Abstract—The accurate measurement of chromatic dispersion and Polarization Mode Dispersion of installed optical fiber cables at different transmission wavelengths become essential for optimizing and upgrading long-haul and DWDM optical networks. This paper aims to prove the possibility to undertake such measurements with high-accuracy and over a very long distance (5000 km) and through several passive components and amplifiers.

Index Terms—Chromatic Dispersion, DWDM, Fiber Optics, Polarization Mode Dispersion, STM-64

1. Introduction

The aim of this paper is to demonstrate the possibility to characterize the chromatic dispersion (CD) and polarization mode dispersion (PMD) of a DWDM optical network is essential to guarantee a high quality of the optical transmission. In addition, the accurate measurement of CD for each operating wavelength will allow network designers to optimize the use of expensive dispersion compensators.

2. Test and measurement configuration

The measurement has been undertaken between Halifax, Nova Scotia, Canada and Southport, UK representing a total distance of 5500 km. This optical link of Hibernia Atlantic featured 119 EDFAs. The chromatic dispersion analyzer FTB-5800 and the PMD analyzer FTB-5500B of EXFO where located in the UK and the broadband source was located in Canada. The repeater characteristics were as following:

- Output power: +12.0 dBm
- Repeater noise figure: 5.5 dB for all repeaters
- Repeater bandwidth: ~ 22 nm (1539 to 1561 nm)
- Single-amp gain flatness: ~ 1 dB
- End-to-end gain flatness: 4 to 5 dB

The fiber dispersion map was as following:

- The regular spans are assumed to be a fifty-fifty mix of Corning Submarine LEAF™ optical fiber and Corning Submarine SMF-LS or similar types of fiber.
- Every few spans, there is one span assumed to be Corning Submarine SMF-28 or a similar type of fiber for periodic inline dispersion compensation.
- The length of SMF is selected so that the middle of the wavelength range (~ 1550 nm) is fully dispersion-compensated.

Table 1 below presents the typical fiber parameters, which were assumed during system design:

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Submarine LEAF fiber</th>
<th>Submarine SMF-LS fibre</th>
<th>Submarine SMF-28 Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation at 1550nm (dB/km)</td>
<td>0.21 dB/km</td>
<td>0.20 dB/km</td>
<td>0.19 dB/km</td>
</tr>
<tr>
<td>Effective area (Aeff)</td>
<td>70 µm²</td>
<td>50 µm²</td>
<td>80 µm²</td>
</tr>
<tr>
<td>Dispersion at 1550nm (D)</td>
<td>-3.5 ps/nm-km</td>
<td>-2.5 ps/nm-km</td>
<td>17 ps/nm-km</td>
</tr>
<tr>
<td>Dispersion slope at 1550nm (D)</td>
<td>0.12 ps/nm²-km</td>
<td>0.05 ps/nm²-km</td>
<td>0.06 ps/nm²-km</td>
</tr>
<tr>
<td>Polarization Mode dispersion (PMD)</td>
<td>&lt;0.07 ps/km⁻¹</td>
<td>&lt;0.07 ps/km⁻¹</td>
<td>&lt;0.08 ps/km⁻¹</td>
</tr>
</tbody>
</table>

Table 1: Hibernia Atlantic typical fiber parameters.

3. Polarization Mode Dispersion Measurement

3.1. Measurement strategy

In laboratory conditions, exact PMD measurements are achieved using nine SOP Muller set: 3 orthogonal input states, each analyzed with three output orthogonal polarizers (similar to the PSA method used, for instance, by EXFO FPMD-5600). The sophisticated setup required for such a measurement is not practical when characterizing installed fiber. On the other hand, a single combination of I/O polarization will suffer from a large uncertainty given by Equation 1, which for a 5-ps PMD and 3-THz (24 nm) bandwidth will show 1.6-ps uncertainty.

\[
\frac{\sigma_{PMO}}{PMD} = \sqrt{\frac{1}{\frac{8}{2\pi}} \left( \frac{1}{1 + \frac{1}{4} \left( \frac{PMD}{\sigma_{PMO}} \right)^2 } \right)^2}
\]
Scrambling both the DUT input and output polarization (with polarization scramblers) decreases the uncertainty by the square root of the number of polarizations: about 1/10 with 96 I/O polarization combinations and 1/5 with 30 I/O polarization combinations. This represents the strategy adopted for measuring PMD on Hibernia Atlantic’s cable.

3.2. PMD measurement results

The PMD measurement setup includes two independent polarization scramblers to scramble both the input polarization of the fiber link and the input polarization of the PMD analyzer. The two polarization scramblers IQ-5100B are set to cover the Poincaré Sphere in 100 seconds.

The optical signal received by the PMD analyzer is a combination of ASE generated by each EDFA and of the broadband FLS-5800’s signal. The upper trace of Figure 3 gives the total optical signal received, and the two other traces show the two polarizations, each detector “seeing” one polarization (EXFO PMD analyser FTB-5500B uses a patented technology to separate the two states of polarization at the output of the interferometer onto two separate detectors). The structure observed in the two polarized signals is due to PMD (similar signal to what the fixed analyzer method would use with an OSA). The broadband source FLS-5800 signal reaches the PMD analyser at an intensity of approximately 3 to 5 dB (peak-to-valley difference).

The PMD value is computed from the auto-correlation and the cross-correlation envelopes of the two interferograms acquired by the PMD analyzer two detectors (Adding the info of both detectors leads to the auto-correlation, while the difference gives the cross-correlation).

The measured PMD is 4.5 ps. The observed distribution is in agreement with the theoretical uncertainty of a single measurement.

Two sets of 30 PMD values were acquired without the two polarization scramblers. These acquisitions were made about half an hour apart, each time with a setup modification at the analyzer end. A certain amount of residual polarization scrambling—due to fiber working its way back to a stable condition—was still present.

1 Stress release of fiber after manipulation. Loose tube fiber does not show such stabilization because there is no stress induced by manipulating the fiber.
A third set of 30 PMD measurements was performed 24 hours later, after all fibers were perfectly settled, making for an almost polarization-scrambling-free condition. When we compare the standard deviation of the 96 measurements made with polarization scrambling at both ends (0.5 ps) with the first two measurements of Table 2, we see that the variation in PMD values indicates relatively good sampling of available polarization. The third measurement shows a very small standard deviation, 0.1 ps, indicating improper sampling of the fiber/analyzer SOP (proving that multiple measurements at a single input/output SOP bring no additional PMD information). The 3.8-ps PMD value is not as reliable as the two others. The exact theory specifies that without proper polarization scrambling, the error can be as important as 1.5 ps. This is not caused by the analyzer, but by the fact that only one of the nine possible analyzer/DUT SOPs is sampled; in comparison, this is like trying to measure the volume of a solid knowing only one of its three dimensions.

<table>
<thead>
<tr>
<th>No polarization scrambling</th>
<th>Average PMD value (ps)</th>
<th>Standard deviation (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>File name: fkb2_2003_04-23-13_17_47.pmdB</td>
<td>5.0</td>
<td>0.4</td>
</tr>
<tr>
<td>File name: fkb2_2003_04-23-14_04_44.pmdB</td>
<td>4.7</td>
<td>0.4</td>
</tr>
<tr>
<td>File name: fkb2_2003_04-23-10_59_44.pmdB</td>
<td>3.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2: PMD Measurements with no controlled polarization scrambling.

3.2. PMD measurement validation

PMD value validation is achieved by adding known PMD emulators\(^2\) to the measured fiber. The test was done with and without polarization scrambling, as indicated in the first column of Table 3. The error associated with each measurement is calculated using the single-measurement uncertainty (see Equation 1 on page 4), and then dividing this number by the square root of the number of measurements made with polarization scrambling. The standard deviation of the measurements made without polarization scrambling indicates that the fiber was not completely stabilized, causing some polarization scrambling. The retrieved value’s accuracy is also limited by the optical bandwidth difference between the emulator’s calibration and the measurement. Calibration was performed using a very broad source, while the measured fiber link’s 119 EDFAs limited the optical bandwidth to approximately 3 THz (24 nm).

Both emulators’ PMD values were retrieved well within the 95% confidence level, proving that Hibernia Atlantic Fiber #2 PMD measurements were accurate.

\(^2\) PMD emulators are made of a combination of special fibers that generate stable known PMD values. For this test, 5-ps and 10-ps (approximate values) PMD emulators were used.

4. Chromatic dispersion measurement

The chromatic dispersion measurement setup consists of the EXFO FLS-5803, a C-band 100-MHz SLED, an attenuator for controlling the optical intensity of the signal injected in the first EDFA, the Hibernia Atlantic fiber and the FTB-5800 CD analyser.

4.1. Optical and RF Signal at the CD Analyzer

From the information available at the time of test planning, the optical signal in the default reference wavelength region (1562.25 nm) was believed to be good enough to allow easy setting of the measurement parameters. In fact, it was a lot lower than hoped and expected.

![Figure 3: RF signal intensity at the Hibernia Atlantic Fiber #2 output.](image)

This weak signal in the reference wavelength region is responsible for the difficulties encountered during the optimization of the source signal intensity. Averaging through the GUI was possible, thus allowing the system to acquire the RF signal with acceptable uncertainty.
4.3. Chromatic Dispersion measurement results

The Hibernia Atlantic fiber’s chromatic dispersion (CD) was measured using a 0.5 nm step and an averaging time of 30 seconds per RGD point. This measurement was repeated 20 times. The RGD trace was fitted using a quadratic least square equation. The average CD parameters derived from the RGD fit are $\lambda_0 = 1551.42$ nm ± 0.15 nm, and $S_0 = 402$ ps/nm² ± 9 ps/nm² (see Figure 4).

![Figure 4: Typical CD measurement results.](image)

The 20 CD traces are presented in Figure 5. All 20 measurements show very good repeatability, indicating that the analyzer was properly set for the available signal.

![Figure 5: 20 consecutive CD measurement traces.](image)

4.4. Validating CD results

A known standard fiber is added at the source end. The CD measurement of the Hibernia Atlantic fiber is subtracted from the Hibernia Atlantic fiber + standard fiber. The result should be equal to the standard fiber alone.

The standard retrieving test was done based on a single acquisition for the Hibernia Atlantic fiber + standard fiber and the averaging of 20 measurements previously analyzed. The expected uncertainty is then dominated by the single measurement of the Hibernia Atlantic fiber + standard fiber combination, which is $\approx 25$ ps/nm at about 1548 nm, $\approx 110$ ps/nm at 1560 nm and $\approx 80$ ps/nm at 1540 nm.

Result are shown in Figure 7. The difference between the standard fiber and its retrieved value is +27 ps/nm at 1540 nm, and +67 ps/nm at 1560 nm, which is well within the uncertainty of a single measurement. If 20 measurements were made both on the Hibernia Atlantic fiber and the standard fiber combination and the Hibernia Atlantic, the difference between Curve A and Curve B would be reduced by a 4.5 factor (square root of 20).

![Figure 7. Network CD with and without standard fiber added.](image)

5. Conclusion

With the utilization of an improved interferometric PMD analyzer and a phase shift method Chromatic Dispersion Analyzer which are made insensitive to the spectral shape of the incoming optical signal, we demonstrated that extremely long fiber optics links featuring amplifiers, gain-flattening filters and other passive devices can easily be characterized. This will allow network designers and telecom operation teams optimize and upgrade their network in a very efficient way.