Seismic Sensing in Submarine Fiber Cables

Mattia Cantono(1), Jorge C. Castellanos(2), Valey Kamalov(1) , Antonio Mecozzi(3) , Rafael Muller(1), Shuang Yin(1), Zhongwen Zhan(2)

(1) Google LLC, USA, mcantono@google.com
(2) Seismological Laboratory, California Institute of Technology, Pasadena, USA
(3) Department of Physical and Chemical Sciences, University of L'Aquila, Italy

Abstract *Optical fibers are ubiquitously deployed in terrestrial and submarine networks, making them attractive for sensing activities. We review optical technologies used for seismic sensing and show results of polarization sensing experiments performed over Google's submarine cable Curie, connecting US to Chile.*

Introduction

Over the last decades, optical fibers have been deployed ubiquitously to enable the Internet and the associated services and applications. The pervasiveness of single mode fibers is now pushing researchers and telecom providers to explore complementary usage opportunities for optical fiber networks, from time/frequency distribution to sensing for smart city and scientific applications. This paper focuses on the sensing capabilities of optical fibers for environmental vibration monitoring, mainly focusing on seismic and oceanographic sensing. First, we provide an introduction to different sensing technologies for seismic monitoring. Then, we report on some seismic sensing activities performed on Google's global fiber network making use of telemetry information obtained from operational coherent receivers used for data transmission. Finally challenges and next steps are discussed.

Sensing Technologies

The unique low losses characteristics of single mode optical fibers have made them attractive for applications beyond data transmission. Over the last three decades, optical sensing has emerged as a promising alternative to traditional electronic sensing for sensing quantities such as strain, temperature and pressure [1]. Several of these sensing techniques make use of the unique capability provided by optical fibers of providing information about an external variable such as strain or pressure in multiple location along the length of the optical fiber itself. These techniques rely on light back scattering in optical fibers to implement the so-called *distributed optical fiber sensors* (DOFS). Among DOFS, Distributed Acoustic Sensing (DAS) has emerged as a popular technique for geophysics applications and environmental monitoring [2-3]. DAS is based on the detection of the phase of the Rayleigh backscattering arising from distributed locations along the fiber length. DAS has been proven to be extremely sensitive to external perturbation while also capable of providing a very high spatial resolution. However, as DAS makes use of backscattered light, its spatial range is limited typically to less than 150km and in general DAS measurements cannot be go beyond optical devices that include isolators for back-scattered light such as optical amplifiers. Furthermore, as DAS requires the transmission of high-power laser pulses to ensure high spatial resolution and reach, it is often best used on dark fiber plants with no active telecommunication channels.

Other sensing techniques for seismic sensing that do not rely on spatially distributed disturbances measured through light backscattering have been recently demonstrated as long reach alternatives to DAS. Marra *et. al.* [4] demonstrated the detection of earthquakes in submarine cables and terrestrial fiber networks by detecting perturbations on the absolute phase of a laser source induced by mechanical disturbances. This interferometric technique - which has been invented as a byproduct of time/frequency dissemination techniques – requires to use a sub-Hz laser source to maintain light coherence during propagation. This technique cannot spatially resolve environmental disturbances, as it relies on the measurements of light phase at the end of an optical link. Mechanical disturbances on the fiber itself are therefore integrated along its length, preventing localization with a single link configuration. On the other hand, this technique has a reach much larger than DAS and can cover several thousands of kilometers. Furthermore, although phase sensing requires dedicated hardware such as the ultra-stable laser, this technique can be used over optical fiber links carrying active traffic. The tone generated by the sub-Hz linewidth requires only a fraction of the optical bandwidth required for data channels while having similar power levels.

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Tab. 1: Comparison of optical sensing techniques for seismic monitoring with optical fibers

	DAS [2,3]	**Phase** [4,5]	**Polarization** [6-8]
Equipment Requirements	DAS interrogator required	Ultra-stable laser source	Regular coherent linecards
Fiber Requirements	Dark	Spectrum required	No impact on existing channel plan
Sensitivity	Medium/High	High	Medium
Localization	Yes	Feasible	Feasible
Reach	< 100 km	> 10,000 km	> 10,000 km
Scalability	Poor	Medium	Good

To remove the need for dedicated hardware, in [6,7] we make use of the rich set of parameters used for channel estimation in digital signal processing (DSP) units of coherent receivers to detect mechanical perturbations to the optical fiber. Specifically, we make use of the polarization transfer matrix estimation capabilities of the DSP to track the state of polarization (SOP) evolution of optical channels along the fiber and monitor how mechanical disturbances affect their evolution. This technique has the advantage of not requiring specific hardware for sensing, nor wasting spectrum or fiber resources as it does not affect regular data transmission. This method is also highly scalable as it relies on widely deployed coherent transponders.

Similarly to the phase technique this measurement method accounts for the integral effect of all the different mechanical disturbances affecting the fiber over its entire length. This complicates the ability of localizing disturbances with a single measurement and limits the overall spatial resolution accuracy when localizing events using multiple measurements or bidirectional measurements. From a sensitivity standpoint, polarization-based measurements have a limited dynamic range and this can pose challenges for detection of events in noisy environments such as terrestrial or aerial fiber installations. A more detailed description and theoretical framework behind polarization sensing for seismic events can be found in Ref. [8].

Table 1 summarizes and compares the different sensing techniques described above. In the next section, we report results related to polarization sensing measurements that took place in the Curie submarine cable.

Polarization-based seismic sensing over Curie

The Curie cable system is a 4-fiber pair, 10,500km submarine system connecting Los Angeles (USA) to Valparaiso (Chile). From early 2020, we have been monitoring the SOP of several data channels through commercial coherent transponders from various manufacturers. SOP signals have been sampled with a sampling period between 50ms and 60ms. A windowed averaging and time-dependent rotation was applied to the SOP data to filter out long-term drifts of the polarization signals caused by thermal effects in the transponders or cable landing stations [7]. Data is then analyzed with standard time-frequency analysis methods to detect disturbances caused by earthquakes in frequency ranges of the order of 0.1 Hz as well as primary microseisms events caused by ocean swells in frequencies ~0.06 Hz. Over the course of the last 18months, we were able to detect tens of earthquakes between 5Mw and 7.7Mw with epicenters ranging from few tens of kms to the cable up to ~1500km away from it [7].

Figure 1 reports a spectrogram showing a 6.8Mw earthquake and its aftershock sequence that took place in September 2020 offshore of Chile. The SOP signal clearly shows packets of energy (identified as vertical lines) in the spectrogram at the time of the events [7]. In general, the characteristic frequencies of seismic events depend on the distributed interaction between seismic waves impinging different section of the cables.

Figure 2 shows instead the results of primary microseisms events caused by ocean swells on the SOP signal. These types of events last for several days and are caused by distant storms in the ocean that are triggering pressure

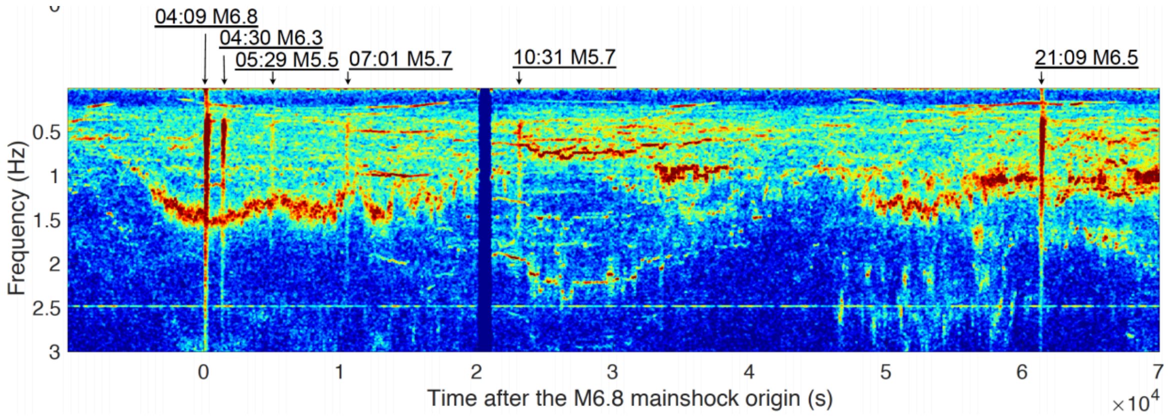

Fig. 1: SOP signals of the 01 September 2020 M6.8 submarine earthquake offshore Chile. Five of the largest aftershocks (between M6.5 and M5.5) can be clearly identified as vertical wavepackets in the spectrogram

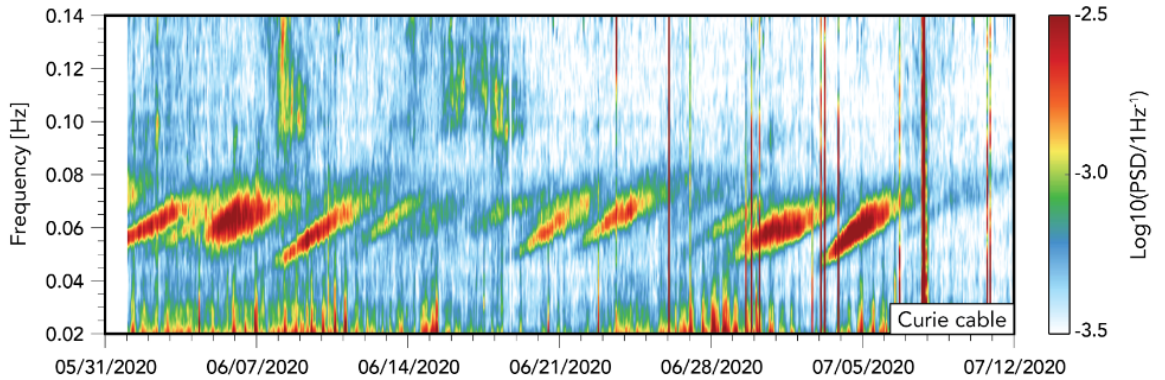

Fig. 1: Spectrogram of the SOP modulation recorded over the Curie cable in June-July 2020. Energy dispersion around 60mHz is clearly visible and can be associated with primary microseism caused by ocean swells.

perturbations in shallow waters that are then causing birefringence modulations in the optical fibers of the cable [7,8]. This sensitivity to pressure-induced strain and the capability of detecting ocean swells, indicates the potential of polarization sensing in submarine optical cables to be used for tsunami detections [7]. Such capability would allow to use existing submarine cables to complement existing early warning systems for tsunami for greater societal benefits for coastal communities globally.

Conclusions and Next Steps

The global application of optical sensing techniques for environmental sensing on the existing optical fiber network infrastructure could enable unprecedented wider societal benefits when applied to early warning system for seismic events, as well as great scientific advancements in the understanding of Earth's interior dynamics. In order to achieve this goal several challenges must be solved. Improvements in event classification, sensitivity, localization ability, theoretical understanding of the implications of mechanical disturbances on optical signals are much needed. Both the scientific community and the telecommunication industry need to partner up and collaborate to tackle these challenges.

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