Local Wind Impact Sensing using State of Polarization Measurement on a Live Short-Haul Aerial Fibre Cable

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Abstract: A short aerial cable spun on a high-voltage line is used to monitor wind-induced stress on the cable infrastructure. Span-by-span localized early warnings may be issued based on the state of polarization transients.

1. Introduction

Optical fibre networks have high penetration in transport, metro, and fibre-to-the-home (FTTH) networks, facilitating the establishment of high-density sensor networks. Sensing applications include security and availability aspects revealing physical activity along a fibre route, like excavation close to buried cables, trawling near sub-sea cables, and extreme weather conditions that may impact aerial cables. If early warnings of extreme impacts can be issued based on monitoring data, potential damage and subsequent network outages may be avoided. Fibre sensing may also be important for sensing climate and geophysical parameters, such as earthquakes and tsunamis. This opens up new service offerings and business opportunities for network operators, capitalizing on existing infrastructure.

Monitoring fibre cables has been demonstrated using both distributed acoustic sensing (DAS) and state-of-polarization (SOP) sensing. DAS enables spatial resolution and very high sensitivity but is limited to approximately 150 km distance [1] and involves a costly interrogator. On the other hand, monitoring vibrations using SOP sensing integrates events along the entire fibre length without spatial information. Hence, the number of sources impacting SOP along the cable path increases with the length of the fibre, increasing the complexity of differentiating events. SOP sensing can be achieved using low-cost methods matching the requirements of the telecom industry. This includes extracting information from coherent transceivers in long-haul transport and metro networks [2], and a simplified Polarization Beam Splitter (PBS) based low-cost implementation with high integration potential [3]. A comparison between full Stokes-parameter measurement and PBS-based measurement demonstrated that the low-cost PBS measurements were only slightly less sensitive to SOP variations compared to full polarization-state characterization [4,5].

Several studies have confirmed the expected strong SOP fluctuations, due to temperature, wind, electric current and lightning in aerial fibres [6-10] showing how fluctuations can have a considerable impact on the communication system performance. The low-frequency SOP variations are strongly correlated to the average wind speed, while the 50/60 Hz component is strongly correlated with the electrical current in the power transmission line (high-voltage (HV) line). Therefore, more recent research has focused on using SOP monitoring for sensing and monitoring link health. Notably, Mazur et.al. [11,12] demonstrated that SOP monitoring on a 524 km long aerial link is sufficient for monitoring link health, as well as for wind and/or current sensing. All these studies are based on the use of link lengths of several 10s of kilometres or more, thus providing very limited information on the localizations of the perturbations.

Monitoring SOP on short aerial link lengths on the order of a few kilometres enables local information on wind impacts and link health, but this has not been investigated. Furthermore, the use of the strong 50/60 Hz Faraday effect-induced polarization rotation signal for sensing the impact of wind on aerial links has not yet been explored. This strong single-tone signal will vary with the SOP fluctuations induced by other temporal variations, thus carrying information on these effects.

In this paper, we propose using a short aerial cable spun on an HV line for SOP sensing the local average wind speed and wind gusts by utilizing both baseband detection and detection of the resulting amplitude and phase modulation of the 50 Hz signal from the main frequency. The aerial cable is a 1.5 km section of a 6 km long fibre path carrying live 10 Gb/s data. The results show that SOP sensing in short aerial cables is sufficiently sensitive to provide information on local wind impact. Furthermore, we demonstrate that using the 50 Hz Faraday-induced signal for sensing can possibly improve low-frequency sensitivity by reducing the effects of 1/f noise and drift in the receiver electronics, and the data highlights the usefulness of the spectral components around 50 Hz.

2. Methodology and Field Test Setup

The 6 km cable path includes a 4.5 km buried section (500 m alongside a railway line and 4 km along a road) and a 1.5 km section spun around an HV air AC powerline. In the node room, the signal goes through 20 km of Dispersion

Compensating Fiber (DCF) before a copy of the signal is dropped to the SOP monitor using a Reconfigurable Optical Add Drop Multiplexer (ROADM) network element as shown in Figure 1.

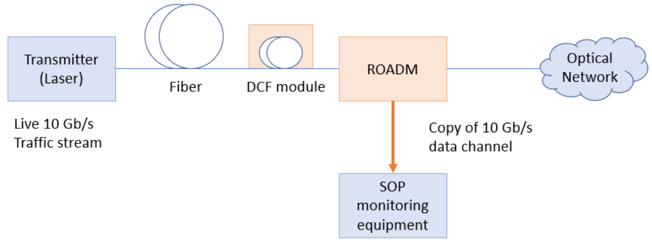

Fig. 1. Schematic of the field test setup of the SOP monitoring.

The PBS-based SOP monitor outputs two signals (V_1 and V_2) corresponding to the power variation in the two orthogonal polarization components. A measure of the polarization variations is derived from the difference-signal, V_1-V_2, corresponding to variations in the Stokes parameter S_1. The difference-signal is also proportional to the optical power fluctuations. The power fluctuations are derived from the sum-signal, V_1+V_2, corresponding to variations in the Stokes parameter S_0. The receiver sensitivity for SOP variations is increased through AC-coupling the signals, suppressing the DC component with a 1st-order high-pass filter with cut-off frequency of approximately 10 Hz.

3. Results

To investigate the SOP signal correlation with the wind we selected two days (December 8th (Day 1) and December 14th (Day 2), 2022) with significantly different wind characteristics according to data from the Norwegian Meteorological Institute. Figure 2a shows the wind on Day 1 stayed under 3 m/s till 19:00, then increased steadily to 6 m/s approaching midnight. The time-frequency analysis of the SOP variation shows the SOP variations increase with wind speed. Figure 2b shows the time-frequency analysis of the SOP variation and wind speed during Day 2. The wind speed trend is opposite of that of Day 1, and the SOP variation shows strong signals in the early hours, while gradually dropping towards the end of the day. The strong SOP variations, especially around 0.5 Hz, 2 Hz, and 14 Hz, are likely due to wind-induced slow oscillations of the cable as also found on longer cables in Wuttke et.al. [8].

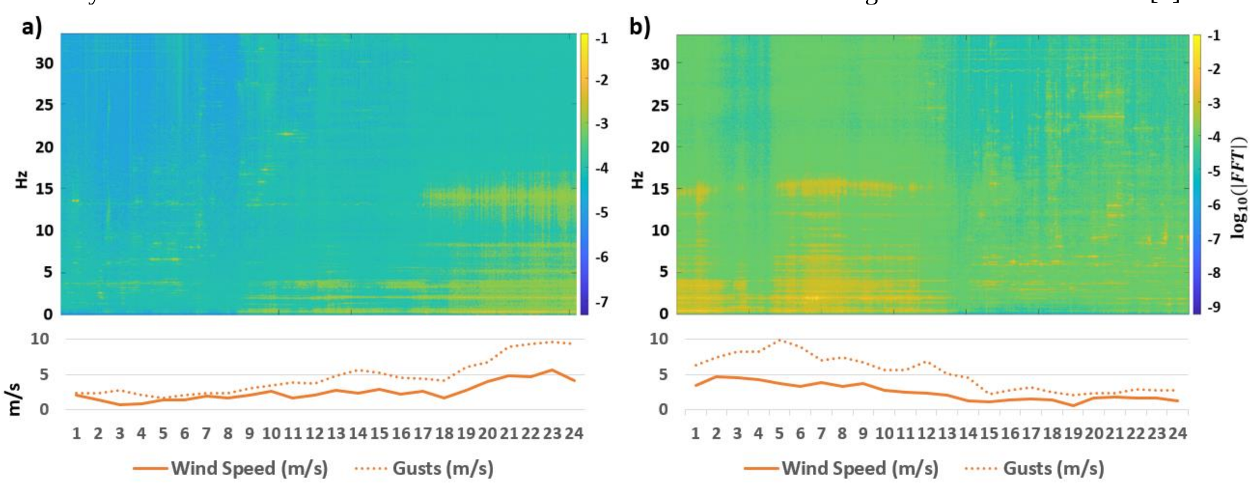

Fig. 2. SOP time-frequency plot below 35 Hz and wind speed (average speed and gusts) for a) Day 1 and for b) Day 2. Note that the receiver has a 1st order high-pass frequency characteristic with a 10 Hz cut-off frequency.

The upper panel in Figure 3 shows the power spectral density (PSD) analysis in the 0.1 – 1000 Hz frequency band for three different times of Day 1. Detailed PSDs around 50 Hz (± 5Hz) are shown in the lower panel. At 00:00 the wind is weak and with almost no measurable SOP signal below 5 Hz, while the current on the HV line results in a significant component at 50 Hz. The sidebands at 50±0.1Hz and 50±4 Hz indicate the presence of slow oscillations on the HV line. At 09:00 the wind starts to increase resulting in an SOP signal in the low-frequency band, especially around 0.5 Hz, 2 Hz, and 14 Hz as also seen in the time-frequency plot above. The increased 50 Hz signal is due to the increased daytime energy delivered over the HV line. At 23:59 we have high, gusty, wind resulting in increased SOP signal over a wide frequency range, most noticeable up to 20 Hz. The 50 Hz signal is now deceased, due to the reduced nighttime energy delivered over the HV line, but exhibits well-defined sidebands around 0.5 Hz, 1.5 Hz, 2 Hz and 4 Hz corresponding to wind-induced oscillations of the HV line. The broad wings of the 50 Hz lines, most noticeable at

00:00 and 9:00 are partially due to the relative stability of the receiver clock (Raspberry Pi here) wrt. to the 50 Hz mains frequency. This could be removed by slaving the receiver clock to the 50 Hz mains frequency.

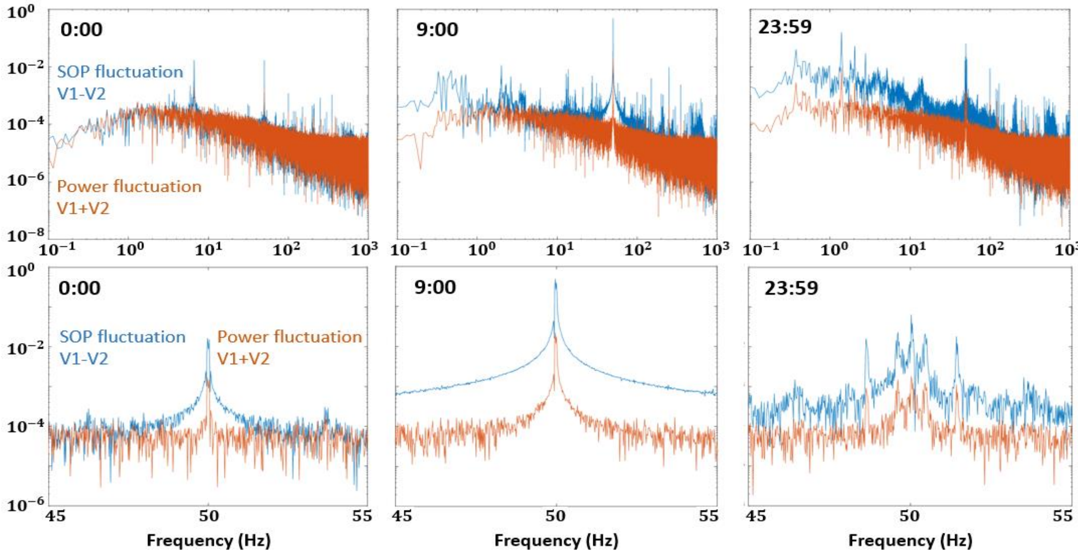

Fig. 3. PSD of the SOP fluctuations (blue traces) and of the power fluctuations (red traces) at times a) 00:00, b) 09:00, and c) 23:59 on Day 1. The PSD is computed from a one-minute time series. The 50 Hz component in the sum signal is due to a 12 % unbalance in the receiver not accounted for in the signal analysis. Note that the receiver has a 1st order high-pass frequency characteristic with a 10 Hz cut-off frequency.

4. Conclusions

Early warnings of severe wind-related stress on aerial cables can significantly mitigate the risk of power and network disruptions, as well as infrastructure damage. The ability to pinpoint the location of such an event may be crucial but challenging when using SOP sensing. However, the low-cost span-by-span SOP sensing method demonstrated in this study offers a promising solution for enabling local fibre-stress information in metro and local area networks. Notably, even on the short 1.5 km fibre path, the 50 Hz frequency signal, generated by the magnetic field on the HV line, remains dominant. However, as wind speed increases, low-frequency signal components become significant, and their amplitudes provide information about the wind's impact on the cable's integrity. The amplitude of the 50 Hz frequency component provides data on the electrical power delivered over the HV cable, while the high-resolution power spectral density around 50 Hz carries information about the wind impact on the cable.

In conclusion, our proposal entails the implementation of SOP monitoring for local network cable spans, combined with the application of threshold detection on frequency components that arise during windy conditions. This approach enables the timely issuance of early warning messages to preempt potential damage to both power and telecommunications infrastructure.

5. Acknowledgements

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6. References

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