400 portable field platform. To understand the measurement method behind this P-OTDR, which uses DOP statistics rather than birefringence data, let us first review some of the physics of PMD.

Distributed PMD: Back to Basics

A fiber's PMD depends on its birefringence β, its length *L* and its coupling length h through the following approximation:

$$PMD \approx \frac{\beta L}{\sqrt{L/h}}.$$

In layman's terms, the birefringence (here in units of ps/km) is the relative propagation delay between the fiber's fast and slow polarization axes. The coupling length is the distance after which a significant portion of energy in one mode (fast or slow) has been transferred to the other mode (more specifically, the coupling length h is defined as the length for which the spatial correlation of the birefringence decreases by $1/e^2$).

As can be seen from the equation, PMD accumulates with distance. Since the birefringence and the coupling length are known to vary along the length of the fiber (due to the fiber manufacturing process and local constraints), the local value of both parameters must be known in order to determine the distribution of PMD.

The birefringence can be obtained by measuring the evolution of the state of polarization (SOP) of a lightwave propagating through a fiber. Indeed, the state of polarization is known to rotate at a rate that depends on the local birefringence of the fiber.

In order to appreciate the difficulty in performing such a measurement, consider the beat length L_b. It is the distance corresponding to a full rotation of the SOP and is inversely proportional to the birefringence:

$$L_b = \frac{\lambda}{\beta c} \quad ;$$

where λ is the wavelength and c is the speed of light in vacuum. For example, a birefringence of 1 ps/km yields a $L_b \sim 5.2$ m at 1550 nm; higher birefringence corresponding to shorter beat length (see the table below).

The concept of an OTDR that is sensitive to the state of polarization (SOP) of the backscattered signal was introduced twenty years ago. In its simplest form, it consists of an OTDR wherein a polarizer is introduced in the return path, just prior to its detector. Now, the beat length as seen from the backscattered signal is actually equal to $L_b/2$ because the light travels twice through the birefringent region. Therefore, the adequate knowledge of the birefringence, leading to significantly high PMD values in a short fiber, requires an OTDR spatial resolution of the order of 1 m or less.

Typical OTDRs do not have a useful dynamic range with such a high spatial resolution (pulse length of 10 ns or less), and the requirements on the OTDR performance become even more stringent for fibers with a higher birefringence. Consequently, the SOP-P-OTDR measurement technique is normally limited to low-birefringent fibers. Alternatively, one could use a more complex P-OTDR system in order to improve the dynamic range at these resolutions. The use of EDFAs to boost the transmitted and received signal and tunable high-power pulsed laser source has already been proposed. Other means, such as coherent detection techniques, or photon counting, have also been explored, but they have yet to prove reliable in the field.

Birefringence [ps/km]	Beat length [m]	P-OTDR pulse [nsec]
0.05	100	250
0.1	50	125
0.2	25	60
0.5	10	25
1	5	12
2	2.5	6
5	1	2.5
10	0.5	1.2

Table 1: Typical OTDRs do not have a useful dynamic range with the high spatial resolution required for SOP discrimination.

A simple P-OTDR with limited spatial resolution can be used to detect high-PMD fibers. Based on the PMD equation above, one can calculate the minimum birefringence needed to generate a PMD value of 1 ps in a 1-km fiber link for different coupling lengths. It turns out that a very large birefringence (> 6 ps/km) is needed for a fairly short coupling length ($h < 25$ m). It is therefore expected that most fiber segments with a PMD coefficient above 1 ps/sqrt (km) will correspond to cases where the coupling length is long ($h > 50$ m).

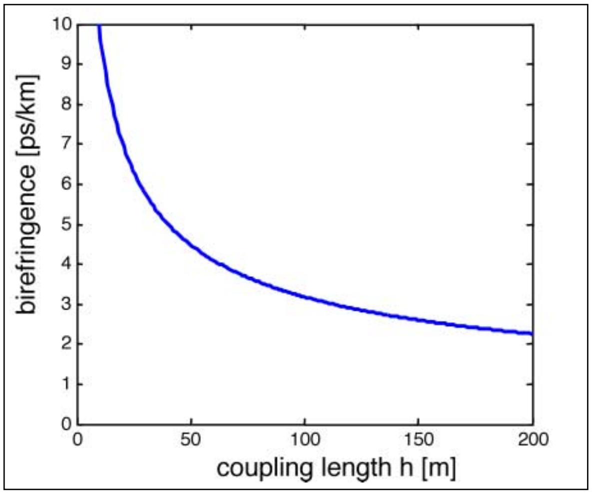


Figure 1: Minimum birefringence needed to generate a PMD of 1 ps in a 1 km fiber for different coupling lengths h.

For a more intuitive point of view, consider the following: In a fiber with a short coupling length, energy is frequently exchanged between the fast and slow modes. This frequent coupling reduces the amount of delay that can be acquired between the two polarization modes and the fiber's PMD increases slowly with distance (i.e., proportionally to the square root of the fiber length). In contrast, when the coupling length is long, little coupling occurs, longer delays are acquired and PMD increases much more rapidly (i.e., linearly with distance).

Consequently, fibers with very little mode coupling (long *h*) are more likely to show high PMD values and, therefore, the detection of a long coupling length should be sufficient to identify the high-PMD sections of the fiber link.

The degree of polarization (DOP) is what allows us to estimate the coupling length. It can be shown that, over a given distance, if the birefringence axis is stable, then the DOP is constant. However, if the birefringence moves, the DOP changes. The statistics of the DOP are therefore related to the statistics of the birefringence (i.e., to the coupling length *h*). The parameter that comes into play is the distance along the fiber for which the value of the mean DOP has varied significantly. This parameter (denoted as h_{DOP} by analogy with *h*) is directly proportional to the fiber's coupling length (the correlation length of the DOP, h_{DOP}, is defined as the length for which the spatial correlation of the DOP decreases by $1/e^2$).

Studying DOP statistics therefore allows us to locate high-*h* link spans and to determine where you can expect high PMD. And that is achievable with a low-resolution OTDR.

DOP Statistics: PMD Classification Rules for Fiber

The drawback of using a low-resolution OTDR is that since it is only sensitive to coupling lengths (i.e., it does not measure the local birefringence), only a probability of having a certain level of local PMD can be associated with the measurement.

In order to make the instrument intuitively useful to operators, classification rules have been established based on numerical simulations of the relation between the coupling length and h_{DOP} and on the observation that low birefringence is detected by a high mean DOP.

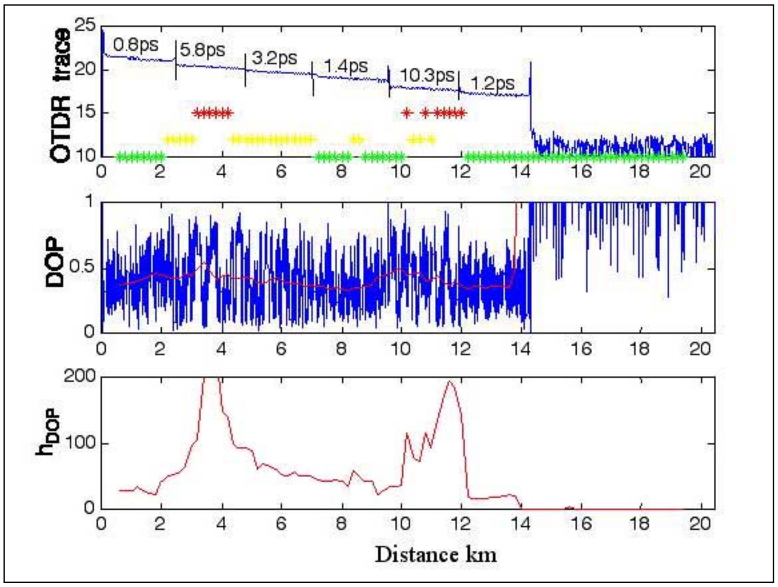
A simple color labeling is then used in the interpretation of the P-OTDR data in order to classify the fiber segments according to the probability of their respective PMD values–low (green), medium (yellow) and high (red).

Field Applications: Locating Potentially High-PMD Fibers

P-OTDR measurements were taken on deployed legacy fibers at various sites belonging to different Telecom carriers. The fibers originated from several different manufacturers and varied between 0 and 15 years of age.

Measurement Site A

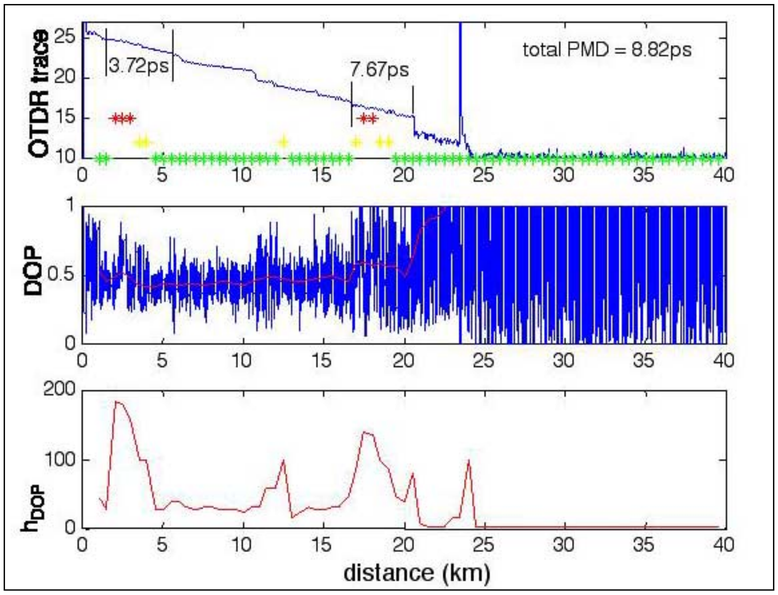
The first site had an underground cable of 2.3 km consisting of several old NZDS fibers. Each fiber was initially characterized with a standard interferometric test set in order to measure its end-to-end PMD. The measured PMD values ranged from 0.8 ps to 10.3 ps. Different fibers in the cable were then spliced together in a loopback configuration to build a longer link of 14.3 km for which the PMD values of each section were known. The figure below shows how the P-OTDR can differentiate between good and bad fibers. Indeed, there is a very strong relationship between the measured value of the local h_{DOP} and the PMD of each individual section. The results indicate that for these fibers, high PMD originates mostly from weak mode coupling and that our technique was appropriate to locate high-PMD sections.



Site A: Fibers from a 2.3-km buried cable spliced in a loopback configuration.
The fiber's PMD values were measured using an interferometer test set.
The P-OTDR correctly classified the fibers according to low (green),
medium (yellow) and high (red) PMD contributors.

Measurement Site B

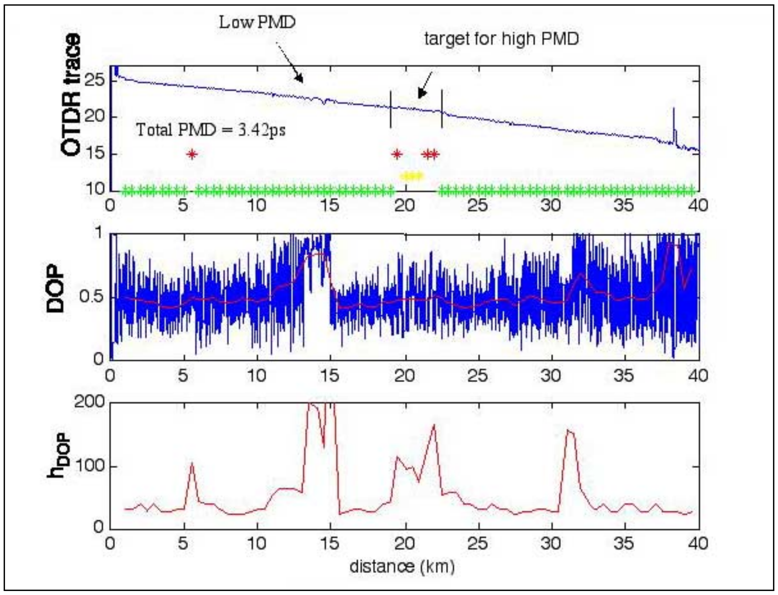
The link at the second site consisted of concatenated (spliced) old NZDS fibers from different suppliers with a total length of 23.5 km. The PMD of the individual fibers was unknown initially but the total link PMD was measured with a standard interferometric test set to be 8.82 ps. In this case, the P-OTDR identified only two potentially bad fiber segments. The link was then momentarily disjoined in order to isolate the segments identified by the P-OTDR, and the results were validated by measuring their PMD (again with a standard interferometric test set).



Site B: Link made of spliced old NZDS fibers from different suppliers.
The P-OTDR identified two potential high-PMD contributors.
This was confirmed by measuring the segment's PMD using an interferometric test set.

Measurement Site C

The link at the third site consisted of spliced old NZDS fibers from different suppliers with a total length of 38.4 km. The total link PMD was measured with a standard interferometric test set, which obtained a value of 3.42 ps. Here again, the P-OTDR identified two potentially bad fiber segments. Indeed, even though h_{DOP} is large, between 13 km and 15 km, the corresponding mean DOP is characteristic of a low-birefringence region and low PMD is predicted. The same applies to the h_{DOP} peak around km 32. It was not possible to open the link and validate the P-OTDR findings at this site.



Site C: Link made of spliced old NZDS fibers from different suppliers for a total length of 38.4 km. The P-OTDR identified two potential high-PMD contributors. Indeed, even though h_{DOP} is large, between 13 and 15 km and around km 32, the corresponding mean DOP is characteristic of a low-birefringence region and low PMD is predicted.

P-OTDR: A Solution to Higher-Bit-Rate Upgrade

A simple test set based on DOP statistics obtained with the P-OTDR has, therefore, been proven, in the field, for locating high-PMD sections on a fiber link (typ. > 1ps) by the detection of long coupling length. Although the measurement technique does not attribute a PMD value to the individual fiber segment because the OTDR's spatial resolution is too low to measure the local birefringence, the instrument successfully segments a fiber link into sections according to their PMD contribution. Furthermore, its potential measurement distance range is much higher than that of other techniques due to the use of a long pulse.

The DOP-based polarization-OTDR is, without a doubt, a very powerful troubleshooting tool for operators who transmit over fibers exhibiting high PMD, as it allows them to upgrade parts of their high-dispersion fiber links, prior to upgrading their systems to higher bit rates–a cost-effective solution to an otherwise costly dilemma.

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