Non-Intrusive PMD Measurements on Active Fiber Links Using a Novel Coherent Polarization Analyzer

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Abstract— This paper describes the principle of a non-intrusive measurement method for determining the end-to-end PMD in active fiber links carrying live commercial traffic. These in-service measurements are made possible by a novel high-resolution optical spectrum and polarization analyzer that JDSU has recently developed.

I. INTRODUCTION

Excessive polarization-mode dispersion (PMD) in fiber-optic links may severely impair the transmission of high-speed optical signals and, in certain cases, lead to temporary outages of one or more WDM channels [1-2]. Thus, the end-to-end PMD in a fiber link should be accurately characterized before a link is put into service. Such PMD characterization may be performed using one of the several PMD measurement method described in the literature and international standards [2-3]. However, one common feature of these methods is that the fiber link has to be taken out of service for the duration of the measurement, because a special optical probe signal has to be injected into the input of the link in order to analyze the PMD-induced polarization transformations in the fiber. A typical setup for such out-of-service PMD measurements is shown in Fig. 1, where a broadband light source serves as the probe signal.
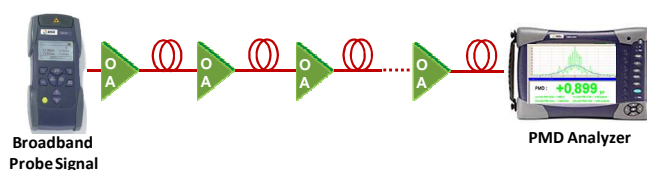

Fig.1: Typical setup for conventional PMD measurement on out-of-service fiber links.

Such out-of-service measurements are generally acceptable when a new fiber link is being installed, or when a link has been put out of service for other reasons. However, they are highly undesirable when PMD needs to be measured in a link that already carries commercial traffic. Such a situation may occur, for example, when one or more signals transmitted through an installed link are considered to be upgraded to a higher line-rate, e.g. from 10 Gb/s to 40 Gb/s, or during normal troubleshooting. With conventional out-of-service measurement methods, all signals carried by the link would have to be re-routed to other links before the PMD measurement could be performed.

This paper describes an alternative and truly non-intrusive method for measuring PMD in fiber links that carry commercial DWDM traffic. Unlike conventional techniques, this new method does not need special probe signals to be injected into the fiber, but rather uses the transmitted optical traffic signals to characterize the PMD in the fiber link. Hence, a PMD measurement can be performed while the link remains *in service*.

Such non-intrusive PMD measurements have been made possible by a new high-resolution optical spectrum and polarization analyzer, which JDSU has recently developed [4]. This instrument is capable of analyzing the frequency dependence of the state of polarization (SOP) *within* the bandwidth of each transmitted optical signal. This polarization analysis can be performed on any type of single-polarized traffic signal, such as conventional 2.5- or 10-Gb/s NRZ signals or even 40-Gb/s DPSK or QPSK signals, but does not require the signals to be launched in certain polarization states. The instrument does not require knowledge of the particular modulation format or baud-rate of the transmitted signals and, hence, may be readily employed in mixed transmission systems carrying signals of different baud-rates and/or modulation formats.
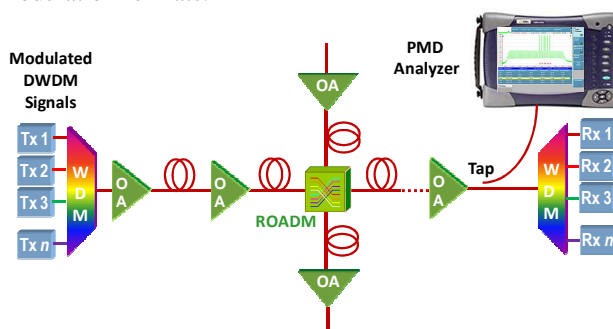

Fig. 2: Typical setup for non-intrusive PMD measurements on active fiber links using JDSU's in-service PMD analyzer. In the above example, the signal path includes an optical add-drop multiplexer (ROADM).

In order to perform a PMD measurement, the instrument simply needs to be connected to a broadband monitoring port (or tap) at the end of the fiber link.

Obviously, these in-service PMD measurements have absolutely no impact on the operation of the network. Another advantage of this method is that it allows direct end-to-end PMD measurements in ROADM networks, hence avoiding errors associated with the concatenation of span-by-span PMD characterization.

The mean differential group delay (DGD) in the fiber link (i.e. its "PMD") is determined from the average frequency dependence of the measured polarization state variations in the individual traffic signals. The accuracy of the mean DGD obtained from these measurements increases with the number of traffic signals that are analyzed. When only a few signals are transmitted through the link, the measurements may have to be repeated several times after sufficiently long waiting periods. In this case, the mean DGD will be calculated from the average of all measurements.

The accuracy of the method has been asserted in various lab and field tests and found to be in excellent agreement with that of standard methods over a wide range of mean DGD values [4-5].

II. Principle of Non-Intrusive PMD Measurements

The end-to-end PMD in optical fiber links is typically characterized by the mean DGD, $< \Delta \tau >$, or alternatively by the root-mean-square DGD, $< \Delta \tau^2 >^{1/2} = (3\pi/8)^{1/2} < \Delta \tau >$ [2] The mean DGD may be estimated by measuring the instantaneous DGD, $\Delta \tau$, at various optical frequencies across the optical bandwidth of the transmission system, using for example the standard Jones matrix eigen-analysis (JME) method, and then simply averaging the results [2-3]. However, it is also possible to obtain $< \Delta \tau >$ by measuring $\Delta \tau$ repeatedly at the same optical frequency after sufficiently long waiting periods, or from a combination of time and frequency measurements [5-9]. In either case, measuring $\Delta \tau$ at a given optical frequency ν usually requires the injection of a special probe signal into the input of the fiber link at well-defined launch polarization states [2-3, 6], whereas commercial DWDM traffic signals are usually launched in arbitrary polarization states which cannot be easily controlled or varied.

The non-intrusive measurement method described below determines the mean DGD from polarization measurements on transmitted DWDM signals that may be launched in arbitrary polarization states. Instead of measuring $\Delta \tau$ directly, the PMD analyzer measures a slightly different quantity which is commonly referred to as "effective" or "partial" DGD and

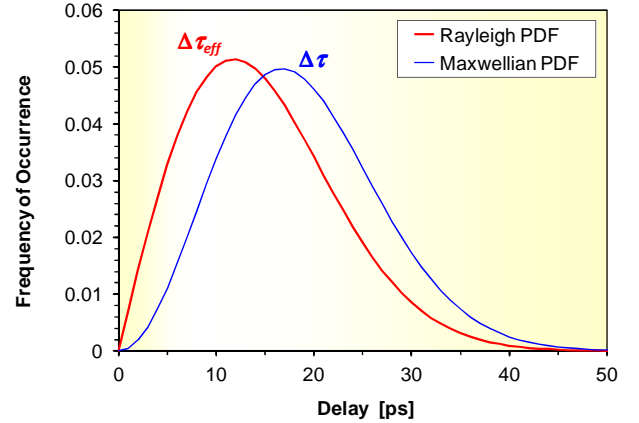denoted $\Delta \tau_{eff}$ in the following. This quantity was originally

Fig. 3: Statistical distributions of the effective DGD $\Delta \tau_{eff}$ (following a Rayleigh PDF) and the standard DGD $\Delta \tau$ (following a Maxwellian PDF).

introduced to characterize the PMD-induced distortion in DWDM signals that are launched at arbitrary SOP into the fiber link [1-2]. It is defined as the magnitude of the component of the PMD vector in Stokes space that is orthogonal to the launch SOP of the optical signal [1, 7]. Its relation to the DGD $\Delta \tau$ is given by

$$\Delta \tau_{eff} = \Delta \tau \left| \sin \varphi \right| ,$$

$$(1)$$

wherein φ represents the angle formed by the Stokes vectors representing the launch SOP of the signal and the principal states of polarization (PSP) of the fiber, which is usually unknown. However, it is easily seen in (1) that for any given $\Delta \tau$, $\Delta \tau_{eff}$ may assume a value between 0 and $\Delta \tau$, depending on the launch SOP of the signal. Consequently, $\Delta \tau$ and $\Delta \tau_{eff}$ both are random variables of time and optical frequency. However, because of (1), the statistical distribution of $\Delta \tau_{eff}$ is substantially different from that of $\Delta \tau$. While the probability of measuring a certain value of $\Delta \tau$ is given by a Maxwell probability density function (PDF), as shown in Fig. 2, the probability of measuring a certain value of $\Delta \tau_{eff}$ is given by a Rayleigh PDF [2, 7, 10],

$$\frac{\Delta \tau_{eff}}{< \Delta \tau^2 >} \exp\left(-\frac{\Delta \tau_{eff}^2}{2 < \Delta \tau^2 >} \right) .$$

$$(2)$$

It turns out that the mean value of this distribution, $<\Delta\tau_{eff}>$, is directly proportional to the mean DGD $<\Delta\tau>$ [2, 7], i.e.

$$<\Delta\tau> = (4/\pi)<\Delta\tau_{eff}> . \qquad (3)$$

Therefore, it is possible to estimate the desired mean DGD from the average value of a sufficiently large ensemble of $\Delta\tau_{eff}$ measurements, taken at different optical frequencies and/or different times.

As described in more detail below, $\Delta\tau_{eff}$ may be measured directly on the transmitted DWDM signals without requiring knowledge or control of the launch SOP of the individual signals. For highest accuracy of the mean value $<\Delta\tau_{eff}>$, the measurements should be performed, on all DWDM signals that traverse the link under test, either simultaneously or consecutively in time. However, signals that have traversed other fiber spans prior to entering the link under test should not be included in the average of $\Delta\tau_{eff}$.

If the number of signals passing through the link is relatively small and/or their frequencies are not spaced sufficiently far apart, then the $\Delta\tau_{eff}$ measurements should be repeated several times at predetermined time intervals Δt and over a sufficiently long time period. Depending on the speed of the polarization fluctuations in the fiber, the total measurement time required may be several hours or even days. A more detailed discussion of the measurement accuracy is provided below in section IV.

III. HIGH RESOLUTION OPTICAL SPECTRUM AND POLARIZATION ANALYSER

It is well known that PMD introduces frequency-dependent variations in the polarization states of the transmitted signals [1-2]. In particular, the various spectral components of a modulated optical signal, which are all in the same polarization state at the transmitter, are transformed into different SOPs. The difference in the SOPs increases with the value of $\Delta\tau_{eff}$. Hence, it is possible to measure $\Delta\tau_{eff}$ directly on the transmitted optical signals by analyzing the polarization states of the various spectral components *within* the bandwidth of each individual signal, which may be accomplished with the help of a frequency-selective optical polarization analyzer [7, 10].
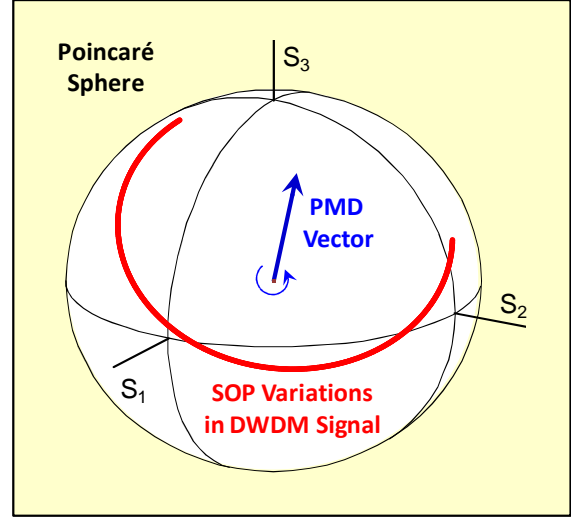

Fig. 4. *Representation of the PMD-induced SOP variations on the Poincaré sphere. The rotation axis is determined by the PSPs in the fiber link, and the length of the arc traced by the SOP rotation is proportional to $\Delta\tau_{eff}$.*

Within the relatively narrow optical bandwidth of a DWDM signal, one may approximate PMD-induced polarization transformation on the Poincaré sphere by a uniform precession of the SOP vector about a randomly oriented axis [2, 7], as shown schematically in Fig. 2. The axis of rotation is determined by the orientation of the PSPs, whereas the angle through which the SOP is rotated within the bandwidth $\delta\nu$ of an optical signal is $\Phi = 2\pi\Delta\tau\,\delta\nu$, i.e. proportional to $\Delta\tau$. However, the length of the arc traced by this SOP rotation is given by $2\pi\Delta\tau_{eff}\,\delta\nu$ and hence proportional to $\Delta\tau_{eff}$ [1, 7]

Thus, $\Delta\tau_{eff}$ may be deduced from the length of the arc traced by the SOP variations. Even though it is possible in some cases to determine $\Delta\tau$ directly from the rotation angle Φ, the results become very unreliable when the launch SOP is nearly identical with one of the PSPs of the fiber, i.e. when the arc in Fig. 4 has collapsed to almost a single point. Therefore, it is far more accurate to measure $\Delta\tau_{eff}$ instead of $\Delta\tau$.
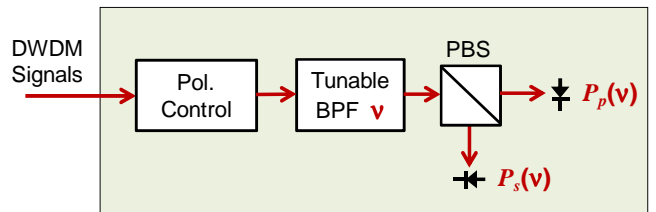

Fig. 5. *PMD analyzer with tunable optical band-pass filter (BPF) and conventional polarization beam splitter (PBS).*

Figure 5 shows the simplified block diagram of a frequency-selective polarization analyzer to detect the polarization variations within the spectrum of a modulated DWDM signal. The apparatus employs a variable polarization controller (PC)

followed by a tunable optical band-pass filter (BPF) and a conventional polarization beam splitter (PBS). The purpose of the polarization controller is to adjust the relative orientation of the PMD-induced SOP rotation in such a way that

1. the SOP at the center of the signal spectrum ($\nu = 0$) is a 50/50 mix of the two polarization eigenstates of the PBS, and

2. the axis of the PMD-induced rotation (on the Poincaré sphere) is orthogonal to the eigenstates of the PBS.

The desired polarization transformation is obtained when the two detector currents $P_p(\nu)$ and $P_s(\nu)$ exhibit the highest sensitivity to the PMD-induced polarization rotation at $\nu = 0$, i.e. when $\left| \partial P_p / \partial \nu \right| = \left| \partial P_s / \partial \nu \right|$ is maximal [4]. The desired quantity $\Delta \tau_{eff}$ may then be calculated, in a straightforward manner, from the frequency dependence of the angle [4],

$$\theta(\nu) = 2 \arctan \left(\sqrt{\frac{P_p(\nu)}{P_s(\nu)}} \right) , \qquad (4)$$

$$\Delta \tau_{eff} = \left| \frac{\partial \theta(\nu)}{2\pi \, \partial \nu} \right| . \qquad (5)$$

Figure 6 Figure 6 displays an example of a properly transformed SOP rotation and the resulting frequency dependence of $\theta(\nu)$. The eigenstates of the PBS are assumed to be parallel with S_1 and the PMD- induced SOP rotation is the same as in Fig. 4.
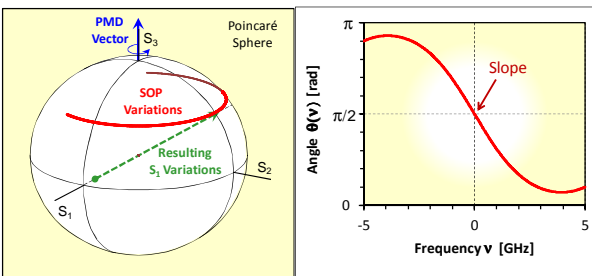

Fig. 6. PMD-induced SOP variations of Fig. 4 (left) and resulting frequency dependence of $\_\_$ (right) after proper transformation by the polarization controller. The eigenstates of the PBS are aligned parallel with S_1.

It is easily seen in Eqns. (4) and (5) that $\theta(\nu)$ can vary rapidly with frequency when measuring fibers with relatively large PMD. Thus, the polarization analyzer of Fig. 5 needs to employ a broadly tunable optical band-pass filter with a FWHM bandwidth of less than 1 GHz, so as to accurately measure these large variations. It turns out that such filters are difficult to manufacture without introducing undesired polarization effects. To circumvent this problem, JDSU has

developed a PMD analyzer which is based on a coherent receiver with polarization diversity detection [4]. In this implementation, which is shown schematically in Fig. 7, the spectral components to be analyzed are selected by a broadly tunable local oscillator laser with a line width of about 1 MHz.
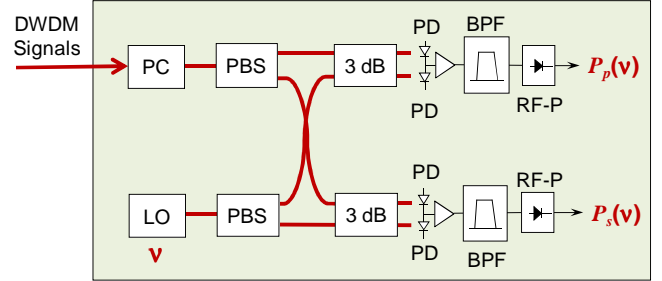

Fig. 7. PMD analyzer using coherent receiver with polarization diversity (PC: adjustable polarization controller; LO: tunable local oscillator laser; 3 dB: 3-dB splitter/combiner; PD: photo detector; RF-P: RF power detector).

Just like in Fig. 5, the incoming optical signal first passes through a variable polarization controller before it is separated into two orthogonal polarisation components by a polarization beam splitter. The two polarization components are then separately mixed with the output light of the local oscillator laser, and the resulting beat signals are detected with two balanced photo-detectors. The received electrical signals are bandwidth limited to about 200 MHz and fed into two RF-power detectors, which generate two electrical signals, $P_p(\nu)$ and $P_s(\nu)$, that are proportional to the optical signal power in two orthogonal SOPs at optical frequency ν, similar to Fig. 5.
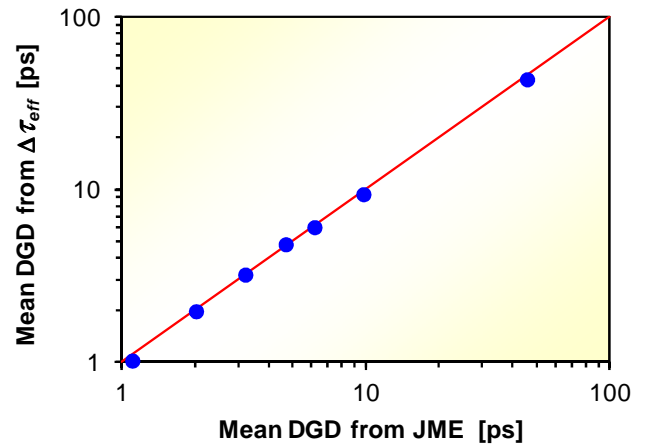

Fig. 8. Comparison of mean DGD values measured with the coherent PMD analyzer and a standard Jones matrix eigen-analysis method. The measurements were performed on various combinations of fiber spools and PMD emulators with $<\Delta\tau>$ ranging from 1 to 50 ps [4].

The local oscillator laser scans rapidly across the spectrum of the selected DWDM signal at a speed of 100 GHz/ms and with sub-GHz accuracy. This scan is repeated several times at various settings of the input polarization controller in order to

find the desired scan with $P_p \approx P_s$ and maximal slope $\left|\partial\theta/\partial\nu\right|$ at $\nu = 0$.

The main advantage of this coherent polarization analyzer is its high spectral resolution, which is twice the electrical bandwidth of the receiver, i.e. about 400 MHz. This resolution is sufficient to measure $\Delta\tau_{eff}$ in fiber links with high PMD and on narrow-band DWDM signals. When a signal has experienced large amounts of DGD, e.g. $\Delta\tau = 150$ ps, the angle $\theta(\nu)$ in (4) becomes a fairly steep function of ν, with a slope of almost 1 rad/GHz. Obviously, one needs a polarization analyzer with sub-GHz resolution to accurately measure such steep slopes. In addition, high spectral resolution is also essential for measuring $\Delta\tau_{eff}$ in narrow-band signals, like 2.5 Gb/s NRZ signals, where $\theta(\nu)$ may only be measured over a frequency range of about $\delta\nu = \pm 1.25$ GHz around the carrier frequency. When such a signal experiences a DGD of about $\Delta\tau = 1$ ps, for example, the useful length of the arc in Fig. 2 is at most only about 0.25% of that of a full great circle.

Another important advantage of the coherent polarization analyzer is its fast tuning speed of about 100 GHz/ms, which minimizes measurement errors caused by rapid polarization fluctuations in the fiber link. These fluctuations may arise, for example, from mechanical movement or physical vibrations of the fiber. Since they are superimposed on the PMD-induced polarization rotations, they potentially can cause large measurement errors in $\Delta\tau_{eff}$. However, these errors can be kept small by tuning the polarization analyzer rapidly across the spectrum of each DWDM signal. At a tuning rate of 100 GHz/ms, even rapid polarization variations of up to 1000 rad/s, which have been observed in buried terrestrial fibers [11], would cause only small measurement errors of the order of 1.6 ps in $\Delta\tau_{eff}$. Fortunately, these errors tend to be random and not systematic, so that they essentially cancel one another when $<\Delta\tau_{eff}>$ is calculated from a large set of individual $\Delta\tau_{eff}$ measurements.

Figure 8 shows the results of PMD measurements performed with the coherent polarization analyzer on various combinations of single-mode fibers and PMD emulators, with $<\Delta\tau>$ ranging from 1 to 50 ps. The measured values are plotted against reference measurements taken with a commercial JME analyzer and show very good agreement between the two methods [4]. The accuracy of the instrument and the validity of the test method have also been confirmed in various field trials. Tests on terrestrial fiber links with buried cables have shown that accurate PMD measurements can be obtained within a few hours of total measurement time [5].
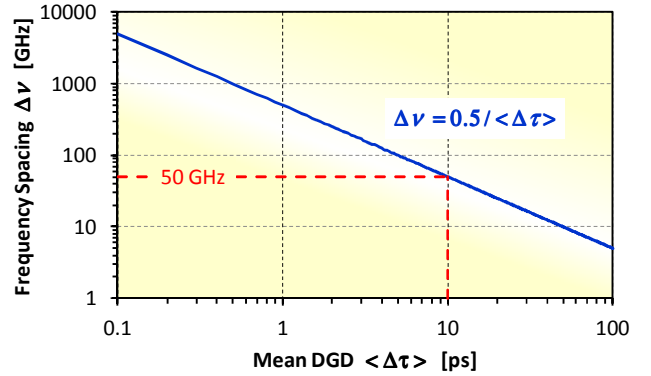

Fig. 9. Frequency spacing of DWDM signals required for statistically independent DGD measurements.

IV. ACCURACY OF MEAN DGD MEASUREMENTS

Aside from the measurement errors discussed above, the accuracy of the mean value $<\Delta\tau_{eff}>$ also depends strongly on the total number of individual $\Delta\tau_{eff}$ measurements taken at different frequencies and/or at different times on the optical signals. Because $\Delta\tau_{eff}$ is a random variable, which fluctuates with time and frequency, the mean value $<\Delta\tau_{eff}>$ calculated from a finite set of measurements also varies randomly. The uncertainty of $<\Delta\tau_{eff}>$ may be characterized by the standard deviation [2, 12],

$$\sigma = 0.523 <\Delta\tau_{eff}> \Big/ \sqrt{N} , \qquad (6)$$

wherein N denotes the total number of *statistically independent* measurements of $\Delta\tau_{eff}$.

Statistical Independence of Measurements in Frequency

Measurements that are performed simultaneously (or nearly at the same time) on two signals with different carrier frequencies, ν_1 and ν_2, are considered to be statistically independent when the frequency spacing, $\Delta\nu = \left|\nu_1 - \nu_2\right|$, is substantially larger than $0.5/<\Delta\tau>$ [2, 12]. For instance, if $<\Delta\tau> = 10$ ps and the signals are spaced at least 50 GHz apart, then $\Delta\tau_{eff}$ measured on one of the signals is statistically independent from $\Delta\tau_{eff}$ measured on the other signal. Thus, the number of statistically independent measurements in frequency, N_ν, can be readily calculated once a first estimate of $<\Delta\tau_{eff}>$ has been obtained and then used to calculate the uncertainty of this estimate from Eq. (6).

Statistical Independence of Measurements in Time

Successive $\Delta\tau_{eff}$ measurements on the same optical signal but taken at two different times, t_1 and t_2, are considered statistically independent when the time interval, $\Delta t = |t_1 - t_2|$, is substantially larger than the correlation time, Δt_{corr}, of the PMD fluctuations in the fiber [6, 13]. It is important to note that Δt_{corr} may vary widely from link to link, because PMD fluctuations generally arise from changes in the physical environment of the fiber (e.g. temperature variations), which may be very different in different fiber links [6, 13-16]

Therefore, Δt_{corr} is usually unknown prior to a PMD measurement. However, it is possible to estimate Δt_{corr} from a series of consecutive measurements on one or several DWDM signals by calculating, separately for each signal, the normalized autocorrelation function [6, 13],

$$ACF(\Delta T, \nu) = \frac{\sum_{i=1}^{M-m} \left[\Delta\tau_{eff}(t_i, \nu) - <\Delta\tau_{eff}(\nu)>\right] \cdot \left[\Delta\tau_{eff}(t_{i+m}, \nu) - <\Delta\tau_{eff}(\nu)>\right]}{(M-m) \cdot \left[<\Delta\tau_{eff}(\nu)^2> - <\Delta\tau_{eff}(\nu)>^2\right]} \quad (7)$$

wherein $\Delta T = m\Delta t$ is the time lag and $T = M\Delta t$ the total measurement time. The mean correlation time Δt_{corr} is then determined from the frequency-averaged autocorrelation function, $ACF(\Delta T) = <ACF(\Delta T, \nu)>_\nu$ (where the average is taken over all measured optical frequencies) as the time where $ACF(\Delta T)$ has decreased to $1/e^2$ (or 13.5 %) of its value at $\Delta T = 0$ (see Fig. 12 below).

Once Δt_{corr} is known, the number of statistically independent measurements per signal frequency is given by $N_t = (1 + T/\Delta t_{corr})$. Thus, the total number of independent measurements in time and frequency is $N = N_t \cdot N_\nu$, which is used in Eq. 6 to estimate the uncertainty in the mean value $<\Delta\tau_{eff}>$.

V. EXAMPLE OF IN-SERVICE PMD MEASUREMENTS ON AN ACTIVE FIBER LINK

To verify the accuracy of the non-intrusive PMD measurement method described above, JDSU has conducted a series of field tests on various terrestrial fiber links. One of these field trials, which is described in more detail in [5], was performed on a 414-km long transmission link carrying 19 active 10-Gb/s
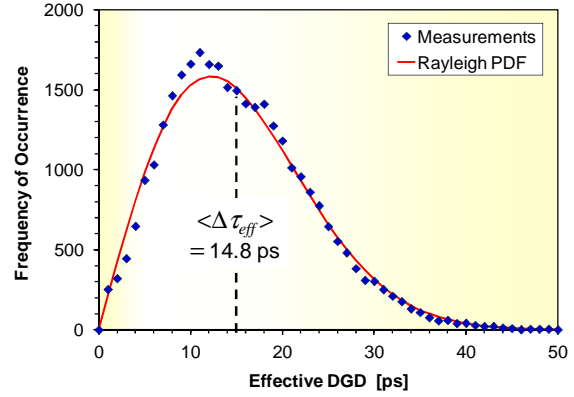
NRZ-OOK signals spaced at least 100 GHz apart.

Fig. 10. Statistical distribution of 31290 measurements of $\Delta\tau_{eff}$ on an active fiber link carrying 19 DWDM signals [5].
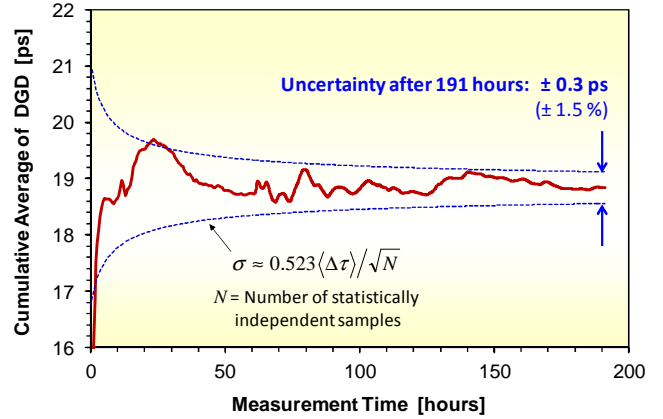

Fig. 11.   Convergence of the mean DGD calculated from the cumulative average of $\Delta\tau_{eff}$ versus measurement time (solid curve) and estimated uncertainty (dashed curves). The mean DGD after 191 hours is 18.8 ps with an estimated uncertainty of ±0.3 ps [5].

The PMD analyzer was connected to a monitor tap at the end of the link, as shown schematically in Fig. 2, and configured to automatically measure $\Delta\tau_{eff}$ 1680 times in each of the 19 DWDM signals over a total measurement time of 191 hours, yielding a total of 31920 measurements. The mean value of all measurements was $<\Delta\tau_{eff}>$ = 14.8 ps, corresponding to a mean DGD of $<\Delta\tau>$ = 18.8 ps. This result is in excellent agreement with earlier end-to-end PMD measurements on the same fiber link, which yielded a value of 18.6 ps [8-9].

The statistical distribution of the 31920 $\Delta\tau_{eff}$ measurements, shown in Fig. 10, closely follows the expected Rayleigh PDF for $<\Delta\tau_{eff}>$ = 14.8 ps, thus confirming that the data set was sufficiently large for a meaningful estimate of $<\Delta\tau>$. Furthermore, Fig. 11 displays the mean DGD calculated from

the cumulative average of $\Delta\tau_{eff}$ as a function of measurement time. It is clearly seen in this graph that the initial estimates of $<\Delta\tau>$ (e.g. 1 hour after the start of the measurement) deviate substantially from the expected value (i.e. by more than 15%), and that the accuracy improves with time, as the number of independent $\Delta\tau_{eff}$ measurements increases. To estimate the uncertainty in $<\Delta\tau>$, we have calculated in Fig. 12 the auto-correlation function $ACF(\Delta T)$ defined in Eq. (7) and found that the average correlation time of $\Delta\tau_{eff}$ was of the order of about Δt_{corr} = 3 hours in this particular fiber link. Hence, after 191 hours the instrument had sampled about 64 statistically independent measurements on each of the 19 DWDM signals, yielding a total of about 1200 statistically independent measurements. With this number we have then calculated the expected uncertainty of $<\Delta\tau>$ as a function of measurement time from Eqs. 3 and 6 and found it to be a good estimate for the statistical variations in $<\Delta\tau>$ (see dashed curves in Fig. 11).
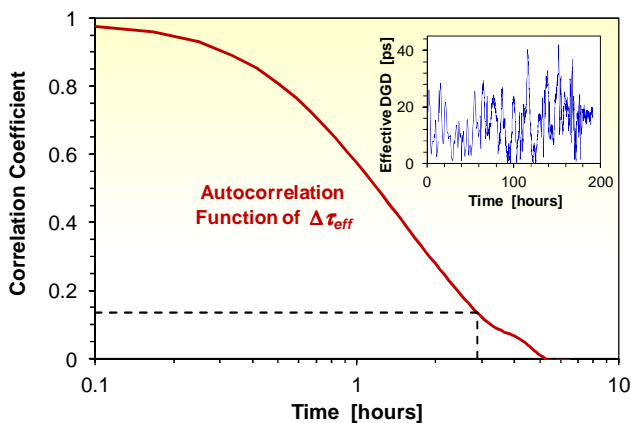

Fig. 12. Autocorrelation function of $\Delta\tau_{eff}$ versus time averaged over all measured DWDM signals. The measurements are completely de-correlated after about 3 hours. The inset (upper right) displays an example of the $\Delta\tau_{eff}$ variations in one of the 19 DWDM signals [5].

The following table lists the calculated measurement uncertainty for a few selected measurement times. Note that these numbers were calculated for the particular fiber link under test and may be very different for other links.

Elapsed Time [hours]	Relative Uncertainty in $<\Delta\tau_{eff}>$ and $<\Delta\tau>$
1.5	± 10%
14	± 5%
66	± 2.5%
191	± 1.5%

Table 1. Relative uncertainty of mean DGD as a function of elapsed measurement time for the in-service PMD tests shown in Fig. 11.

The above data clearly show the square-root relationship between measurement time T and uncertainty σ for $T >> t_{corr}$, where quadrupling of T reduces σ only by a factor of two. Thus, if the desired measurement accuracy is not obtained within the first 10 to 100 hours of a long-term measurement, it will be very time-consuming to improve it further. In the above field test, it would have required an additional 575 hours of measurement time to reduce the uncertainty from ±1.5% to ±0.75%. Although such high accuracy is rarely required for end-to-end PMD characterization of a fiber link, such long-term measurements can be readily performed with this instrument without impacting the data traffic on the link.

VI. CONCLUSIONS

We have described a novel field-deployable test instrument for non-intrusive measurements of end-to-end PMD in active fiber links. The instrument performs a high-resolution spectral analysis of the polarization state variations in the transmitted DWDM signals and thereby measures the effective DGD experienced by each signal. The mean DGD of the fiber link is then determined from the time and frequency average of a series of effective DGD measurements. The accuracy of the PMD measurement increases with the number of DWDM signals and the total measurement time.

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