J., & Dado, M. (2022). High-speed operation of fiber-optic link impaired by wind gusts. In F. Jakab (Ed.), 2021 19th IEEE International Conference on Emerging eLearnin

High-Speed Operation of Fiber-Optic Link Impaired by Wind Gusts

Jozef Dubovan*, Jan Litvik*, Radovan Korček*, Daniel Benedikovič*, Andrej Veselovský**, Ivan Glesk***, Jarmila Müllerová****, and Milan Dado*

*University of Žilina, Faculty of Electrical Engineering and Information Technology, Department of Multimedia and Information-Communication Technologies, 01026 Žilina, Slovakia

**Energotel, a.s., 82108 Bratislava, Slovakia

*** Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G11XQ, United Kingdom

**** University of Žilina, Faculty of Electrical Engineering and Information Technology, Institute of Aurel Stodola, 03101 Liptovský Mikuláš, Slovakia

e-mail addresses: jozef.dubovan@uniza.sk; jan.litvik@uniza.sk; daniel.benedikovic@uniza.sk; radovan.korcek@uniza.sk; veselovsky.andrej@energotel.sk; ivan.glesk@strath.ac.uk; jarmila.mullerova@uniza.sk; and milan.dado@uniza.sk

Abstract— **The fast signal transmission is critical long-haul communication systems. They represent the key advancements, shaping information-communication technologies. Fiber-optic transmission suffers from many degradation effects, and of particular concern are stochastic fiber impairments represented by polarization mode dispersion (PMD). The PMD is critical as it limits link operation at data rates higher than 10 Gbps. In this work, we report on experimental measurements and theoretical analysis characterization for PMD-based propagation effects in optical fibers influenced by wind gusts. The study was performed on fiber-optic link that runs through 111-km-long optical power ground wire cables. Measured maximum of DGD was up to 10 ps for a wind speed of 20 m/s. This wind condition, the optical link maintained a reliable operation only for established 10 Gbps, while considerable link degradation was seen for data rates of between 40 and 100 Gbps.**

I. Introduction

Fiber-optic transmission links evolved rapidly in the last decades, and now they offering information-communication capacities that exceed 1 Pbps over single-mode optical fibers. Fiber-optics links are not only used in long-distance systems, but they are also appealing for metro and access network topologies [1-3].

Besides optical communications, optical fibers are widely utilized in sensing and monitoring. The main areas are in high-way roads, bridges, railways, or power cable lines, among others. In this case, such systems use photonic sensing of target physical quantities. This typically encompasses for temperature, stress strain, or random environmental variations such as rain, sun, snow, or wind. For these scenarios, both single-mode and multi-mode optical fibers can be employed. Single-mode optical fibers are usually preferred compared to multi-mode counterparts due to adverse inter-modal interference between many fiber modes. Indeed, single-mode optical fibers can be used at the same time as high-capacity transmission links as well as effective in-line sensors or in-built monitors, without the additional complexities for installation and operation [4-6].

Single-mode fibers suffer from many degradation effects that deteriorate the quality of transmitted optical signals. This includes deterministic (attenuation, chromatic dispersion, and Kerr's effects) and stochastic (polarization mode dispersion (PMD)) mechanisms that govern signal degradation. The PMD effect is critical due to its stochastic nature. The PMD mechanism becomes prevalent degradation factor for transmission systems operating at transmission bit rate that are higher than 10 Gbps. The PMD originates from random birefringence and is induced by non-optimal fiber circularity, additional vibrations, temperature variations, or even bending and twisting. This intrinsic randomness re-arranges the light polarization state of optical signals at the output, and thus it is different compared to the input state. As a direct result, the PMD effect generates a certain time delay, yielding to a time-domain spreading of propagating modulated optical pulses. This means that a single optical pulse splits into two orthogonally polarized states (in respect to the cross-sectional x and y axes), and thus these two parts of the same optical signal travel across the fiber with various group velocities. In turn, this results in a considerable temporal overlap between optical signals, which then restricts the bandwidth of the optical transmission system as well as it limits the transmission speeds, at which the optical communication system can reliably operate or it prevents future capacity scaling. From a optical system/network point of view, the maximum time delay that can be tolerated is typically only a 10% of the transmission bit length. It is worth to mentioned that the length of the transmission bit is an inverse function of the transmission bit rate, considering the conventional on-off keying modulation technique. From this, it becomes apparent that optical transmission systems that operate at high bit rates are substantially more affected by PMD [6-10].

Direct evaluation of polarization-based effect, and this their parameters, in the fiber-optics links is a non-trivial task. Experimental characterization and measurements are not easy to carry out, because both internal and external aspects factors need to be considered. On the other hand, it is a rather useful step to properly quantify the PMD parameters (and its stochastic nature) in the fiber-optic transmission links. This is particularly critical in situations, where external environmental changes are dominant, but they are very difficult and challenging to control [11-13]. At this stage, it is necessary to noting that there are many opportunities to reduce the impact or to get rid of the detrimental influence of PMD in respect on ultra-fast optical systems and networks by utilizing a variety of modern optical or oven opto-electrical PMD compensation schemes [14-15].

In this work, we perfomed an experimental measurements of PMD in single-mode optical fibers that are impacted by environmental variations — in this study, by the wind gusts. More specifically, we showed how the wind gust influences the polarization characteristics of commercial optical fibers that are built inside power wire cables and we linked this influence directly to high-speed signal transmissions using in-house simulations and eye diagram evaluation [16].

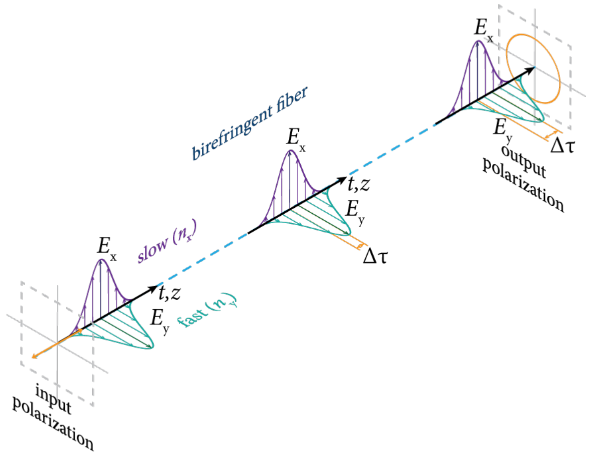

Figure 1. Propagation of two orthogonally polarized fiber modes within an optical fiber.

II. PMD FUNDAMENTALS: THEORY AND MODELLING

A. Theoretical background of PMD

The PMD originates from fiber birefringence as a results of fiber manufacturing imperfections, including degraded core ellipticity, bending, twisting, and material impurities/inhomogeneities. On an optical signal level, modulated optical pulse undergoes changes in a pulse propagation time for two orthogonally polarized modes (along two principal fiber axes; x and y, respectively). These two orthogonal modes propagets via optical fiber, but both with different group velocities. The propagation of two orthogonally polarized modes, yet of the same optical input signal, in the optical fiber is illustrated in Fig. 1. This effect then yields time changes in the arrived pulse, and thus time-domain spreading. From a signal-to-system level perspective, these time changes are standardly evaluated through differential group delay (DGD) and a principal state of polarization (PSP). In scenarios, when optical signal is transmitted through the optical fiber, this effect leads to the PMD - a stochastic fiber-channel impairment with a random nature [17,8].

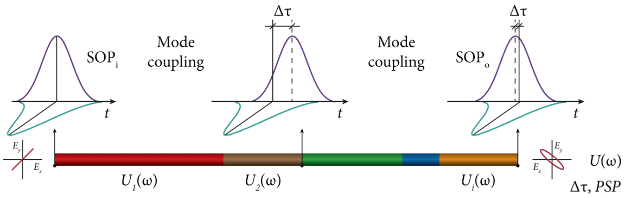

Figure 2. Illustration of PMD modeling

Both internal and external factors can affect the fiber birefringence. This way, both aspect can significantly contribute and enhance the detrimental effect of PMD. Internal factors are coupled with errors in the fabrication process, including manufacturing quality or post-manufacturing treatment and maintenance. In contrast, external aspects, especially environmental variations or weather conditions (rain, wind gust, snow, heat, or temperature variations), stress and pressures, and fiber aging, are much more critical for optical transmission links built upon standard single-mode optical fibers. These factors can have a drastic effect on the PMD properties, and thus on the performance of transmission systems. Their impact is more evident for fiber links operating at data rates of 10 Gbps and higher [16]. On the other side, however, the control or elimination of external factors is not easy. Then, there exists a strong need to elaborate on test techniques for these stochastic changes and to assess their impact on the high-speed signal transmission [17,18].

B. PMD numerical modeling

Two parameters that describe polarization state and PMD are PSP and DGD, respectively. For conventional optical fibers used in optical transmissions over long distances, the distribution of fiber birefringence is typically homogeneous [19], while in scenarios, where optical fibers are used as sensors, this distribution is inhomogeneous [20]. Then, parameters such as PSP and DGD, coupled with the input polarization state (SOP), create a model to quantitatively describe polarization-induced fluctuations in optical fibers. According to this, we built up a numerical model as shown in Fig. 2. In this model, optical fiber is described as a sequence of short segments. Individual fiber pieces have different characteristics of the birefringence. The details of the numerical model and corresponding mathematics are described in Ref. [16].

C. PMD treoretical evaluation

The signal quality is evaluated via eye diagram and then via eye opening, which is defined as follows:

$$EO = s_{1,\min} - s_{0,\max}. \quad (1)$$

Here $s_{1,\min}$ and $s_{0,\max}$ are the minimum for "1" bit and the maximum for "0" bit. The eye opening penalty (EOP) or eye closure is then used to determine optical link quality. We mention here that the inputs for numerical model come fully from the experimental dataset.

$$EOP = -10\log(EO)\ \text{[dB]}. \quad (2)$$

The normalized eye openings are functions of DGD and PSP and they range from 0 to 1. The 2 dB penalty is then used as a figure-of-merit that yield reliable operation of optical transmission system [21,22].

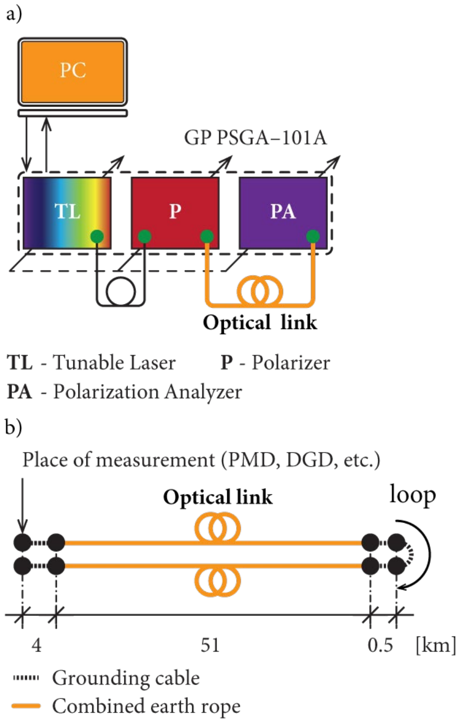

Figure 3. (a) Measured fiber-optic link, (b) experimental set-up.

III. PMD Experimental Set-Up

Experiments were realized using optical power ground wire cables within an existing communication traffic. Such optical cables have single-mode fibers according based on ITU-T G.652 recommendation. The fiber-optic link, shown in Fig. 3(a), was 111 km long, with a 4 km and 0.5 km long cable path installed in the ground for the beginning and ending of the link, respectively. Thus, 92% of the studied fiber link is positioned in the air, which is dominant part of the fiber-optic link.

The test set-up for measurements is shown in Fig. 3(b). The set-up has PMD analyzer and measured optical link. PMD measurements were performed on 88 wavelengths (transmission link channels). This corresponds to a C-band spectral range between 1528.97 nm and 1563 nm. The fiber link spectral channels have 50 GHz standard spacing, following standards for dense wavelength division multiplexing (DWDM) optical transmission systems.

Experimental testing was realized using fiber lines of Energotel, a.s. Žilina. Time duration for tests was 12 days, from 15 to 26 February 2020, in particular. Overal number of performed tests was 15,000, with a collection rate of 60 seconds. As a result, the following optical fiber parameters were retrieved from the experiments: time of measurement, differential group delay (DGD), second order differential group delay (SODGD), principal state of polarization (PSP), polarization dependence loss (PDL).

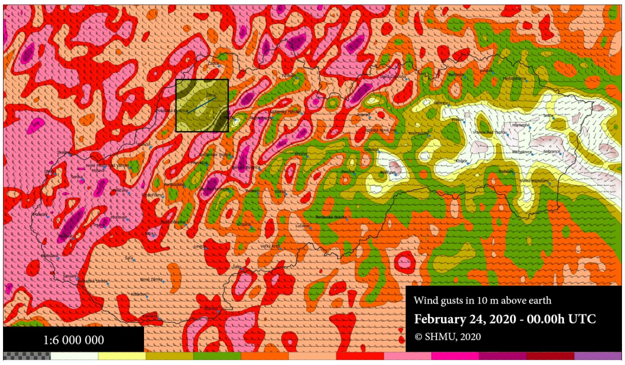

Figure 4. Weather map, depicting strong wind conditions.

For this work, DGD and PSP values are only considered as both parameters form the basis for PMD analysis as well as are directly includes in the model.

IV. Results and Discussion

The optical link under test was situated close to located in a close to the hydrometeorological station, where the environmental conditions were measured. The data for particular weather condition are shown in Fig. 4. These data were retrieved using model provided by Slovak Hydrometeorological Institute. In particular, Fig. 4 depicts weather situation on 24 February 2020. Corresponding wind speed was up to 20 m/s.

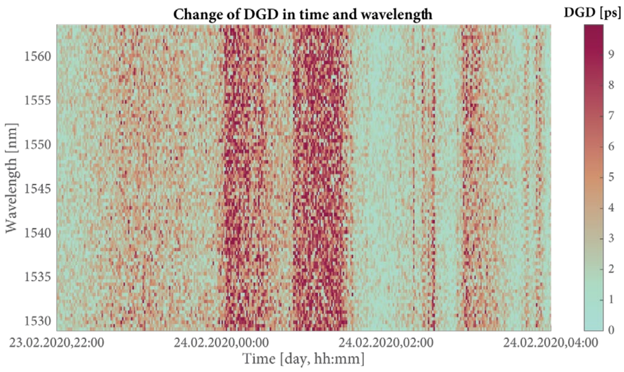

Figure 5. DGD maps versus testing time and spectral channels.

Figures 5 shows measurements of the DGD versus 88 transmission link channels and specific time intervals for the test. Measured values of DGD relate to the weather condition shown in Fig. 4. The highest variations in the DGD were seen on 24 February 2020, from 00.00 to 02.00 a.m. This dataset contains 88,000 values of DGD in total.

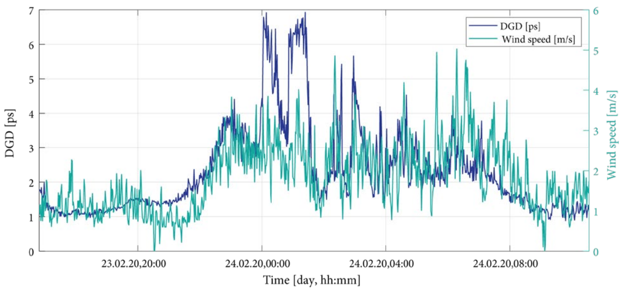

Figure 6. Measured changes in DGD and wind speed versus test time..

By statistical treatment of the data for measured DGD values, as performed in Ref. [16], we can show that during the strong wind condition, the measured data follow a Maxwell-Boltzmann distribution. Under these weather conditions, the average DGD reached a peak value at 1.3 ps and a measured maximum of DGD was ~10 ps. This demonstrates that there is a strong relation between the actual weather conditions (strong wind gusts for a wind speed of 20 m/s) and measured values of DGD. On the other hand, no apparent statistical correlation was found between the weather condition and measured DGD data during a low wind gusts (corresponding to a wind speed of about 5 m/s).

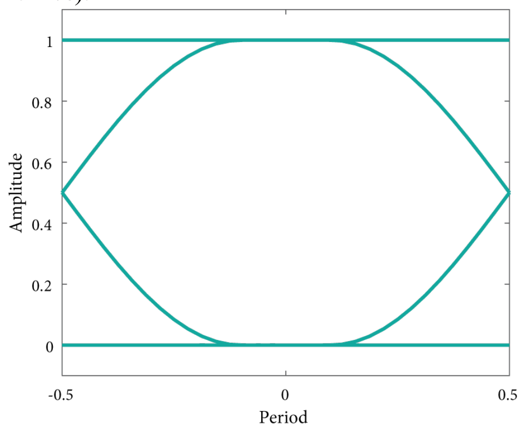

Figure 7. Calculated 10 Gbps eye diagram without the PMD.

The impact of measured PMD on high-speed-modulated optical signals was assessed by using eye diagram inspection. Figure 7 depicts a nominal eye diagram, i.e. an numerically retrieved eye diagram without a PMD impact included. This ideal eye diagram was obtained for an optimal (non-distorted) input optical signal, having a NRZ link format, OOK modulation scheme, and a reference transmission bit rate of 10 Gbps. Moreover, as a reference for the sub-sequent numerical analysis, the nominal eye diagram has a maximal eye opening. Figures 8 and 9 depicts numerically retrieved eye diagrams that are impaired by strong wind gusts. This corresponds to a weather condition with a wind speed of 20 m/s. The eye diagrams of optical signals were obtained for different transmission bit rates: 10, 20, and 40 Gbps for Fig. 8 and 50, 60, 80, and 100 Gbps for Fig. 9.

In the numerical analysis, following values of experimentally measured DGD and PSP were considered: DGD = 9.493 ps and PSP = -0.182, 0.497, 0.849. According to our simulation results, numerical analysis predicts that re-constructed eye diagrams stay open for transmission bit rates of 10 and 20 Gbps (see Figs. 8(a) and 8(b)). On the other hand, for increased transmission bit rates, our numerical model based on experimental data predicts the fact calculated eye diagrams start to have a eye closure . This effect and these trends are obvious at transmission bit rates of 40 Gbps (see Fig. 8(c)) and higher (see Figs. 9(a) to (d)). The fact that eye diagrams start having a eye closure clearly suggests that there can be a higher probability of errors for the transmitted information data. This, in turn, can potentially results in an unreliable operation of the fiber-optic transmission link.

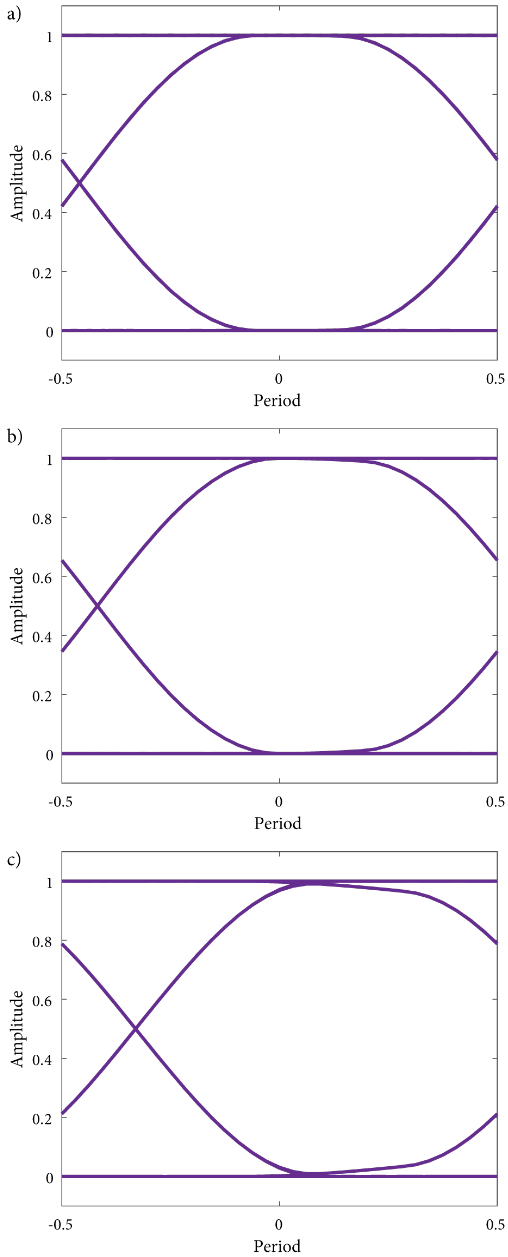

Figure 8. Calculated eye diagrams with the PMD effect included. (a) 10 Gbps; (b) 20 Gbps; and (c) 40 Gbps data rate.

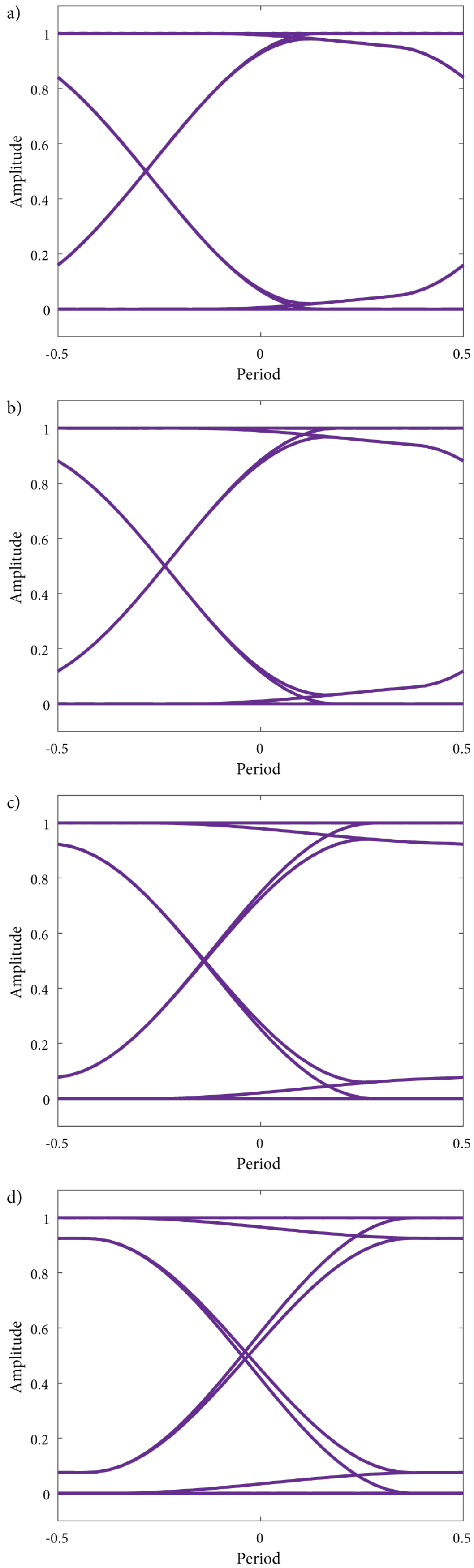

Figure 9. Calculated eye diagrams with the PMD effect included. (a) 50 Gbps; (b) 60 Gbps; (c) 80 Gbps, and (d) 100 Gbps data rate.

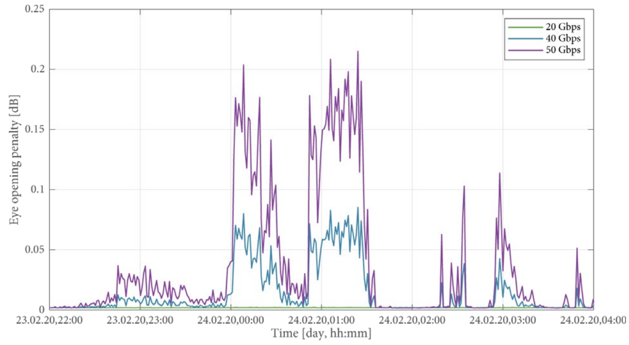

Figure 10. Calculated EOP versus test time under strong wind conditions for data rates of 20, 40, and 50 Gbps.

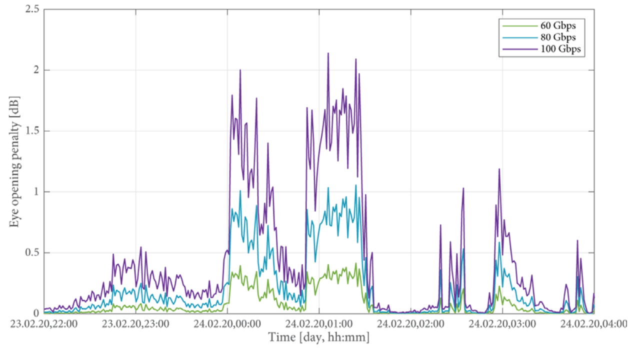

Figure 11. Calculated EOP versus test time under strong wind conditions for data rates of 20, 40, and 50 Gbps.

Last, but not least, the EOP was determined from the numerical analysis and the measured experimental data, i.e. for polarization parameters measured in both time and wavelength.. more specifically, Figures 10 and 11 show an average value for EOP. this was calculated in case of a strong wind condition only as a function of a time. EOP depicted in Figs. 10 and 11 were estimated for transmission bit rates of 20, 40, 50, 60, 80, and 100 Gbps. Taking into the consideration these circumstances, we can see a considerable degradation of the optical signal quality. To be more specific, we can observe that EOP is higher of about three orders of magnitude compared to the 20 Gbps data rate signal, for which the signal degradation was estimated to be marginal, and thus negligible. According to our numerical calculations, strong wind gusts, and thus larger impact of PMD on transmitted optical signals, becomes crucial for considered transmission bit rates that are higher than 40 Gbps. These results indicate that the quality of the fiber-optic transmission link will be lower, and thus link operation will be affected more drastically. which may affect the overall link operation. In the worst scenarios, this may yield an unreliable transmission of optical signals.

V. CONCLUSIONS

In summary, this work offered an experimental and theoretical look for PMD-related degradation mechanisms in optical fibers. These fibers are affected by wind gusts. Optical fiber transmission link under this investigation were installed as a part of commercially used system composed of optical power line wire cables. The experimental and theoretical study was realized under particular weather conditions on 111-km-long fiber link that has 88 wavelength channels positioned in the C-band communication window. DGD parameter enabled characterization of wind-related link changes with a good sensitivity. Maximum DGD's of about 10 ps were experimentally measured under strong wind conditions (wind speed of about 20 m/s). We then used measured data in the model to evaluate the optical link quality via eye diagram inspection and eye opening penalty. We demonstrated that for strong wind condition, the optical transmission through the link was significantly degraded for transmission bit rates that were higher than 40 Gbps. Obtained results can be used for effective monitoring of the fiber link that is affected by external factors such as environmental changes.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the projects "APVV-17-0631 CONSENS: Co-existence of photonics sensor systems and networks in the framework of internet of things" and "PP-COVID-20-0100: DOLORES.AI: The pandemic guard system".

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