PMD: impact on coherent systems, troubleshooting and mitigation on live systems

app note

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Authors:

Gwenn Amice
Senior Applications Engineer

Daniel Gariépy
Senior Optical Specialist

Introduction

Dispersion in singlemode fibers has always been a limiting factor at higher bit rates. However, the recent development of coherent systems has pushed rates beyond 100 Gbit/s.

So, is this the end of dispersion as we know it? Certainly not! Unfortunately, post-compensating capabilities for dispersed signals have their limits and their implementation is costly.

This application note will focus on the more pernicious of the two dispersions: polarization mode dispersion (PMD).

Definitions of PMD, DGD, instantaneous DGD and DGD_{max}

Polarization mode dispersion (PMD): Light can be described as consisting of two orthogonal signals called polarization modes (or principal states of polarization). In a perfect fiber, both polarization modes travel at the same speed.

Polarization mode dispersion occurs when a fiber, whose core is asymmetrically circular, causes the signals to travel at different speeds (i.e., birefringence), resulting in a delay in the arrival time and pulse spreading at the receiver end resulting in a delay in the arrival time and pulse spreading at the receiver end, as shown in Figure 1.

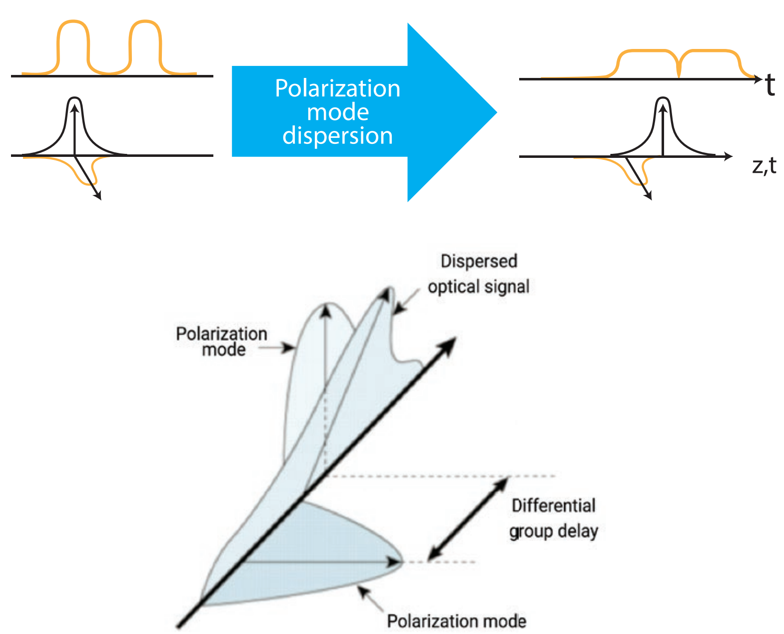

Figure 1. PMD effects on a transmission

Differential group delay (DGD): DGD represents the delay between the two states of polarisation that is observed at a specific wavelength and under specific conditions (fiber position and environmental conditions).

Figure 2 demonstrates the impact of birefringence on DGD:

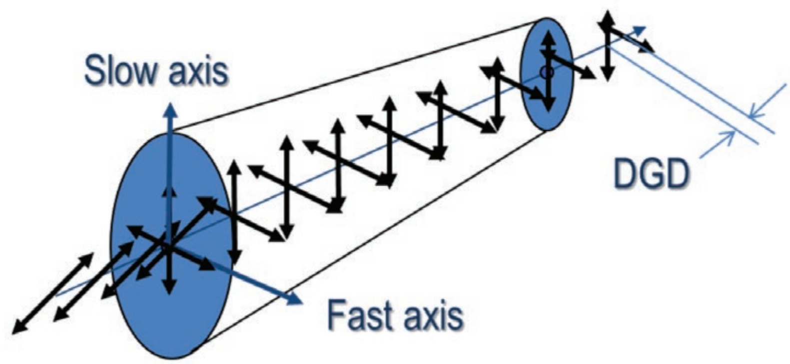

Figure 2. Impact of birefringence on DGD

Depending on link configuration, DGD_{max} can be as high as four times the PMD (mean DGD).

Polarization pulse spreading (PPS): Sometimes referred to as Effective DGD, PPS can be described as the instantaneous DGD that is experienced by an optical signal, at a particular wavelength and at a specific time. Its value varies from 0 to DGD.

Note: the measurement of DGD within a channel width and averaged over the span of a few minutes is referred to as average DGD.

DGD maximum: The delay between orthogonal modes is never the same at every wavelength and varies according to fiber position and environmental conditions, as seen in Figure 3. In the worst case scenario, birefringent sections will line up at a specific wavelength and the delay will be maximized at that wavelength. Depending on the link configuration (high and low DGD segments, aerial and buried segments, etc.), DGD_{max} can be as high as four times the PMD (mean DGD). It is a matter of statistical distribution.

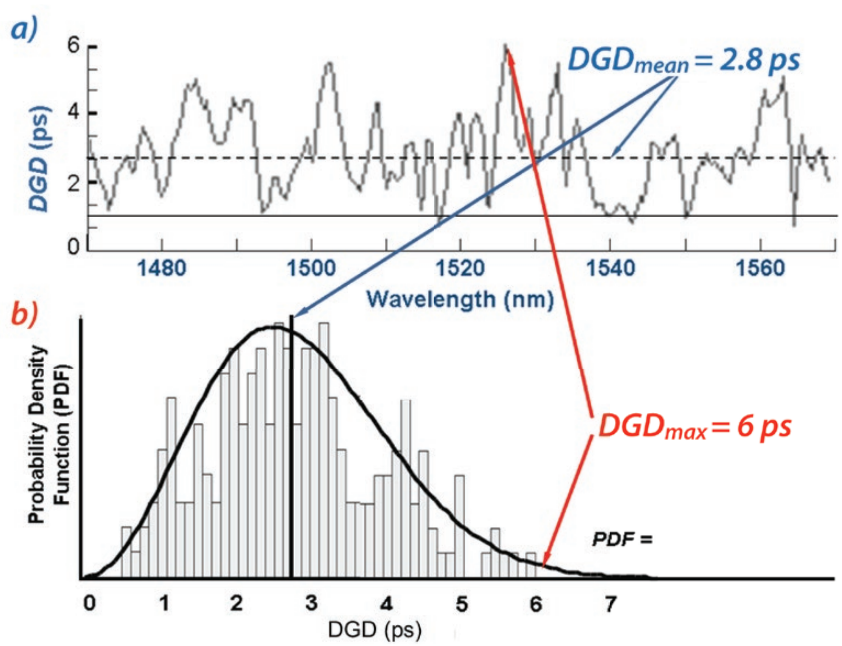

Figure 3. Evolution of the DGD distribution as a function of (a) the wavelength and (b) the time

For example, Figure 4 presents the monitoring of DGD as a function of the time and wavelength.

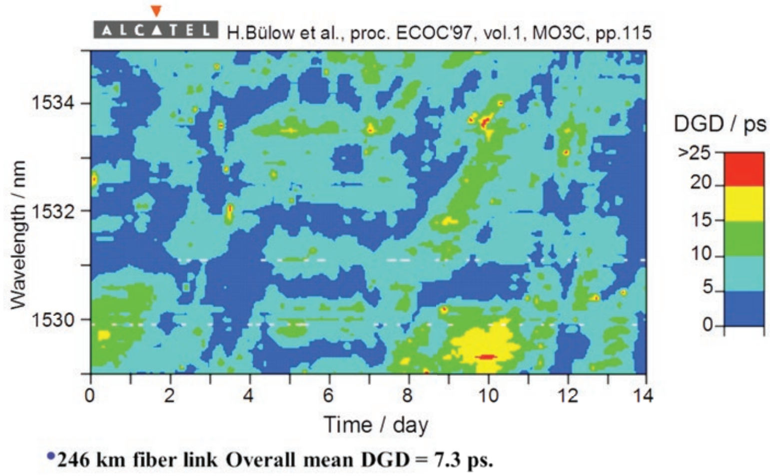

Figure 4. DGD monitoring over time and wavelength

Chromatic dispersion is fairly simple to compensate for since it is linear and does not vary over time.

Coherent system tolerance to DGD, PMD

In a transmission system that uses dual polarization, coherent detection and a local oscillator at the receiver end, the receiver tracks the polarization and different linear distortions and adjusts the algorithms to post-compensate the distortions measured, as can be seen in Figure 5.

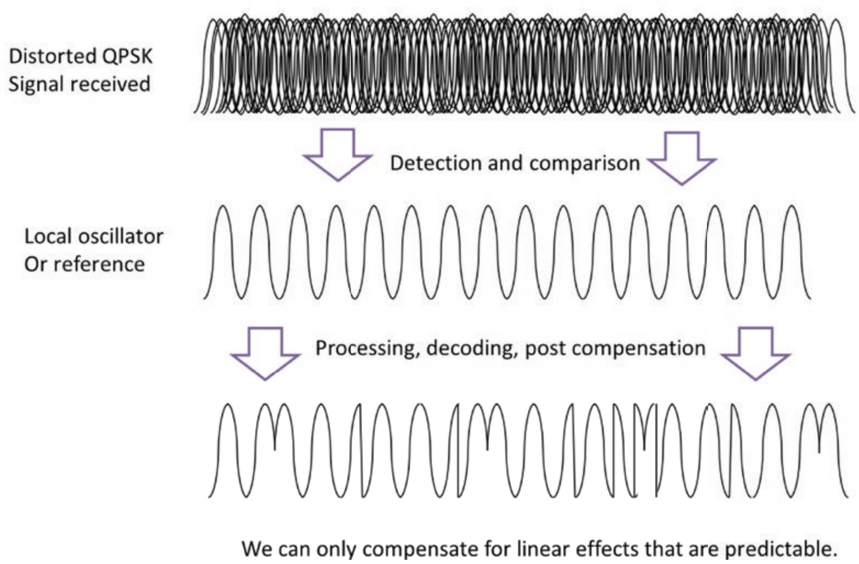

Figure 5. Procedure to compensate the distortions of a coherent signal

Chromatic dispersion (CD) is fairly simple to compensate for since it is linear and does not vary over time.

DGD, however, behaves differently and varies over time. It is measured by the coherent detector, in millisecond intervals, and the post-data treatment is adjusted to mitigate PMD.

On a regular link, the speed of variation of the states of polarization (SOP) can range from very slow to several tens of radians per second during the transient effect. Therefore, in order to monitor SOP variation, the DGD measurement and algorithm adjustment may have to be updated thousands of times per second.

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What happens when DGD_{max} exceeds the transmission system's capacity to recover the signal?

All systems are designed and tested to handle a certain amount of DGD. However, due to the nature of the phenomenon, the DGD_{max} can overcome a system's capacity to compensate for it. When this happens, the system loses track of the distorted signal and the transmission is interrupted.

When the SOP changes quickly, the algorithm is able to recover in a few minutes, but when conditions are stable, the instantaneous DGD observed by the channel can be close to the DGD_{max} for hours on end (see Figure 4). Remember, several minutes at 100 Gbit/s is quite a lot of data!

Precautions, troubleshooting and solutions

As higher bit rates and more sophisticated modulation schemes are deployed, the need for fiber characterization is critical.

The best troubleshooting practice is to fully characterize a link in terms of loss, ORL, CD and PMD, and then use these different characteristics to engineer the networks with the appropriate hardware tolerances and optimized compensations. CD is very predictable simply by the fundamental design of an optical fiber and PMD results from the statistical accumulation of small local index variations, which can only be minimized by the controlled manufacturing processes developed in recent years. The dominant impact of PMD could be induced by a minority of fiber sections, which can be identified using an **FTB-5600 Distributed PMD Analyzer** (QPOTDR - quantitative polarization OTDR).

The recommended tool for troubleshooting existing DWDM systems is the **WDM Investigator™**, which identifies impairments such as PMD-induced pulse spreading (see Figure 1), non-linear effects, crosstalk and carrier leakage.

Case study

In early winter, a major operator requested our expertise when one of their new coherent systems was showing near-limit, average DGD values on two wavelengths at 40 Gbit/s over a 1000-km link. Considering the statistical nature of PMD, the operator was worried that changing environmental conditions could push the DGD_{max} beyond the limits of the system. This was too close for comfort.

We tested the link with the new WDM Investigator™ and the FTBx-5245/5255 optical spectrum analyzer (OSA). The WDM Investigator™ indicates the presence and strength of polarization pulse spreading (PPS) in the tested channels. It monitors a live signal and compares the level of PPS present on that channel, throughout the measurement, to predefined thresholds. The indicator provides a status based on the measured pulse spreading and thus allows operators, at commissioning or troubleshooting, to determine if PMD-induced pulse spreading is affecting system performance. Since the system under test had only polarization-multiplexed (Pol-Mux) channels, a polarized probe channel was inserted in the PPS measurement.

In order to support and confirm the diagnostics of the WDM Investigator™, the measurement values were extracted and compared to a reference measurement of the DGD. This measurement was taken using a variation of the scrambled state of polarization analysis technique described in the standard FOTP-243 (EIA/TIA-455-243).

Phase 1: Investigator and in-band DGD measurement on the live system

The polarized probe channel was inserted a few nanometers away from the active 40G DP-QPSK channels (see Figure 6). Since the PMD-induced pulse spreading measured was greater than 7 ps, the investigator displayed a "risk" (see Figure 7).

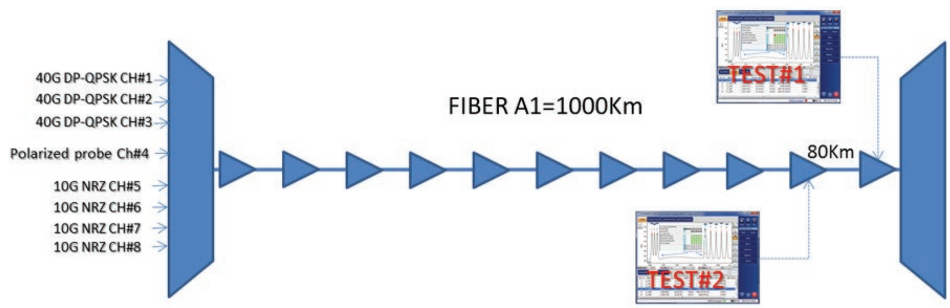


Figure 6. Test location

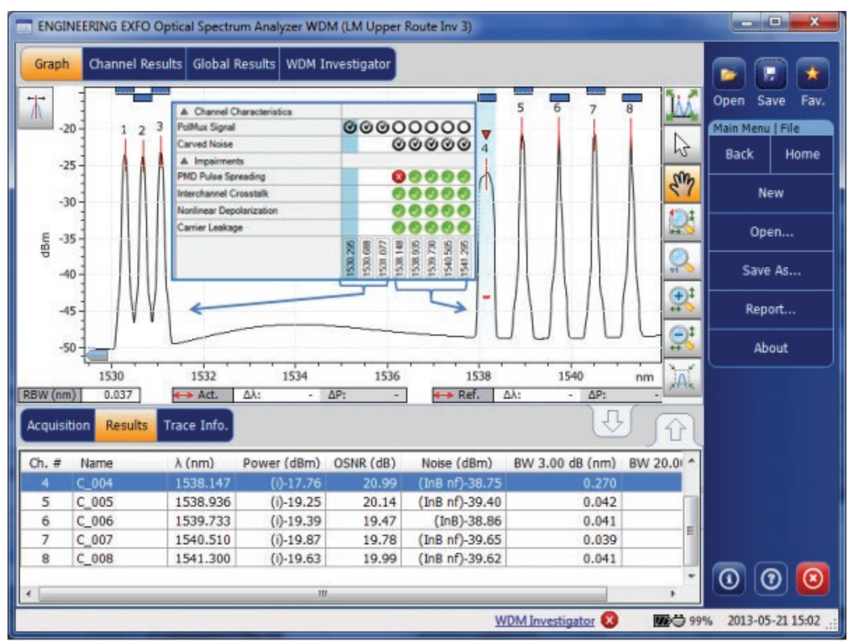


Figure 7. Test #1 - WDM Investigator™ over 1000 km

The WDM Investigator™ results for this channel were taken for the full span of the link (~1000 km) and confirmed by the SSA analysis taken at the same time on the same link (same channel). Table 1 below summarizes these results.

LM (end-to-end link)		
Time	5240BP PPS (ps)	SSA DGD (ps)
1h43	10.2	10.6
1h49	8.7	10.6
1h55	8.6	10.5
2h01	7.6	10.3
2h07	7.1	8.6
2h13	6.5	7.1

Table 1. PPS and DGD measurements over 1000 Km

Measurements seemed to indicate that the last span was indeed the source of the dominant PMD contribution for the entire link...strategy is therefore to focus on this last span.

The table shows that the results are consistent between the PPS (vary from 0 to DGD depending on the launched polarization condition) and DGD (independent of launch conditions, property of the link). This confirmed that the system's DGD was regularly above 10 ps on coherent channels. Note that one of the coherent channels was monitored at 10 ps (end-to-end) at around 1:50 am.

To determine whether or not the main DGD contribution could be on the last span (which was partly aerial) of the link, the measurement equipment was moved to the previous tap location, approximately 80 km upstream from the location of the above series of measurements. The results are presented in the Figure 8.

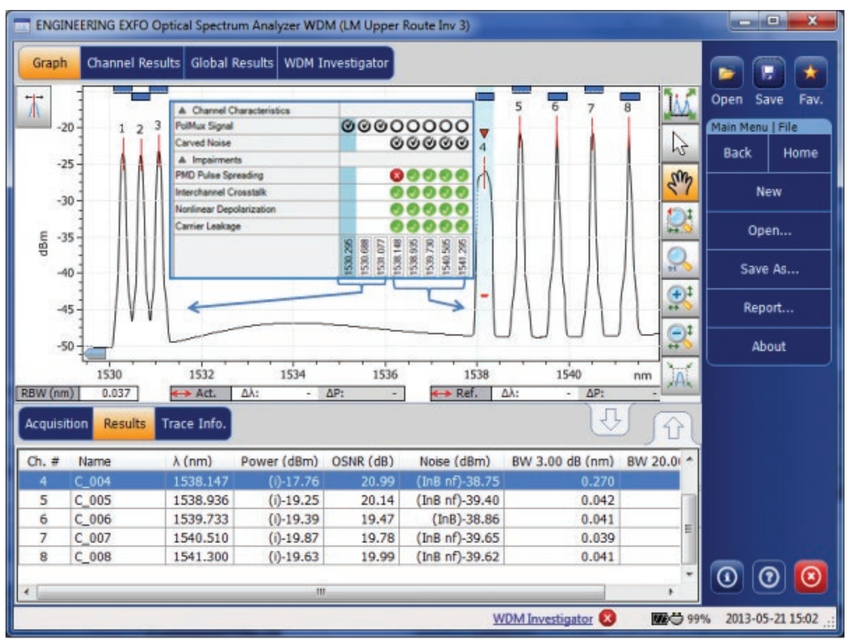


Figure 8. Test #2 - WDM Investigator before the last 80-km span

Measurements seemed to indicate that the last span was indeed the source of the dominant PMD contribution for the entire link. The strategy is therefore to focus on this last span.

Table 2 shows the results of the PPS and DGD measurements on the link excluding the last span.

LP (link without last span)		
Time	5240BP PPS (ps)	SSA DGD (ps)
6h07	2.2	3.5
6h12	2.1	3.3
6h17	1.7	3.2

Table 2. PPS and DGD measurements excluding the last span

Again, the PPS results are consistent with the measured DGD values. The results are significantly lower than the measurements for the full span and are consistently repeated. Although it is not impossible for the DGD to change that much between measurements (3 hours apart), it must be noted that the coherent system's DGD monitoring on the same channel was still displaying 10 ps for the complete end-to-end link.

These measurements seemed to indicate that the last span was indeed the source of the dominant PMD contribution for the entire link because the DGD was over than 9 ps while the total link DGD was approximately 10 ps. The strategy is therefore to focus on this last span.

Phase 2: PMD mitigation and identification of high PMD sections using the FTB-5600 Distributed PMD Analyzer

After the first test, it became clear that the last 79-km section was inducing most of the PMD over of the 1000-km link. The next step was to find a fiber that is able to support the data rate. Fortunately, two other fibers (See the fibers B1 and B2 in Figure 9) were available, but they had not been characterized.

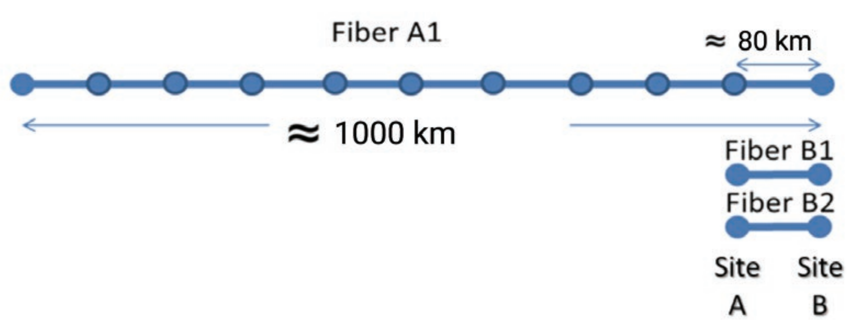
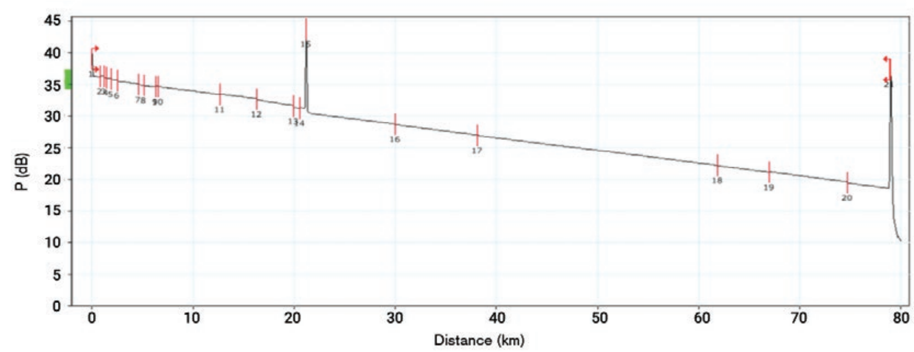


Figure 9. Fibers B1 and B2 selected to replace the last span of Fiber A1

Initial set of measurements clearly reveals that the first 21 km of the fiber is inducing most of the PMD.

The first PMD measurement was taken on Fiber B1 and resulted in 2.52 ps (The results are presented in Figure 10 and Figure 11).



Results	
PMD value	2.52 ps
PMD coefficient	0.2835 ps/km ^1/2
PMD value, 2nd order	40.8616 ps/nm
Measured fiber length	78.952 km

Figure 10. OTDR and PMD single-ended measurement of Fiber B1 from Site B

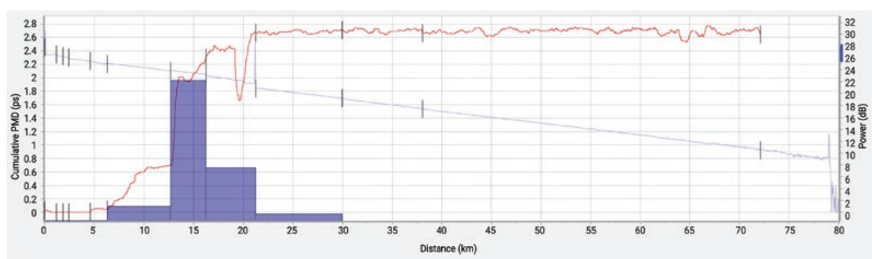


Figure 11. Quantitative distribution of the PMD measurement on Fiber B1 from Site B

This initial set of measurements clearly reveals that the first 21 kilometers of the fiber is inducing most of the PMD.

In order to accurately pinpoint the worst section, a detailed measurement focused on the first 21 kilometers was needed (see Figure 12).

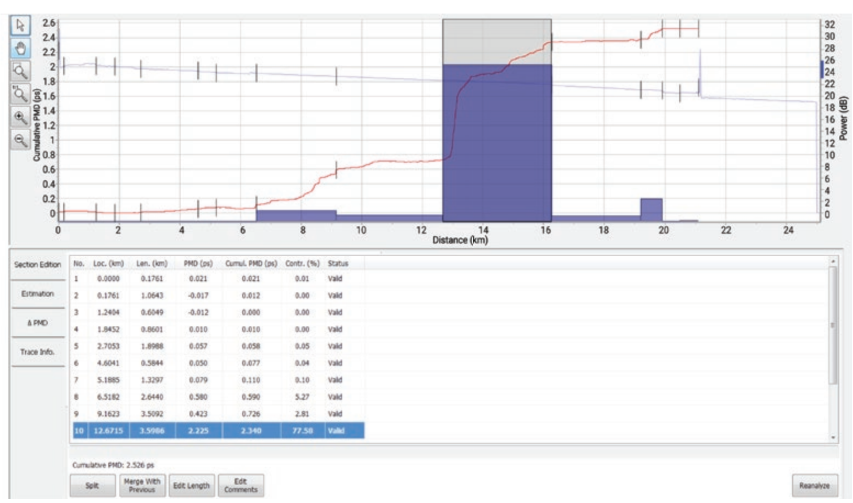
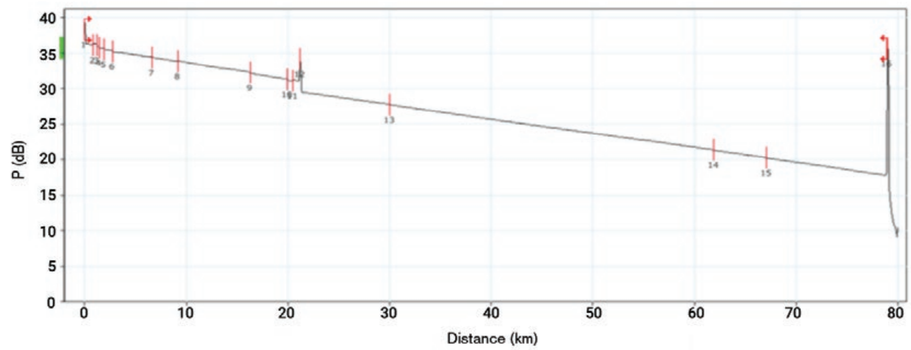


Figure 12. Quantitative distribution of the PMD measurement on Fiber B1 from Site B over the first 21 km

The same measurement was taken from Site A and bidirectional traces were generated to accurately identify the faulty sections and the results are shown in Figure 13 and Figure 14.



Results	
PMD value	9.46 ps
PMD coefficient	1.0642 ps/km ^1/2
PMD value, 2nd order	40.8616 ps/nm
Measured fiber length	78.952 km

Figure 13. OTDR and PMD single-ended measurement of Fiber B2 from Site B

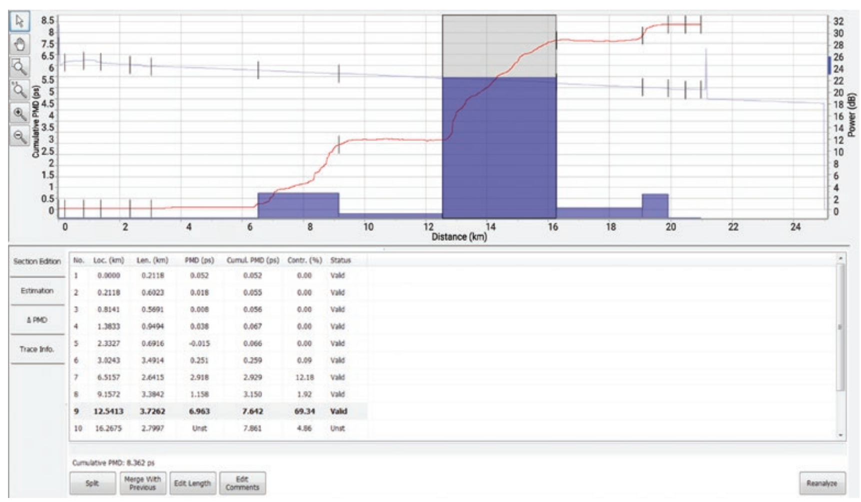


Figure 14. Quantitative distribution of the PMD measurement on Fiber B2 from Site B over the first 21 km

On both fibers, the main contribution (70-75%) was induced by 3.6 km of fiber. On the first 21 km of fiber, the contribution (10%) was induced by 2.64 km of fiber.

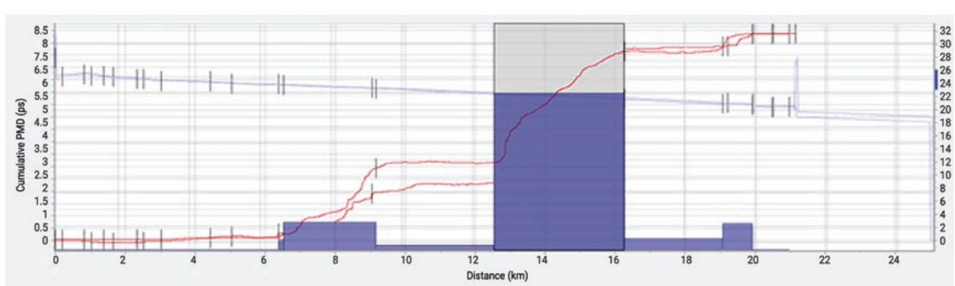


Figure 15. Fiber B1 and B2 QPOTDR FTB-5600 traces

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[FTBx-5245/5255 - optical spectrum analyzers for the field]

If the 3.6-km section is replaced with new fiber (low PMD according to the fiber manufacturer's specifications), the overall PMD would drop to 4.6 ps on Fiber B2 and 1.2 ps on Fiber B1 as can be observed in Figure 15.

Conclusion

Although it is preferable to characterize a link before it is commissioned, it is possible to troubleshoot PMD (DGD) issues once a system is turned up. In the presence of ROADMs, the WDM Investigator™ was shown to be a powerful, non-intrusive troubleshooting tool.

Using the WDM Investigator™ (FTBx-5245/5255), we were able to isolate the trouble and show that the last span of fiber was the main contributor of overall DGD in the complete 1000-km link.

With the **FTB-5600 Distributed PMD Analyzer**, we were able to pinpoint a 3.6-km span that was inducing 70-75% of the overall PMD on the two spare fibers (see Figure 9). This allowed us to reduce the PMD to an acceptable level.

Based on the measurement and our experience, it is also very probable that the last span showing high PMD on the 1000-km link was induced by the same section of cable pinpointed in the last tests.

The customer was able to make the right decision based on the different measurements using the **WDM investigator™** and the **FTB-5600 Distributed PMD Analyzer**.