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Proactive Sensing of Environmental Events through Optical Data Networks: a Path to Intelligent Resilience

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Abstract *Fiber sensing holds potential for global environmental monitoring and cable supervision, provided that compatibility with conventional network architectures and ability to localize and interpret events autonomously are demonstrated. We show our progress on these aspects, based on years-long fiber sensing data analysis in real environments. ©2025 The Author(s)*

Introduction

Optical fibers are the infrastructures that most pervasively cover our planet, with prospects for further growth in upcoming years[1]. These infrastructures are emerging as powerful platforms for sensing environmental events[2], promising more capillary coverage of the Earth than point-like sensors and extending to the most remote areas of our planet, such as seas and oceans[3],[4], where conventional sensing tools are sparse.

Several methods have been proposed in the last decades to detect mechanical deformations of deployed cables, the most advanced of which enable to map the strain along a cable path with resolution of a few meters[5]. However, most of these techniques have a range of <200 km and, relying on back-scattered radiation, are not compatible with the conventional network architecture.

The analysis of the phase[4],[6]–[9] and state of polarization (SOP)[3],[10]–[12] of laser signals propagated in the forward direction through optical fibers overcomes this limitation, unlocking access to an unprecedented number of cables and disclosing applications that span from geoscience and oceanography to real-time infrastructure supervision[13]. This paradigm can be straightforwardly extended to monitor the network operational parameters and quality of transmission, by collecting streaming telemetry data from the conventional network equipment alongside deformations of connecting fibers.

The combination, collective analysis and interpretation of different sources of information would give access to a complete and dynamical knowledge of the network and its surroundings, supporting self-healing functionalities, improving maintenance planning and paving the way for photonic-based early-warning and alert systems.

However, this idea presents a number of challenges. First, phase and SOP analysis of transmitted optical signals only measure the integrated deformation of the cable, being thus more sensitive to background noise than commercial distributed sensing systems and requiring complex strategies to extract the location of disturbances[4],[7],[13]; the sensitivity and localization resolution achievable with these techniques depend on the event being studied and are yet to be fully understood. Second, the ability to autonomously discriminate events having different origin requires complex data analytics and takes advantage from Artificial Intelligence Machine Learning (AI-ML) tools, that nevertheless must excel in reliability, real-time computation and efficiency at a time. Third, the collection and orchestration of an heterogeneous and variegated set of information requires the design of an advanced, hierarchically structured, software-defined-network (SDN) framework and presents inherent technical challenges in terms of latency and data-stream management, synchronization, data compression and pre-processing.

This paper shows progresses in meeting those requirements, based on year-long analysis of cable deformations collected with different techniques on operational optical cables laid in noisy, yet typical environments. Building on our recent research, we describe an integrated fiber sensing approach that goes beyond the mere recording of events and has the aim to turn collected data into exploitable information, suitable for fulfilling time-critical tasks and improve the quality, efficiency and added value of modern optical networks.

Experimental setup

Our research testbed is an operational optical cable owned by the Italian telecommunication company Open Fiber. The fiber is mostly housed in the road infrastructure, contains a few hundreds of meters of aerial cables and is terminated in two medium-size towns in a highly seismic area in central Italy, being therefore subject to various types of solicitations. In 2021, we installed a first ultra-stable laser for high-resolution phase analysis; the setup was upgraded in 2022 with a second laser interrogator that probes the fiber in the opposite direction, to enable disturbance location along the path via cross-correlation analysis[14]; recently, we installed a pair of Polarization Beam Splitter (PBS)-based SOP analyzers, that record SOP changes of two counter-propagating intensity-modulated, direct-detected (IMDD) data signals generated by conventional C-band 10G transceivers (TRXs)[15].

This complex setup enabled us to investigate different aspects related to our purpose. Thanks to almost uninterrupted phase data acquisition over the past years, we were able to systematically characterize the detection sensitivity of the cable to several tens of earthquakes of various magnitude and distance from the cable[6]. Furthermore, our extended dataset contains not only earthquake recordings, but also the signature of other environmental and anthropogenic noise effects. It thus represents a relevant resource to assess the autonomous recognition of events via AI-ML driven analytics. The implementation of counter-propagating probing signals allows us to assess the possibility to localize events by cross-correlating time recordings collected at the two cable endpoints. Finally, since our sensing equipment relies on different techniques and devices and is hosted in various physical locations, we investigated methods to combine data at the software level, abstract the information, and build a Digital Twin (DT) of the network[16]. This is crucial for developing an optimized, energy-efficient (lowest Joule/bit) software-defined network control and multi-layer orchestration.

Results

We systematically evaluated the earthquake detection ability of phase measurements by analysing hundreds of events happened in a period of two years (2022-2024)[6]. For this study, we extracted fiber recordings in coincidence with all regional earthquakes reported by the National Institute of Geophysics and Volcanology (INGV) and assigned them quantitative scores based on the quality of the detection, according to criteria such as the ability to identify the arrival of P- and S-waves, their matching with predicted arrival times, and their spectral content (0: event not distinguishable from noise, 10: event detected with best quality). Figure 1 shows the timetrace and spectrogram of a Magnitude 3.4 event recorded by the fiber at 32 km distance to which we assigned the highest score.

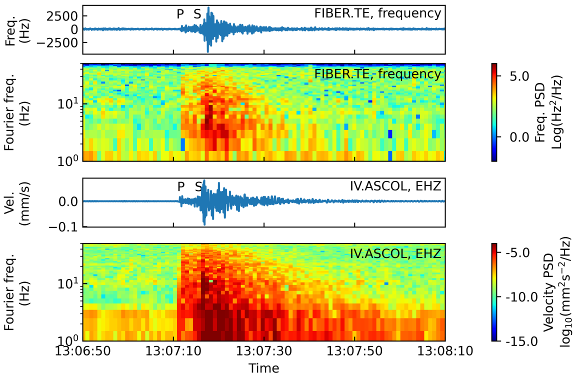

Fig. 1: From top to bottom: timetrace and spectrogram of fiber and IV.ASCOL seismometer recordings in occurrence of a magnitude 3.4 event happened 32 km from the fiber on 27/02/2022. Fiber recordings are here shown in terms of the first derivative of optical phase, i.e. in terms of a frequency shift.

The figure also shows the timetrace and spectrogram recorded by seismometer IV.ASCOL of the Italian seismic network, located at one of the cable endpoints. The arrival of P and S waves is recognised on fiber recordings with similar quality as the conventional seismometer. The peculiar dispersive behaviour in the arrival times of the S-wave Fourier components is also clearly distinguishable. Although the quality of recordings was found to vary significantly over the day due to strong variations in the anthropogenic background noise, we were able to reliably detect events having magnitude >2.5 in a range of 50 km from the fiber[6].

In addition to earthquakes, we observed signatures of other recurring events, among which we clearly identified: oscillations of suspended aerial portions of the cable triggered by wind gusts; vehicle passage on specific points of the road mantle having high sensitivity, e.g. manholes or uneven asphalt coverage; road maintenance and construction works; and other features of unknown origin. Using the previously-developed catalog of classified earthquake events as a training dataset, we developed a ML tool able to discriminate among the various occurrences. The workflow includes denoising of time-series data, recursive segmentation and extraction of meaningful features, followed by clustering of similar events. First results are promising for the identification of P- and S-wave earthquake signals, while anthropogenic events that are generally shorter in duration and have higher spectral content require finer tuning of segmentation and feature extraction parameters.

Following early experiments carried out in controlled environments[7], we investigated the possibility to locate events along the deployed cable path by launching coherent laser signals in opposite directions and cross-correlating synchronized measurements. The quality of localization strongly depends on the spectral content of the event to be

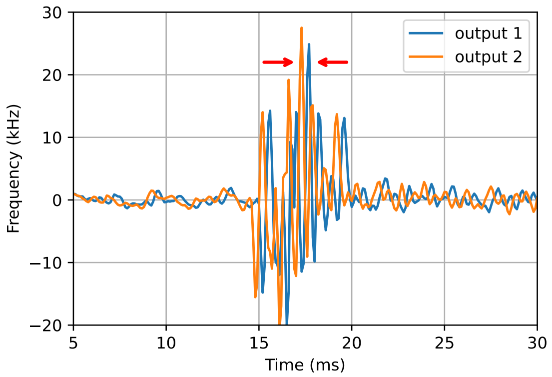

Fig. 2: Synchronous recordings of phase deformations of a pair of counter-propagating laser beams collected at opposite cable endpoints. The delay between the two is consistent with the excitation position at the 1 km-level.

located, the signal to background noise ratio, and the accuracy of timestamping, which shall be at the $1\,\mu\mathrm{s}$ level. As this is more stringent than possible with the Network Time Protocol synchronization generally available at network endpoints, we developed an *ad-hoc* hybrid software/hardware-based synchronization procedure that preserves the required alignment between the two acquisitions. Figure 2 shows the two synchronous recordings of a tapping event, as collected by measuring phase variations at opposite endpoints. The delay between the two is consistent with the position of the tapping point and indicates the possibility to locate this type of events with km-level accuracy, which is sufficient for most cable supervision applications. Other anthropogenic events can be located with similar accuracy.

For the development of an accurate and time-varying network's DT, to build the needed digital shadow, we aim to use both sensing data derived from photonics techniques probing the cable (e.g., phase data from laser interferometry with alien laser interrogators, SOP data from dedicated acquisition boards, etc.) as well as telemetry data from conventional network elements (e.g., amplifiers gain, temperature, optical signal/noise ratio, bit error rate and SOP data from transceivers (TRXs), etc.). An example is proposed in[17], where the accurate DT of an amplified line is built using typical telemetry data and a fully agnostic approach—without prior knowledge of network element data, including fiber types—thus enabling optimized control. In[18], instead, the DT is constructed solely based on data obtained by probing an alien domain through a TRX exposing telemetry data, thereby enabling the use of the alien domain as-a-service. An accurate DT can also be used to generate synthetic data that captures potential failures, as demonstrated in[19], thereby allowing the training of ML methods that enable proactive taking of countermeasures. Telemetry data—particularly the SOP—can be leveraged to train ML models to detect impending malicious events, enabling proactive network restoration[20]. They can also support environmental surveillance over the network's geographical footprint by means of pre-trained ML models. Examples include traffic monitoring[21] and earthquake early detection, potentially enabling life-saving early warnings[22].

Conclusion

We show how the analysis of forward transmitted optical signals in operational telecom cables can be leveraged for environmental monitoring and cable supervision purposes. With exceptionally long datasets available, we were able to quantitatively assess the detection sensitivity to earthquake events as a function of their magnitude and distance to the cable, and we developed a ML tool for their automated recognition, based on a set of manually-labeled recordings. Furthermore, we unambiguously identified the signature of other environmental and anthropogenic events, and show the ability to localize the position of non-recurring and non-stationary disturbances along the cable, even in presence of strong background noise as typical in real-world conditions.

These results showcase the achievement of important prerequisites toward the development of a smart and systematic network sensing approach that goes beyond occasional and application-driven data recording. In fact, integrating fiber sensing in the conventional network supervision and turning automatically collected data into exploitable information are seen as necessary steps in view of the development of early-detection and network resilience tools. To achieve these goals, the DT technology supported by real-time-updated telemetry and distributed deformation data is an important asset as it enables to validate recordings by comparing multiple sensing approaches, simulate evolving scenarios and take considered actions.

This research lays the foundation for a dual-purpose optical network that simultaneously supports communication and environmental monitoring, addressing the increasing demand for secure, adaptive infrastructures.

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