Estimation and Localization of DGD Distributed Over Multi-Span Optical Link by Correlation Template Method

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Abstract: We propose a longitudinal DGD monitoring technique based on correlation template method at Rx-DSP. Estimation and localization of distributed DGD profile over 12×75 km-long SSMF span link are experimentally demonstrated with errors below 1 ps. © 2024 The Author(s)

1. Introduction

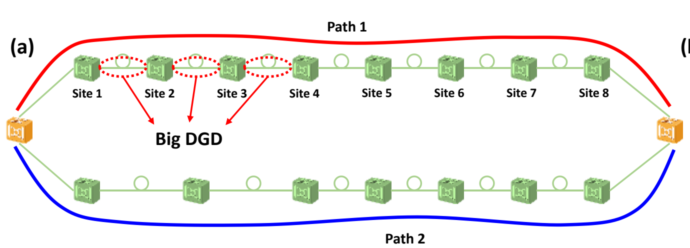
Optical performance monitoring is a crucial task for maintaining reliable transmission quality in optical transmission links and for swift recovering from link faults. Modern meshed optical networks comprising numerous devices, components, and fiber spans are evolving toward agile, disaggregated, and open networks, amplifying the importance of performance monitoring. The monitoring parameters may include the signal power, chromatic dispersion (CD), optical-signal-to-noise ratio (OSNR), polarization-dependent loss (PDL), and differential group delay (DGD). Fig. 1(a) shows a schematic illustration of the physical link topology of a deployed network. The two paths in the network consist with bidirectional aerial optical cables (OPGW, optical ground wire). While we operating this network, a big DGD detected in one direction of the path 1. Since there is no effective method yet to monitor the local DGD, a span-by-span testing only reveals a significant DGD across three spans in the middle of path as shown in Fig. 1(b). This example not only indicates the need of monitoring DGD but also highlights the potential value of longitudinal DGD monitoring (i.e., local DGD) in localizing potential sources of failure or performance degradation.

Recently, the digital longitudinal monitoring technique has seen various applications such as the power profile estimation (PPE), fiber type identification, loss anomaly detection, amplifier gain profile estimation, PDL monitoring, and MPI localization [1]. These applications all utilize the Kerr effect-induced nonlinear distortion at Rx, which contains information about local signal waveforms. Similarly, the local DGD is embedded within the received waveforms as a form of nonlinear distortion, allowing for retrieval at Rx DSP. In this paper, we propose and experimentally demonstrate a longitudinal DGD monitoring method, and the results show that the local DGD can be accurately monitored across the entire link with errors less than 1 ps.

2. Principle of correlation-template method for longitudinal DGD monitoring

Digital longitudinal monitoring relies on the uniqueness of local waveforms generated as a result of dispersion, and consequently, the unique Kerr nonlinear distortion that is imprinted on the signal waveform as a part of noise. Fig. 2 shows the experimental setup and block diagram of the proposed DGD monitoring based on the correlation template method [2]. We may assume the linear waveform at Tx ($z = 0$) is $E_{\mathrm{Lin}}(0,t) = E_{\mathrm{Lin},x}(0,t) + E_{\mathrm{Lin},y}(0,t) = \sqrt{P_x(0)}u_x(0,t) + \sqrt{P_y(0)}u_y(0,t)$, where $P_i(z)$ is the signal power at location z, $u_i(z,t)$ is the normalized signal waveform at location z and time t, and subscripts i can be x or y, indicating two orthogonal polarizations of the propagating signal. In the enhanced regular perturbation (eRP) model, the accumulated nonlinear noise at Rx ($z = L$) is $E_{\mathrm{NL}}(L,t) \equiv \int_0^L \gamma P(z)\Delta u_z(L,t)dz$, where γ is the nonlinear coefficient. The partial nonlinear distortion can be written as [3],

$$\Delta u_z(L,t) \equiv -j\widehat{D}_{z,L}\widehat{N}_{\mathrm{eRP}}\widehat{D}_{0,z}E_{\mathrm{Lin}}(0,t), \tag{1}$$



(b)

Monitoring Path	Distance (km)	Loss (dB)		DGD (ps)	
		Forward	Backward	Forward	Backward
Site 1 ↔ Site 2	45.145	17.4	15.4	≈50	2
Site 2 ↔ Site 3	62.783	21.4	20.9	≈40	3
Site 3 ↔ Site 4	44.011	21.7	15	≈40	2
Site 4 ↔ Site 5	40.322	16.7	16.5	5	3
Site 5 ↔ Site 6	87.956	24	24.4	7	1
Site 6 ↔ Site 7	102.0	26.7	26.1	8	3
Site 7 ↔ Site 8	71.402	21.1	21.4	3	2

Fig. 1: (a) Physical link topology of an optical network (b) Test data of the network

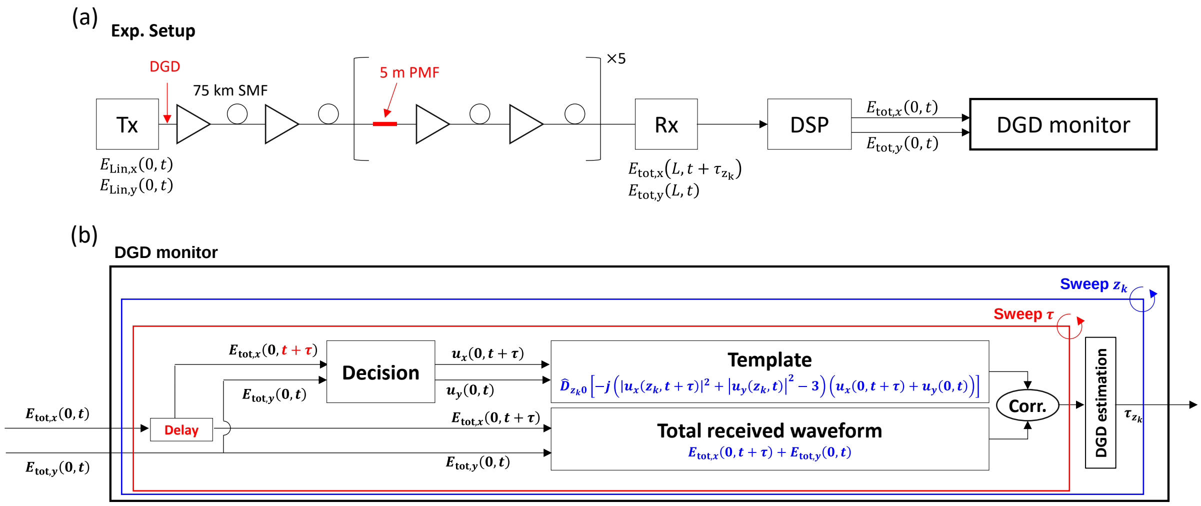


Fig. 2: (a) Experimental setup (b) Algorithm for longitudinal DGD monitoring

where $\widehat{D}_{z_1,z_2}$ is the CD operator corresponding to the distance from z_1 to z_2, $\widehat{N}_{\mathrm{eRP}} \equiv (|\cdot|^2 - 1.5\langle|\cdot|^2\rangle)(\cdot)$ is the nonlinear operator based on eRP model for dual-polarization (DP), and $\langle\cdot\rangle$ is the time average. Thus, the total waveform at Rx can be written as $E_{\mathrm{tot}}(L,t) = E_{\mathrm{Lin}}(L,t) + E_{\mathrm{NL}}(L,t)$. Assuming a local DGD ($\tau_{z_k}$) at the location z_k, the nonlinear distortion generated from the location is $\Delta u_{z_k}(L,t,\tau_{z_k}) \equiv -j\widehat{D}_{z,L}\widehat{N}_{\mathrm{eRP}}\left(\sqrt{P_x(z_k)}u_x(z_k,t+\tau_{z_k}) + \sqrt{P_y(z_k)}u_y(z_k,t)\right)$. At Rx, the received signal is recovered by standard DSP (including DGD compensation) and then fed into the DGD monitor as shown in Fig 2(a). Since the correlation template generated from the DGD-compensated signal does not represent the true local nonlinear distortion, its correlation between the received waveform is reduced. However, in the DGD monitor, an artificial time delay which mimics the local DGD can be added into the input signals to generate correlation templates using Eq. (1) as,

$$\Delta u_{z_k}(L,t,\tau) \equiv -j\widehat{D}_{z,L}\widehat{N}_{\mathrm{eRP}}\widehat{D}_{0,z}\left(u_x(0,\ t+\tau) + u_y(0,t)\right), \tag{2}$$

where τ is the time delay applied while generating the correlation template. The location z_k, for example, has the maximum correlation when the time delay exactly matches with the local DGD, $\tau = \tau_{z_k}$, and the correlation drops when τ mismatches with respect to the τ_{z_k}. By scanning τ at a fixed location z_k, the local DGD (i.e., τ_{z_k}) can be obtained by taking the value where the correlation is maximized. Repeating this procedure along the link yields the longitudinal DGD profile.

3. Experimental demonstration of longitudinal DGD monitoring

To demonstrate the longitudinal DGD monitoring method, we used a commercial transceiver linecard supporting a 68-Gbaud DP-QPSK signal. As shown in Fig 2(a), the signal, along with 20 neighboring WDM channels, was transmitted over a dispersion-uncompensated 12-span link consisting of 75-km long SMFs. We set the span launch power to be ~ 5 dBm. Additional DGD was introduced at Tx by adjusting its polarization skew and/or by inserting 5-m long polarization maintaining fibers (PMFs) to the input of every 2 spans. Each PM fiber could generate the maximum DGD of ~8 ps depending on the input state of polarization (SOP). After transmission, the received signal was detected and sampled by 96-Gsa/s ADCs and then digitally processed. The demodulated signals for two polarizations, $E_{\mathrm{tot},x}(0,t)$ and $E_{\mathrm{tot},y}(0,t)$ were used for the DGD monitor as shown in Fig. 2.

We first added an artificial time delay, τ, to one of the input signals, and then utilized the symbols after decision to generate the normalized signal waveforms at Tx, $u_x(0,t+\tau)$ and $u_y(0,t)$. To estimate the local DGD at a specific location z_k, we generated a correlation template for the location by using Eq. (2) and calculated the correlation with the regenerated total signal waveform $E_{\mathrm{tot}}(0,t,\tau) = E_{\mathrm{tot},x}(0,t+\tau) + E_{\mathrm{tot},y}(0,t)$. By scanning τ, the local DGD, τ_{z_k}, was obtained by selecting τ that maximized the correlation. Fig. 3(a) shows correlation curves as a function of τ

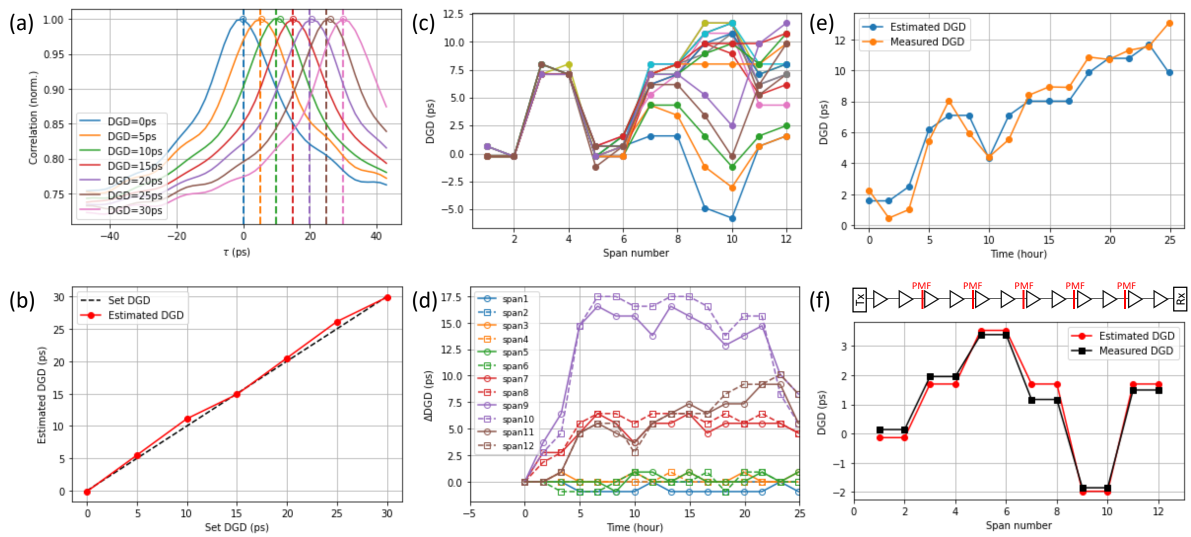


Fig. 3: (a) Correlation curves by scanning time delay for location $z = 0$ (b) Estimated DGD values at $z = 0$ (c) Longitudinal DGD profile monitored at each span input for 12 span link (d) Local DGD evolution by time at each span (e) Comparison between estimated DGD (at Rx) and measured DGD by Rx-DSP (f) Comparison between estimated DGD profile and measured DGD profile by Rx-DSP

at $z = 0$ where the initial DGD was added by adjusting Tx skew. Vertical dashed lines indicate the Tx skew values, showing a good alignment with the peaks of each correlation curves. Fig. 3(b) shows the estimated DGD as a function of Tx skew (i.e., local DGD at Tx). This exemplifies that accurate estimation of the local DGD can be achieved by evaluating τ at each correlation peak.

For longitudinal DGD profile estimation, we captured the waveforms in the presence of PMFs and repeatedly performed the local DGD estimation for each span input location. It should be noted that the DGDs originating from PMFs are determined randomly depending on the input SOP to the fiber. The results are shown in Fig. 3(c). The measurements were taken for 25-hours and the different colors in Fig. 3(c) represent the averaged DGD profiles measured at different times. The initial 6 spans showed a consistent DGD over time, while the latter 6 spans exhibited instability, suggesting more SOP changes occurring after the 6th span. The DGD profiles are replotted in Fig. 3(d) in order to show the local DGD evolution by time. As the PMFs were inserted every 2 spans, the patterns of local DGD evolution were clustered by 2 adjacent spans separated by PMFs. This observation implies the proposed method is monitoring the local DGD. In addition, we compared the estimated DGD at the end of link with the value measured by using W-coefficients at Rx-DSP [4], as depicted in Fig. 3(e). Although they showed a strong agreement, it is important to note that this comparison only relates to the accumulated DGD at Rx. Thus, we performed Rx-DSP-based measurement by sequentially disconnecting each span to obtain the local DGD at the input of each span. In this separate measurement, we kept the total measurement time short to minimize the DGD drift resulting from SOP changes during the measurement period. The measured DGD profile is presented in Fig. 3(f) with the DGD profile estimated by our proposed method. The estimated DGD profile is well matched with the measured DGD, showing errors less than 1 ps.

4. Conclusion

We have proposed and experimentally demonstrated a longitudinal DGD monitoring based on correlation template method. By generating a correlation template with an artificial time delay, the local DGD can be estimated by observing the correlation changes with respect to the artificial time delay. The method accurately estimates local DGD with errors below 1 ps for the range from 0 to 30 ps. In addition, a local DGD profiles along the link is obtained. It is worth to note that the application of this technique is not limited to DGD induced by polarization mode dispersion, but it is also applicable to differential modal group delay induced by different group velocities of multiple spatial modes propagating a multimode fiber in a spatial division multiplexing link.

5. References

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