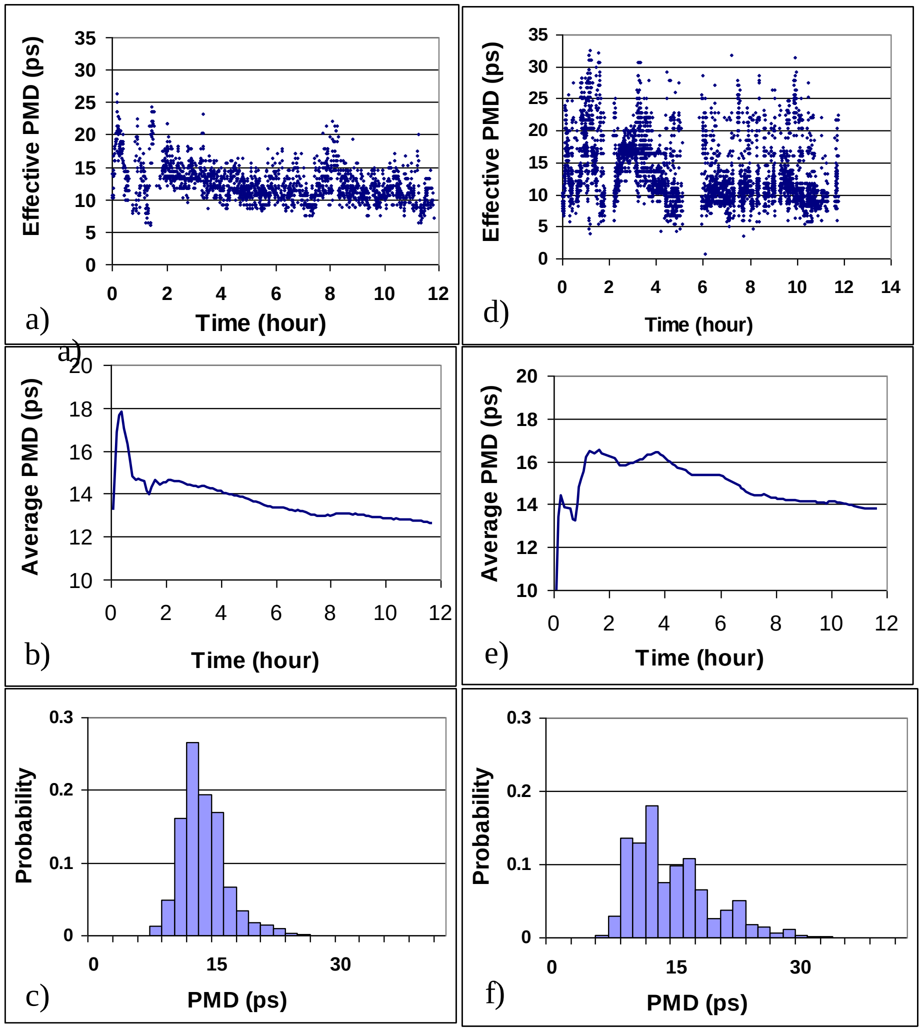

Fig. 7. (a)-(c): experimental results of long term PMD monitoring using TCA source. (d)-(f): experimental results of long term monitoring using 40Gbps signal itself. (a) & (d): instant PMD vs. time; (b) & (e): average PMD vs. time; (c) & (f) probability density function of PMD of all PMD values in (a) and (d) respectively. Note that in the test of using TCA source, there are much more valid data points available because of the periodic 45 degree polarization rotation capability of the TCA source.

Finally, we use a 40Gbps signal with advanced DPSK modulation format itself to perform long term monitoring of the PMD in a system. The test setup is shown in the lower half of Fig. 5 and the results are shown in Figs. 7d-7f. Here we use a different DWDM channel to perform PMD measurement from that using a TCA source shown in Figs. 7a-7c. Because we have no freedom of rotating the input SOP, much fewer data points are valid. As discussed previously, all data points with a DOP_1 above 90% were removed during data processing and the processed data are shown in Fig. 7d. The data discontinuities in Fig. 7d are the results of removed invalid data points with DOP_1 larger than 90%. As shown in Fig. 7e, the average PMD stabilizes with time, as the data points increase, towards the expected value of 12.3 ps. The probability density as a function of PMD is shown in Fig. 7f and the resulting average PMD is 13.7 ps. Because much fewer data points are valid for a certain period of time than in the case of Figs. 7a-7c, much longer monitoring time is required for getting more accurate

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result than for the case of using TCA source. Unfortunately, we were only allocated 12 hours for the test. Nevertheless, the obtained 13.7 ps is already sufficiently close to the expected value of 12.3 ps. Note that because measurements using TCA source and 40Gbps signal are performed with different DWDM channels at different times, their instantaneous PMD values are expected to be different, as shown in Figs. 7a and 7d. The results of PMD long-term monitoring at Veriizon 1500km test bed is summarized in Table 2 below. In the table, the test on channel #35 using TCA is also included.

Table 2. Summary of demonstration at Verizon 1500-km test bed

	PMD by time average	PMD by channel average	Expected PMD
TCA to empty channel #35 (13 hours)	12.9ps	12.9ps	12.3ps
TCA to empty channel #50 (12 hours)	12.6ps		
40G signal in channel 193.1 THz (12 hours)	13.7ps		

5. Experimental results of field trial

To further test the feasibility of the method for a field technician to measure and identify the PMD of an installed link, we performed the in-service PMD measurement field trial in a long-haul route in an operational network. The expected mean DGD of the route is 19.77 ps, calculated from the mean DGD values of the individual fiber sections, each measured using commercially available PMD measurement equipment before the long-haul system was installed. The length of the route is 414 km with a ROADM at each end, as illustrated in Fig. 8. There are four in-line optical amplifiers in the route. Add/drop ports are accessible in both ROADMs. In this trial a TCA signal shown in Fig. 3 is injected at Node A and is dropped at Node B to be used for PMD measurement. There are 23 traffic-carrying channels along the route, most having a data rate of 10 Gb/s. 16 idle DWDM channels, from 194.20 to 195.70 THz with a channel spacing of 100 GHz, are used for this trial. Another key objective of the trial is to confirm that our in-service PMD measurement is safe to the live traffic. To this end, the performance of all the working channels is monitored by the NOC during the trial. To ensure that the test signal passes through the route, the idle channels are maintained open temporarily by the NOC during the trial. When the test signal is injected into an idle port, the DWDM system adjusts its optical gain in each amplifier to accommodate the added signal.

We performed two different tests of PMD monitoring: one is to measure the PMD of the route over the 16 WDM channels sequentially in a short period of time (around 15 minutes per channel, including the setup time for each channel) and the other one is to perform long term monitoring for about 3 hours. For the short term PMD test, at least 20 valid data points were taken for each channel and the polarization from TCA source was periodically rotated by 45 degrees every 90 seconds to avoid invalid data points. The average value and its standard deviation of each channel are shown in Fig. 9a. The average PMD over all 16 wavelength channels is 18.57 ps, sufficiently close to the expected value of 19.77 ps. The corresponding error is 6%. The average of more wavelength channels should give even better accuracy. It should be noted that the possible impact of the in-service measurement on the live traffic was monitored very closely with NOC. The measurements triggered no minor or major alarms, thereby demonstrating that in-service PMD measurement methods may safely be applied to traffic-carrying networks.

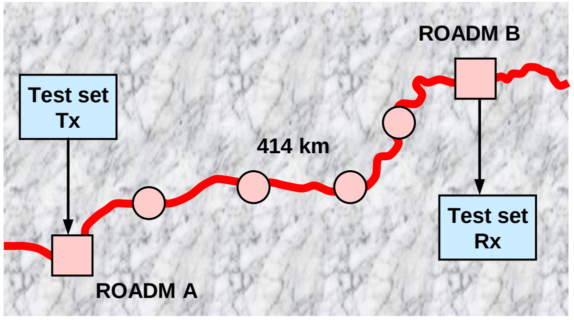

Fig. 8. Field fiber route for the PMD measurement trial.

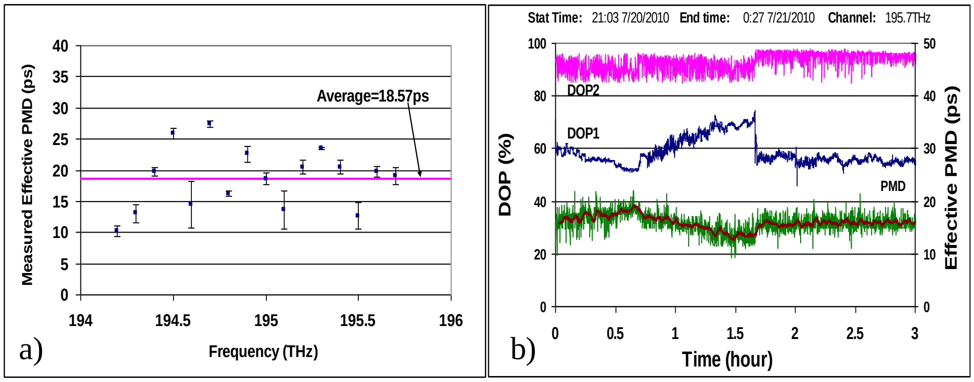

Fig. 9. Field trial results. a) PMD measured over 16 DWDM empty channels. b) PMD monitoring over time of a single channel. DOP1 is the DOP measured before PMD compensator and DOP2 is the DOP after PMD compensator. The PMD in a real system is much more stable than that in a test bed.

We used a DWDM channel at 195.7 THz for long term monitoring experiment and the results are shown in Fig. 9b. Compared with the test at 1500-km test bed, the PMD value is much more stable with time for the selected DWDM channel, especially after 11:00 PM at night. It is likely because the fiber is buried underground. In order to obtain the statistical average PMD of the fiber route, much longer monitoring time (on the order of 10 days) may be required.

6. Conclusion

In summary, we describe a novel method of using PMD compensation to obtain the PMD value of a fiber DWDM channel of an in-service multiple mixed fiber optic network. The method is simple, fast and does not require a tunable or wide bandwidth light source. There is absolutely no impact to the live long-haul and ultra-long-haul traffic to service provider. Only 2 seconds are required to make a measurement. Either a channelized ASE source with a bandwidth around 0.2 nm or a 40Gbps signal itself of any modulation format can be used as the signal source to the PMD monitoring. We successfully demonstrated the method in Verizon’s 1500-km ultra-long haul test bed in Richardson, Texas and in a field trial in a 414-km revenue-generating fiber route using both channel (wavelength) averaging and time averaging methods. The differences between our measured average PMD values and expected PMD values are less than 6% for the cases tested. We anticipate that the method is accurate for a link with an average PMD of 5 ps or more.

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This method can be used 1) for accurately measuring the cascaded PMD of all active and passive components and mixed fiber sections in a fiber route, including EDFAs, multiplexers, demultiplexers, ROADMs, optical fibers; 2) for obtaining the instantaneous effective PMD of each DWDM channel, without requiring a large bandwidth scanning and without interrupting in-service 40G or 100Gbps traffic. The PMD obtained reflects the effective PMD for the particular modulation format used and can be used to determine whether PMD compensation is required for the channel; 3) for obtaining the average PMD of the whole fiber link by long term monitoring a single DWDM channel and gaining knowledge about the PMD degradation of a fiber route. 4) We can also use under or over compensation to reflect the impact on the BER for a specific channel with any type of modulation.

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