Non-blocking PMD monitoring in live optical systems

R. Hui, R. Saunders, B. Heffner, D. Richards, B. Fu and P. Adany

A simple and non-blocking polarisation-mode dispersion (PMD) monitoring technique using coherent detection is demonstrated and applied to a 40 Gbit/s live fibre-optic system. The results demonstrated a clear correlation between the instantaneous differential group delay and the receiver Q-margin. It was also demonstrated that PMD-induced outage can be eliminated by an adaptive PMD compensator.

Introduction: In high-speed fibre-optic communication systems, polarisation-mode dispersion (PMD) is one of the most important factors of performance degradation. In-situ monitoring of PMD in live, multichannel WDM systems will be a key requirement for future dynamic optical networks to ensure quality of operation. Especially, for optical links with exceptionally high PMD values, an in-situ monitoring of PMD during operation will help network engineers to determine the impact of PMD and to select wavelength bands where PMD appears less damaging [1]. Many PMD measurement techniques have been proposed and demonstrated during the last two decades; the most popular include the fixed analyser method, the Jones matrix method, the Poincare arc method and the pulse delay method [2]. All these methods were developed for PMD characterisation instrumentation, which usually require access to both ends of an optical fibre cable to be measured. In live optical networks with installed optical fibres, the source and receiver are at distance and not accessible at the same time. We have recently introduced a novel and simpler method to evaluate differential group delay (DGD) using coherent detection and RF signal processing. This method utilises the spectral characteristics of the digital signal carried by each wavelength channel and measures the PMD-induced polarisation walk-off between the carrier and the clock components [3]. By tuning the wavelength of the local oscillator, the measurement can be performed across various channels in a WDM optical network.

In [3], the PMD monitoring technique was briefly introduced and tested with a fixed PMD emulator. In this Letter, we provide a more detailed signal processing algorithm and report the results of our field measurement applying this technique to a 200 km OC768 SONET optical link. Most importantly, we show that this PMD monitoring technique does not rely on the existence of clock components of the signal and therefore it is independent of the optical modulation format. The results demonstrate clear correlation between the instantaneous DGD and the Q-margin at the receiver. We also demonstrate that PMD-induced outage can be eliminated by an adaptive PMD compensator.

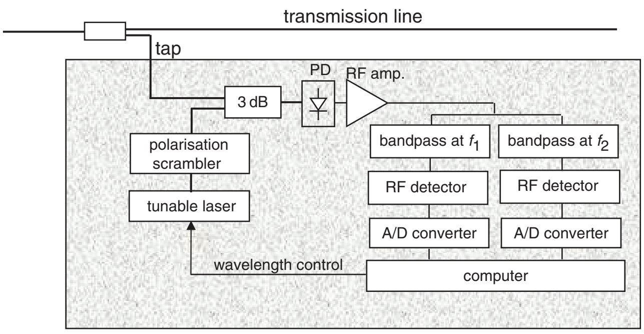

Fig. 1 *Block diagram of non-blocking PMD monitor using coherent detection*

Operation principle and measurement setup: Fig. 1 shows the block diagram of the PMD monitoring system. A small portion of the optical signal is tapped from the WDM transmission link to perform the measurement. An Agilent 8164A tunable laser is used as a local oscillator, which combines with the tapped optical signal through a 3 dB fibre coupler. A polarisation scrambler is placed at the output of the local oscillator to randomly scramble the state of polarisation of the local oscillator. The beating between the optical signal and the local oscillator at the photodiode converts the signal spectrum from optical domain into the RF domain. After the heterodyne optical spectrum is amplified, two RF bandpass filters with bandwidth of 1 GHz are used to select two different frequency components from the signal RF spectrum. The central frequencies of these two RF filters are 15 and 25 GHz, respectively. The first-order DGD of the optical signal can be interpreted by a differential polarisation walk-off between the two different frequency components, therefore the angular walk-off represented on a Poincare sphere can be obtained and the DGD value can be precisely extracted. Here the local oscillator acts as a polarisation discriminator because coherent detection is polarisation selective. It is noted that the two frequency components selected by the RF bandpass filters can be any part of the spectrum of the modulated signal spectrum. Therefore, this measurement setup is relatively independent of the data rate and modulation format of the optical signal. An RF envelope detector is used after each bandpass filter to measure relative RF power variation at the two selected frequencies. The RF power variations are then recorded by a computer through two A-D converters.

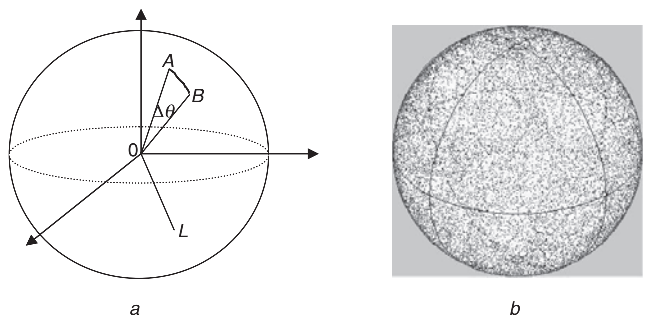

Fig. 2 *Illustration of polarisation walk-off of two frequency components (A, B) on Poincare sphere, and effect of polarisation scrambling of local oscillator by concatenating two polarisation scramblers*

a Polarisation walk-off of A, B on Poincare sphere
b Effect of polarisation scrambling

Fig. 2 illustrates the Poincare arc of an optical signal. The polarisation states of two frequency components selected by the bandpass filters are shown as A and B in Fig. 2 and their angular separation is $\Delta\theta$, which is proportional to the first-order DGD of the system. For an arbitrary polarisation state of the local oscillator represented by L on the Poincare sphere, the coherently detected RF signal amplitude at frequency ω_1 (point A) is:

$$U_A = \eta P_L P_S \cos\phi \cos\theta \qquad (1)$$

where η is a proportionality factor, P_L and P_S are the optical powers of the local oscillator and optical signal, respectively. φ is the angle between vector L and the plane formed by AB and the origin. θ is the angle between vector L projected on the AB plane and vector A. Then the detected signal amplitude at frequency ω_{21} (point B) is:

$$U_B = \eta P_L P_S \cos\phi \cos(\theta + \Delta\theta) \qquad (2)$$

When the polarisation state of the local oscillator is randomly scrambled, both φ and θ are functions of time t. Although we can assume that $\Delta\theta$ is fixed during each measurement, both U_A and U_B are random functions of time and their amplitudes range from 0 to 1. If we can find instances $t = t_m$ when $|U_A|$ is the maximum ($|U_A(t_m)| = \eta P_L P_S$), which corresponds to $\phi = n\pi + \pi/2$ and $\theta = n\pi + \pi/2$, we can evaluate the value of $\Delta\theta$ by measuring $|U_B|$ at the same time with $|U_B(t_m)| = \eta P_L P_S \cos(\Delta\theta)$ and therefore:

$$\Delta\theta = \cos^{-1}\{|U_B(t_m)|/|U_A(t_m)|\} \qquad (3)$$

Once $\Delta\theta$ is defined, the DGD value an optical signal experiences can easily be found by:

$$\Delta\tau = 2\Delta\theta/\Delta\omega \qquad (4)$$

Obviously an important requirement in this measurement is to ensure $|U_A|$ passes through its maximum during each measurement, which requires the polarisation scrambler in the system to cover all possible polarisation states within each measurement. In our system we concatenated two polarisation scramblers (Advantest Q8163 and

HP 11896A) and an example of the scrambled *LO* polarisation state measured within 10s is shown in Fig. 2*b*.

40 Gbit/s optical system field test: A field test was performed on an OC768 SONET system with duo-binary modulation. The system block diagram is shown in Fig. 3, where the 48 km fibre link between Lawrence, Kansas and Topeka, Kansas was looped back twice, which provides an approximately 192 km installed fibre link. To produce a sufficient amount of PMD to observe system BER outages, two pieces of high birefringence (HB) fibres each having 7 ps of DGD were added in the system, one placed immediately after the transmitter and the other before the receiver. An adaptive PMD compensator (PMDC) was also tested in the system. In the test, the intermediate frequency of homodyne detection was set at 20 GHz so that there is sufficient signal energy at 15 and 25 GHz frequency region which can be picked up by the two bandpass filters.

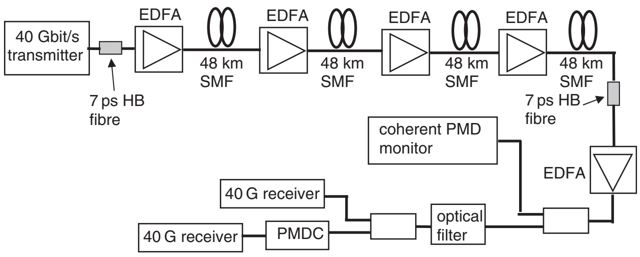

Fig. 3 *Block diagram of PMD monitoring in live transmission system*

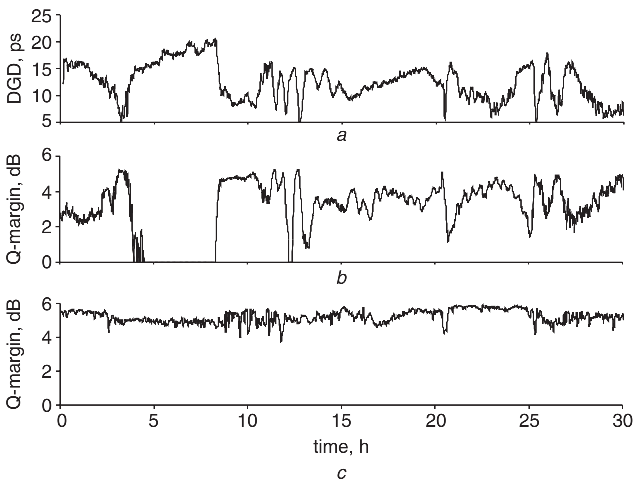

Fig. 4 *Measured DGD values together with measured system dBQ margin without PMD compensation, and with PMD compensation over 30 h period*

a Measured DGD values
b Measured dBQ margin without PMD compensation
c Measured dBQ margin with PMD compensation

Measurements were performed for about a week and Fig. 4 shows an example of comparison between measured DGD and system margin dBQ for a 30 h period. Allowing for variations in alignment between the link's principal state of polarisation and the transmitted state of polarisation, the results clearly show that the system margin is inversely proportional to the instantaneous DGD measured by the monitor. Whenever the DGD level is higher than 15 ps, the system would fail without PMD compensation. We also validated the effectiveness of the PMD compensator because with PMDC the system never failed, even when the DGD level went as high as 18 ps. The link PMD was compensated using a simple two-stage PMDC in which two sections of fixed DGD were concatenated through an adjustable birefringence that allowed for control of the mode-coupling between the sections. A reset-free polarisation controller between the link and the compensating sections allowed the compensator PMD vector to be anti-aligned with the link PMD vector, cancelling the first-order PMD. Both the polarisation controller and the concatenating birefringence were dithered by a control system to find the conditions for best compensation. A polarimeter after the compensator measured the degree of polarisation of the compensated signal: this was the error signal used to close the control loop. The PMDC was able to respond to small changes in the link PMD within several milliseconds. As shown in Fig. 4, the Q-margin of the compensated signal remains relatively constant despite variations in the measured link DGD, whereas reception of the uncompensated signal is observed to fail at high link DGD.

Conclusions: We have demonstrated a PMD measurement technique that does not block or degrade the transmitted signal and requires access only to the receiver end of the link, and have used the technique to monitor PMD in a link carrying live traffic. We have demonstrated the use of a two-stage PMD compensator to actively track and compensate the PMD of a link carrying live traffic, and confirmed that the compensated signal maintains an adequate Q-margin even during high-DGD events that caused the link to fail in the absence of compensation.

Acknowledgment: The authors thank M. O'Sullivan for useful discussions. This work was jointly sponsored by Nortel and Sprint. R. Hui, B. Fu and P. Adany are partially supported by National Science Foundation award 0435381.

18 August 2006
Electronics Letters online no: 20072578
doi: 10.1049/el:20072578

R. Hui, B. Fu and P. Adany (*Electrical Engineering and Computer Science, The University of Kansas, Lawrence, KS 66044, USA*)

R. Saunders and B. Heffner (*StrataLight Communications, 151 Albright Way, Los Gatos, CA 95032, USA*)

D. Richards (*Sprint-Nextel, 6220 Sprint Pkwy, Overland Park, KS 66251, USA*)

References

1 Allen, C.T., Kondamuri, P.K., Richards, D.L., and Hague, D.C.: 'Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches', *J. Lightwave Technol.*, 2003, **21**, pp. 79–86
2 Derickson, D. (Ed.): 'Fiber optic test and measurement' (Prentice-Hall, 1998)
3 Fu, B., and Hui, R.: 'Fiber chromatic dispersion and polarization-mode dispersion monitoring using coherent detection', *IEEE Photonics Technol. Lett.*, 2005, **17**, pp. 1561–1563