Monitoring of polarization-based effects in fiber-optic transmission link caused by environmental variations

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ABSTRACT

The fast transmission of signals around the globe is fundamental to the flow of information for our society. A long-haul transmission certainly represents one of the key advancements that shaped modern ways of communicating and offers a nearly instant access to any available data or a latest information. However, fiber-optic transmission typically suffers from a variety of physical impairments that degrade the signal quality, thus imposing limits on both, the achievable transmission capacity and data reach. Of particular concerns are stochastic fiber impairments, primarily represented by polarization mode dispersion (PMD). The PMD originates from a random birefringence caused by imperfect fiber circularity and other, both internal and external, effects, basically completely re-defining the light polarization state of output signal compared to its initial counterpart. The PMD is particularly critical as it restricts operation of fiber-optic links running at speeds higher than 10 Gbps. This, in turn, hinders fiber link re-adaption towards higher transmission bit rates in future, however. In this context, both in-line link monitoring and testing of PMD-based effects is of great importance within the recently used optical fiber links. However, polarization-based effects are also very sensitive to the environmental changes, substantially degrading transmitted optical signals and reducing link quality. In this work, we provide experimental characterization for PMD-based propagation effects in optical fibers influenced by wind gusts. The investigation was performed on commercially used fiber-optic link that runs through optical power ground wire cables. The 111-km-long optical link under study comprised installed optical fibers with available 88 channels. Here, we monitored environmental changes caused by wind conditions over several consecutive days with a 60 second time frame and sensed PMD impact on the link performance. Here, differential group delay (DGD) was chosen to be a key parameter, enabling for sensitive characterization of wind-related link changes. Measured maximum DGD's were 4 and 10 ps for wind speeds up to 5 and 20 m/s, respectively. In addition, experimentally measured data were used in numerical model to assess the optical link quality. For a low wind condition, we observed negligible quality degradation in the optical link, considering transmission bit rates of 10, 40, and 100 Gbps. Conversely, in case of strong wind condition, the optical link maintained a reliable operation only for established 10 Gbps, while significant link degradation was observed for bit rates of 40 and 100 Gbps. Our work shows promising way to effectively sense and monitor undesired environmental variations and their impact on polarization-based fiber link propagation effects, which in turn, can allow an instant link quality evaluation.

Keywords: Optical communications, optical fiber, polarization mode dispersion, high-speed transmission systems, environmental variations, sensing and monitoring, wind gusts, wind speed

1. INTRODUCTION

Optical communication systems have proven unique for many applications. They demonstrated a great development over the last few decades. In recent days, transmission systems relying on optical fibers attack data capacities over 1 Pbps,[1] showing a large potential for rising applications as diverse as data centers, access networks, or long-haul transmission systems.[2–4]

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Besides the success of fiber-optic transmission networks, optical fibers are greatly exploited for sensing and monitoring.[5,6] Optical fibers found their place in roads, railways, or power lines, amongst other, to prevent issues associated with weight or thermal overload.[6,7] In these applications, sensing of particular physical quantity is harnessed, including parameters such as temperature, strain, or even random external variations. The latter can include impact of rain, sun, snow, or wind. For fiber-optic sensing and monitoring, mono-mode and multi-mode fibers can be utilized.[6,8] However, optical fibers that support propagation of many modes are not preferred for optical links. The light propagating through such a fiber experiences deleterious intra- and inter-modal interference, which degrades the quality of transmitted optical signal. Nowadays, mono- and multi-mode optical fibers have comparable price, and thus mono-mode optical fibers can be easily deployed into the transmission link, even in short distances. Moreover, mono-mode fibers can be used as effective in-line link sensors or in-built transmission monitors, yet obviating the modal dispersion problems of multi-mode optical fibers.

Mono-mode optical fibers suffer from different degradation mechanisms that seriously affect the transmitted optical signal. This mainly includes linear effects of chromatic dispersion or fiber losses, Kerr-based nonlinearities, or even impairments with stochastic nature.[9] The latter is well represented by the polarization mode dispersion (PMD). Typically, the PMD effect on optical signals is marginal for transmission systems running at speeds lower than 10 Gbps. The PMD originates from a random optical birefringence. This birefringence is caused by imperfect fiber circularity and/or additional changes induced by temperature, vibrations, bending or twisting. This random nature changes local birefringence axes, and thus re-defining the light polarization state at the fiber output compared to its input state. As a result, the PMD causes an undesired time delay in the propagating optical signal. Physically, inside the fiber, optical signal splits into two parts that propagate with different group velocities. At the end of propagation path, there is an time delay. Such a time delay leads to temporal pulse broadening that limits the bandwidth of the transmission system, and thus the maximum system speed.[10,11] Direct measurements of PMD parameters in fiber-optic links is challenging due internal and external factors. On the other hand, it is of paramount importance for transmission links with mono-mode fibers to characterize PMD parameters (and their statistical behavior), particularly in situations, where environmental-induced changes play a crucial role.[12–15] In this work, we provided measurements of PMD within optical fibers that are impacted by such environmental changes – particularly we studied the effect of wind gusts. More specifically, we reported on how the wind gust (wind variations) impairs polarization characteristics of commercially employed optical fibers installed within optical power wire cables. PMD measurements are then linked with numerical calculations for high-speed signal transmission using eye diagram inspection.

The manuscript is organized as follows. After an introductory provided in *Section 1*, basic PMD description is given in *Section 2*. *Section 3* details information about our numerical approach as well as numerical evaluation methods that are in use. In *Section 4*, we describe an experimental set-up and testing details, while in *Section 5*, we present experimental as well as numerical results. Finally, conclusions are drawn in *Section 6*.

2. FUNDAMENTALS OF POLARIZATION MODE DISPERSION

The internal optical fiber birefringence stems from the non-ideal fiber manufacturing, including effects of core ellipticity, bending, twisting, or material impurities and inhomogeneities.[16] As a result, these stochastic imperfections cause residual local stress between the fiber core and fiber cladding. Higher stress induces larger fiber birefringence, alongside with changes in thermal and mechanical properties. The latter ones make fiber birefringence highly sensitive to a range of external parameters such as temperature, stress and strain. Consequently, fiber polarization properties are affected too through the changes in a propagation between two orthogonally polarized fiber modes. The propagation of orthogonal modes within an optical fiber is schematically shown in Figure 1. As a result, induced time changes are characterized by differential group delay (DGD) and a principal state of polarization (PSP). In turn, modulated optical signals transmitted via optical fiber is affected by the PMD with a strong stochastic nature.

In practical situations, internal and external factors affect the fiber birefringence, and thus impact the PMD. For a most part, internal factors are associated to manufacturing imperfections. The control of manufacturing imperfections is governed by the quality of the fabrication process, post-fabrication treatment, or fiber positioning within large optical cables.[17] In opposition, external factors such as environmental conditions, mechanical stresses, or fiber/cable aging are much more important for digital transmission links operated with typical mono-mode fibers.[12–15] External factors may have a larger effect on PMD characteristics and may greatly impair the performance of fiber-optic link. The impact of environmental changes is being critical for transmission links working at bit rates higher than 10 Gbps.[11] However, the control of external factors is typically difficult to handle. From this reason, there is a strong requirement to exploit techniques that enable a reliable fiber link monitoring. In turn, this step is also coupled with an effective evaluation of the link quality, especially for high-speed signal transmission.

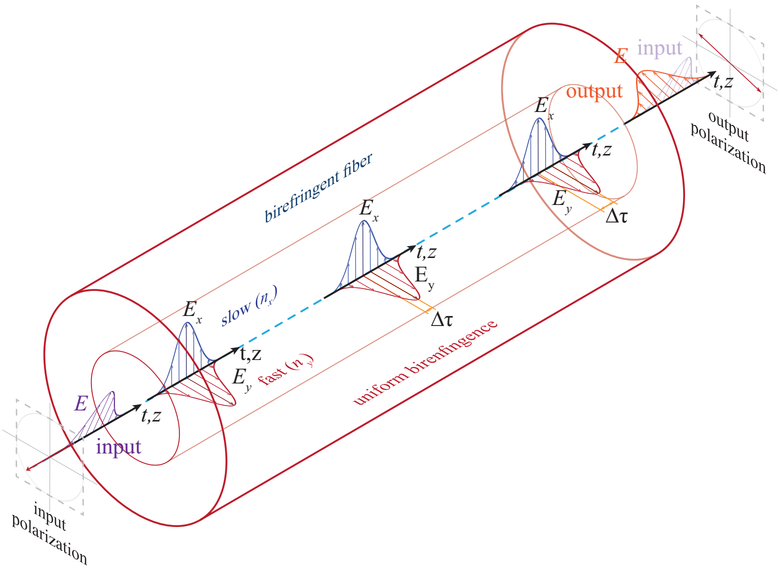

Figure 1. Schematics of the propagation of two orthogonal polarized modes inside an optical fiber.

3. MODELING OF POLARIZATION MODE DISPERSION

Parameters that fully describe light polarization state and PMD are PSP and DGD, respectively. Regular optical fibers are designed to transmit signals over long distances. In this situation, the birefringence distribution is considered as homogeneous,[18] while fibers used for sensing and monitoring showed inhomogeneous distribution of the fiber birefringence.[19] PSP and DGD, coupled with the initial state of polarization (SOP), create a basis to analyze polarization-induced fluctuations in mono-mode optical fibers.[20] We exploit these facts and developed an in-house numerical model to evaluate the impact of PMD on transmitted optical signals. The numerical model considers that the optical fiber is fully described as a sequence of short segments. These small fiber blocks (compared to the overall fiber length) have different characteristics of the birefringence. Thus, for a reliable simulation model, it is crucial to ensure that a sufficient number of individual fiber segments with randomly changed birefringence are taken into the account. Details of the model are described in Ref.,[21] while inputs for the model are purely experimental. The experimental set-up and PMD measurements will be discussed further in *Section 4*.

The signal quality can be assessed by different techniques. here, the signal quality is characterized numerically using eye diagrams. For this, optical non-return-to-zero (NRZ) signal and on-off-keying (OOK) modulation was used. Then, the link quality assessment is done using the eye opening penalty (EOP). At this point, only the impact of pure PMD on high-speed optical signals is considered. For that analysis, the numerical model neglects various noise characteristics of both transmitter and receiver. The signal degradation due to the PMD is represented by EOP. The EOP is defined as follows:[22]

$$EOP = -10 \log EO \; [\mathrm{dB}] \tag{1}$$

and EO as

$$EO = s_{1,\mathrm{min}} - s_{0,\mathrm{max}} \tag{2}$$

where $s_{1,min}$ and $s_{0,max}$ are the minimum value of ”1” bit and maximum value of ”0” bit, respectively and EO is the eye opening. The 2 dB penalty is considered to maintain a reliable signal transmission in the fiber-optic system.[23]

4. EXPERIMENTAL MEASUREMENT SET-UP

PMD measurements were carried out on optical power ground wire cables that are used for a commercial transmission. The optical link consists of cables with mono-mode optical fibers.[24] The total link length was 111 km. 9 km of the optical link is installed in the ground. The rest of the transmission link comprises optical cables that hang in the air. The schematic of the fiber-optic link under study is shown in Figure 2(a), while Fig. 2(b) shows the experimental set-up. The measurement set-up has a PMD analyzer and a fiber-optic link itself. Experimental tests are based on the conventions arising from Jones matrix analysis.[25] PMD measurements were performed on 88 wavelengths across the whole C-band (from 1528.97 nm to 1563 nm). Spectral channels have standard 50 GHz separation[26] used in dense wavelength division multiplexing (DWDM) systems. PMD measurements occurred in optical link operated by Energotel, a.s. Žilina in Slovakia during 12 days, from 15 - 26 February, 2020. The total number of measurements was 15 000 having an data collection rate of 60 seconds. Further details for the measurements can be found elsewhere.[21]

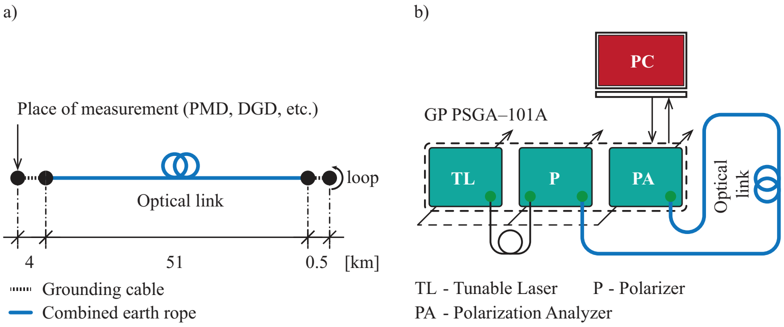

Figure 2. (a) Schematics of the optical link under test. (b) Experimental set-up for PMD measurements.

Experimental work of PMD measurement was performed using afore-described fiber-optic link. The optical link under study was located close to hydrometeorological station, enabling us to retrieve imminent environmental conditions (wind speed and temperature). The local weather conditions during days of measurements are shown in Figure 3. Weather information shown in Figure 3 were modeled via ALADIN simulator provided by Slovak Hydrometeorological Institute.

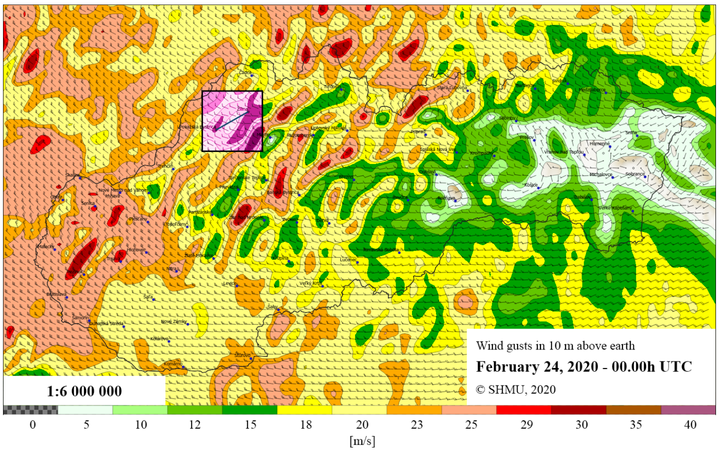

Figure 3. Wind situation in the country. A day of strong wind conditions (February 24, 2020) with a wind speed up to 20 m/s. Squared box highlights the area, where optical cables own by Energotel, a.s. are situated.

5. RESULTS

Figures 4 shows DGD evolution versus 88 spectral channels and time intervals of testing. Results shown in Figure 4 relate to the weather condition depicted in Figure 3. The yellow color in DGD colormap expresses the highest levels of measured DGD. By analyzing the measured data,[21] we showed that for strong wind conditions (with a wind speed up to 20 m/s), the experimental data resemble a conventional Maxwell-Boltzmann distribution. Under such weather conditions, the average

DGD has a peak at 1.3 ps and a maximum of DGD was 10 ps. This shows that there is a strong relation between the measured weather conditions (strong wind gusts for a wind speed of 20 m/s) and measured values of DGD.

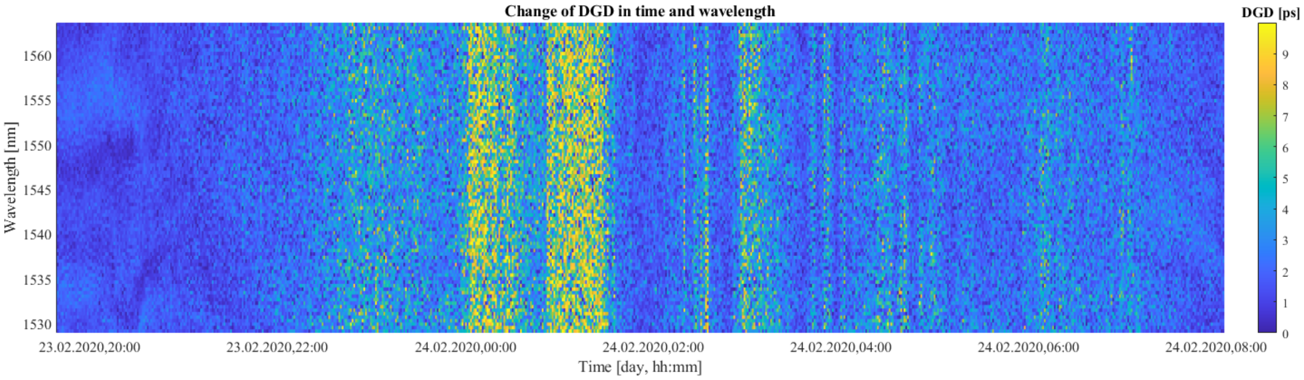

Figure 4. Colormap of the measured DGD versus 88 wavelengths across the C-band and selected time test slots (wind speed up to 20 m/s).

In turn, this suggests that there is a high correlation between the actual wind situation and measured values of DGD. This correlation is shown in Figure 5, comparing the DGD values and a wind speed evolution both as a function of measurement time. We can observed a very good agreement between both evolutions.

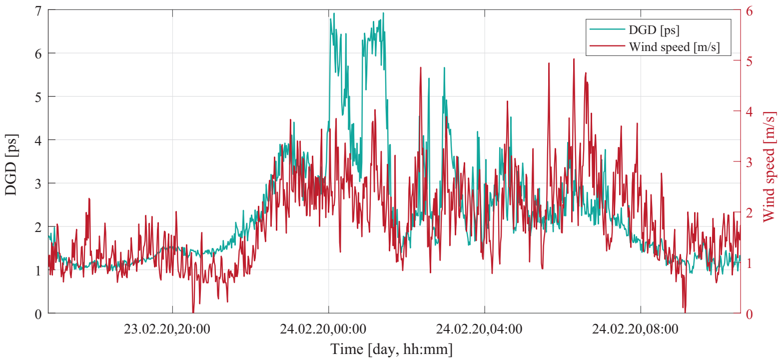

Figure 5. Measured changes in DGD and wind speed as a function of the measurement time.

The effect of stochastic PMD on high-speed optical signals was further numerically investigated using eye diagrams. Figure 6 show eye diagram evolution of OOK modulated NRZ signal for different transmission bit rates. Figure 6(a) shows a nominal eye diagram as a reference for a conventional communication rate of 10 Gbps. In this case, eye diagram has a maximum eye opening. Figures 6(b) to 6(h) show wind-impaired eye diagrams of optical signals with different transmission bit rates of 10, 20, 40, 50, 60, 80 and 100 Gbps. For this, following set of measured polarization parameters was used (DGD = 9.493 ps and PSP = $[-0.182, 0.497, 0.849]$). The chosen parameters correspond to the strong wind conditions, with a wind speed of about 20 m/s. As predicted by numerical analysis, eye diagrams stay open for bit rates of 10 Gbps and 20 Gbps, respectively. In opposition, for higher bit rates, especially those beyond 40 Gbps, calculated eye diagrams start to close. This eye closure may indicate a higher probability of errors for the transmitted optical signals.

Furthermore, the EOP was also calculated for measured polarization parameters in both time and wavelength. Figure 7 shows an average EOP in case of a strong wind condition versus a measurement time. Transmission bit rates under study remain the same. Under these conditions, we may observe a significant signal degradation, reaching three orders of magnitude compared to the reference or weak wind conditions.[21] According to our calculations, strong wind, and thus higher the impact of PMD, becomes particularly critical for bit rates above 40 Gbps. These results suggest that the fiber-optic link quality is reduced, which may affect the overall link operation. In the worst scenarios, this may yield an unreliable transmission of optical signals.

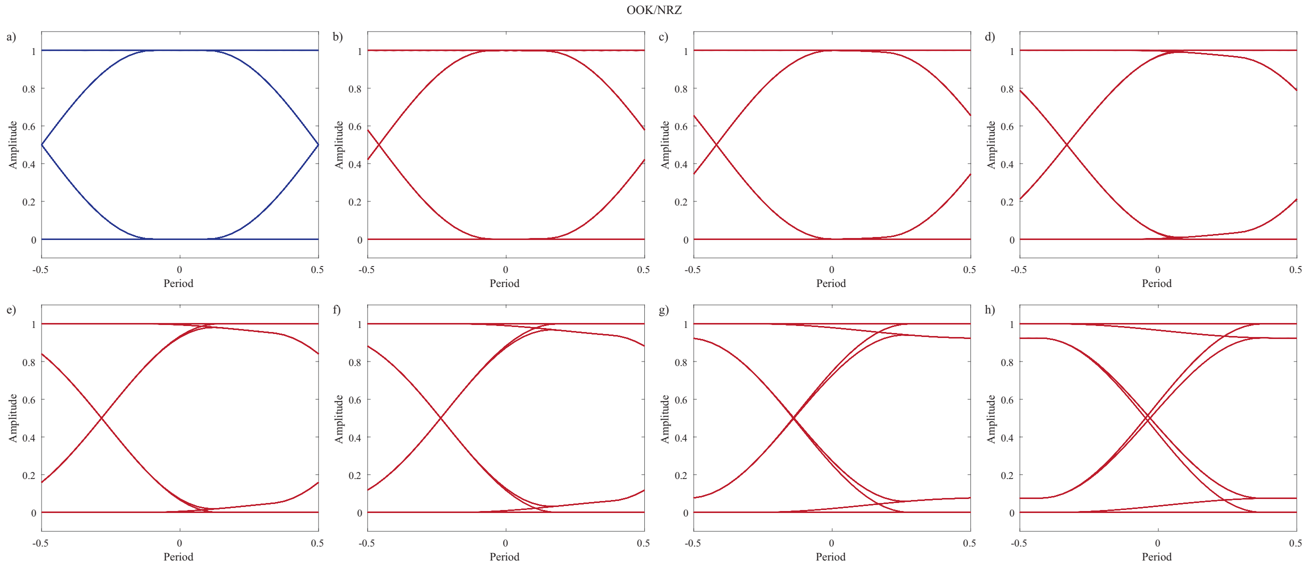

Figure 6. Eye diagrams impaired by PMD under strong wind conditions (wind speed up to 20 m/s) for different transmission bit rates. (a) Nominal eye aperture at a conventional communication bit rate of, with a zero PMD. Wind-impaired eye apertures for transmission bit rates: (b) 10 Gbps; (c) 20 Gbps; (d) 40 Gbps; (e) 50 Gbps; (f) 60 Gbps; (g) 80 Gbps; and (h) 100 Gbps. Optical signal degradation was calculated using measured parameters: DGD = 9.493 ps and PSP = [−0.182, 0.497, 0.849].

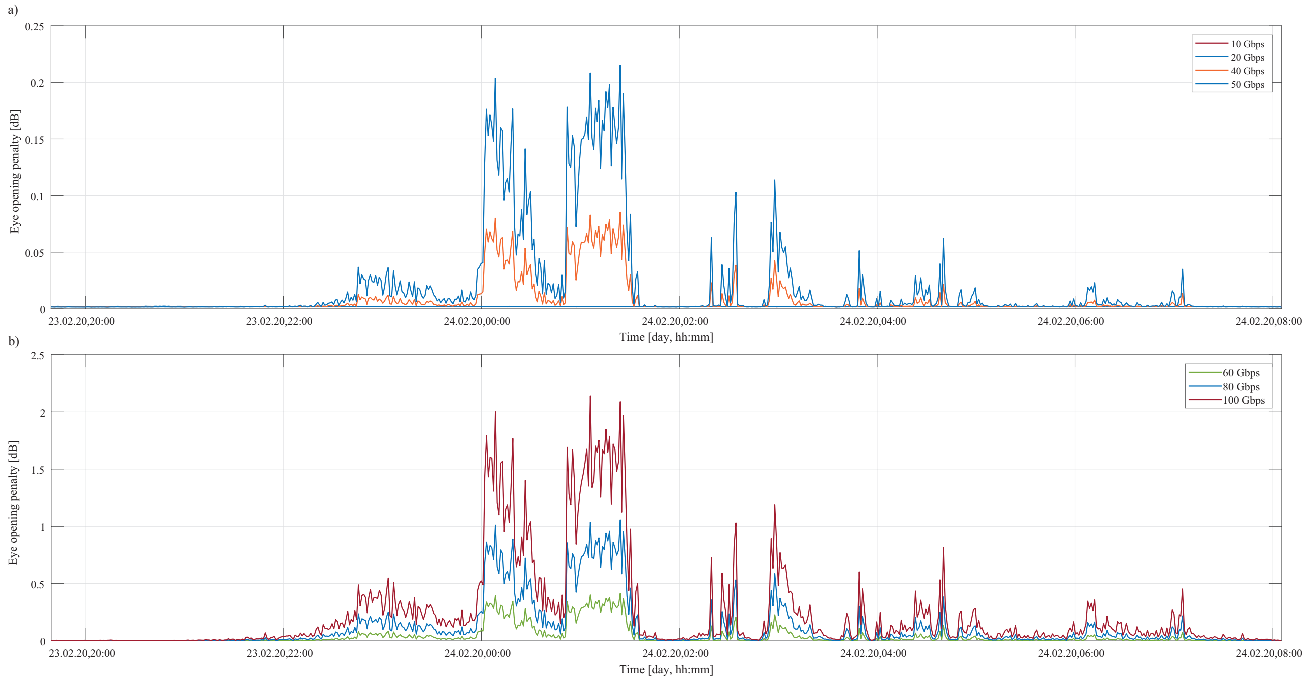

Figure 7. Estimated eye opening penalty versus measurement time under strong wind conditions (wind speed up to 20 m/s) for transmission bit rates of: (a) 10, 20, 40, and 50 Gbps; (b) 60, 80, and 100 Gbps.

6. CONCLUSION

Our work provided an insight to experimental characterization for PMD-based effects in optical fibers that are influenced by wind gusts. Optical fiber under study were installed in commercial fiber-optic link made out of optical power line wire cables. The investigation was performed under different weather conditions on 111-km-long fiber link with 88 spectral channels located across the C-band wavelengths. DGD parameter enabled sensitive characterization of wind-related link changes. Maximum DGD's of 10 ps were measured under strong wind conditions, corresponding to a wind speed of about

20 m/s. Measured data were used in the numerical model to assess the optical link quality. We showed that for strong wind condition, the link transmission become substantially degraded for transmission bit rates higher than 40 Gbps. Our results show good prospects for effective monitoring of environmental variations caused by polarization effects in the fiber-optic link. This can potentially allow an instant link monitoring and sub-sequent quality evaluation.

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REFERENCES

[1] Miyamoto, Y. and Kawamura, R., "Space division multiplexing optical transmission technology to support the evolution of high-capacity optical transport networks," *NTT Technical Review* **15**, 7 (June 2017).

[2] "Cisco Annual Internet Report - Cisco Annual Internet Report (2018–2023) White Paper."

[3] Agalliu, R. and Lucki, M., "Transmission Transparency and Potential Convergence of Optical Network Solutions at the Physical Layer for Bit Rates from 2.5 Gbps to 256 Gbps," *Advances in Electrical and Electronic Engineering* **15**, 877 – 884 (Jan. 2018).

[4] Latal, J., Koudelka, P., Siska, P., Vitasek, J., and Vasinek, V., "WDM-PON network simulation with different implementation of optical amplifier in the line," 919318 (Sept. 2014).

[5] Ferreira, M. F. S., Castro-Camus, E., Ottaway, D. J., López-Higuera, J. M., Feng, X., Jin, W., Jeong, Y., Picqué, N., Tong, L., Reinhard, B. M., Pellegrino, P. M., Méndez, A., Diem, M., Vollmer, F., and Quan, Q., "Roadmap on optical sensors," *Journal of Optics* **19**, 083001 (Aug. 2017).

[6] Haus, J., [*Optical sensors: basics and applications*], Wiley-VCH, Weinheim (2010).

[7] Yin, S., Ruffin, P. B., and Yu, F. T. S., eds., [*Fiber optic sensors*], no. 132 in Optical science and engineering, CRC Press, Boca Raton, FL, 2nd ed ed. (2008).

[8] Apriyanto, H., Ravet, G., Bernal, O. D., Cattoen, M., Seat, H. C., Chavagnac, V., Surre, F., and Sharp, J. H., "Comprehensive Modeling of Multimode Fiber Sensors for Refractive Index Measurement and Experimental Validation," *Scientific Reports* **8**, 5912 (Dec. 2018).

[9] Agrawal, G. P., [*Nonlinear fiber optics*], Elsevier/Academic Press, Amsterdam, fifth edition ed. (2013).

[10] Glesk, I., Seyedzadeh, S., Dubovan, J., Dado, M., and Kwong, W. C., "Investigation of 2D-WH/TS OCDMA System Performance under the Influence of PMD," in [*2020 22nd International Conference on Transparent Optical Networks (ICTON)*], 1–4, IEEE, Bari, Italy (July 2020).

[11] Antoniades, N. N., ed., [*WDM Systems and networks: modeling, simulation, design, and engineering*], Optical networks, Springer, New York (2012).

[12] Bohata, J., Zvanovec, S., and Pisarik, M., "Outdoor atmospheric influence on polarization mode dispersion in optical cables," in [*2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)*], 1–4, IEEE, Beijing, China (Aug. 2014).

[13] Waddy, D., Ping Lu, Liang Chen, and Xiaoyi Bao, "Fast state of polarization changes in aerial fiber under different climatic conditions," *IEEE Photonics Technology Letters* **13**, 1035–1037 (Sept. 2001).

[14] Nellen, P., Bronnimann, R., Held, M., and Sennhauser, U., "Long-Term Monitoring of Polarization-Mode Dispersion of Aerial Optical Cables With Respect to Line Availability," *Journal of Lightwave Technology* **22**, 1848–1855 (Aug. 2004).

[15] Bohata, J., Jaros, J., Pisarik, S., Zvanovec, S., and Komanec, M., "Long-Term Polarization Mode Dispersion Evolution and Accelerated Aging in Old Optical Cables," *IEEE Photonics Technology Letters* **29**, 519–522 (Mar. 2017).

[16] Thévenaz, L. and Berghmans, F., eds., [*Advanced fiber optics: concepts and technology*], Engineering sciences Electrical engineering, EPFL Pr. [u.a.], Lausanne (2011). OCLC: 723495811.

[17] "As telecom demands grow, optical fibers will need to level up."

[18] Wuilpart, M., Megret, P., Blondel, M., Rogers, A. J., and Defosse, Y., "Measurement of the spatial distribution of birefringence in optical fibers," *IEEE Photonics Technology Letters* **13**(8), 836–838 (2001).

[19] Dong, Y., Teng, L., Zhang, H., Jiang, T., and Zhou, D., "Characterization of Distributed Birefringence in Optical Fibers," in [*Handbook of Optical Fibers*], Peng, G.-D., ed., 1–31, Springer, Singapore (2018).

[20] Eyal, A., Dimenstein, O., Tur, M., Zaidman, M., Green, A., and Gali, S., "Polarization mode dispersion in radio-frequency interferometric embedded fiber-optic sensors," *Journal of Lightwave Technology* **19**, 504–511 (Apr. 2001).

[21] Dubovan, J., Litvik, J., Benedikovic, D., Mullerova, J., Glesk, I., Veselovsky, A., and Dado, M., "Impact of wind gust on high-speed characteristics of polarization mode dispersion in optical power ground wire cables," *Sensors* **20**(24) (2020).

[22] Downie, J. D., "Relationship of Q penalty to eye-closure penalty for NRZ and RZ signals with signal-dependent noise," *Journal of Lightwave Technology* **23**(6), 2031–2038 (2005).

[23] Bulow, H., Dubovan, J., and Herschel, R., "Outage Dynamics of 40Gb/s Optical Paths Routed over PMD-Impaired Fiber Links," in [*OFC/NFOEC 2008 - 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*], 1–3 (2008).

[24] "ITU-T G.652, ITU-T Recommendation database."

[25] Heffner, B. L., "Automated measurement of polarization mode dispersion using Jones matrix eigenanalysis," *IEEE Photonics Technology Letters* **4**(9), 1066–1069 (1992).

[26] "ITU-T G.694.1, ITU-T Recommendation database."