Earthquake Emulation for Environmental Sensing in Terrestrial Telecom Networks

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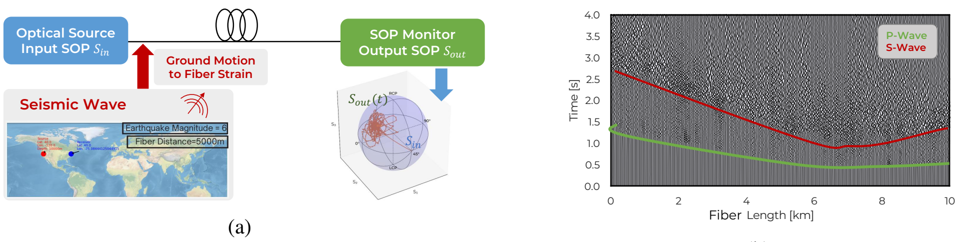
Abstract: There is a huge interest in exploiting the extensive telecom fiber infrastructure for early warning of environmental disasters. We propose a method to generate synthetic earthquakes events to test their detection in terrestrial telecommunication networks.

1. Introduction

Optical fiber communication networks have become pervasive infrastructures to meet the demand for high-bandwidth connectivity. Recently, there has been a growing interest in utilizing these deployed networks as a wide distributed network of sensors [8]. One compelling application lies in earthquake detection [9], enabling early warning systems. Optical fibers have proven to be exceptional mechanical stress sensors, as they affect the phase and state of polarization (SOP) of propagating data signals [7]. However, existing solutions such as distributed acoustic sensing (DAS) or optical time domain reflectometer (OTDR)-based systems have limited reach and necessitate dedicated hardware, impeding their wide adoption [10, 11]. In the access and metro segments, intensity modulated direct detected (IM-DD) transceivers are still widely deployed as 10 Gbps WDM channels or as optical supervisory channels (OSC). Due to the polarized nature of IM-DD signals, the variations in SOP induced by mechanical stresses can be observed by tapping some power and employing a polarimeter or a simpler polarization beam splitter (PBS), photodetectors, and low-speed ADCs for signal processing [12, 13]. By analyzing the temporal evolution of the output SOP, earthquakes can be identified in a timely manner detecting the less intense P-Wave, which precedes the more disruptive S-Wave by several seconds. However, developing robust earthquake detection techniques requires extensive testing and a comprehensive dataset of SOP footprints caused by earthquakes with varying intensity, localization, and other characteristics. Unfortunately, such datasets may not be readily available. To address this challenge, we propose a novel approach for generating synthetic earthquake data based on the waveplate model [6].

2. Synthetic Earthquake Data Generation method and Results

A seismic wave impacting an optical fiber generates a variable fiber longitudinal strain, which in turn produces a SOP variation due to fiber birefringence. Fig.1 reports the reproduced seismogram of an earthquake recorded by a DAS in Iceland in 2015 [5]. Each curve reports the fiber strain at a given time instant (y-axis) and position along a 10.2 km fiber (x-axis). The fiber strain effect on output SOP is shown in Fig.1(a) as a time-scattering the Poincare sphere, which is stochastic due to the random orientation of the birefringence principal axes [6]. The proposed method, subdivided in three steps (Fig.1(a)), targets the generation of synthetic SOP evolutions, controlling the epicentre, intensity and distance with respect to the earthquake characteristics and the input polarization and random birefringence realization on the optical fiber side. In the first step we employ Instaseis and ObsPy [2, 3] to generate the ground motion caused by a seismic wave. These are Python libraries extensively employed by the



(a)

(b)

Fig. 1. (a) Outline of the earthquake SOP monitoring mechanism (b) Seismogram of DAS recorded earthquake [5]

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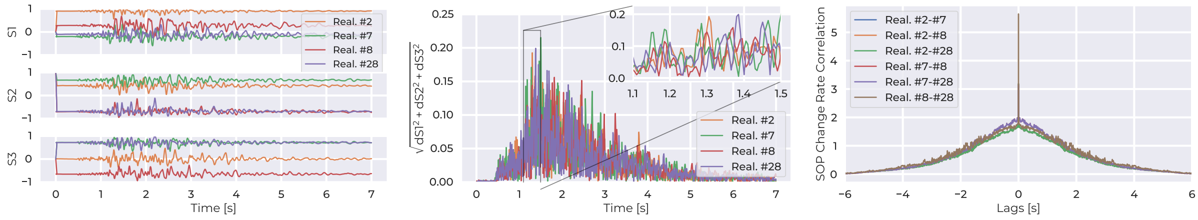

(a) (b) (c)

Fig. 2. (a) Stokes vector and (b) SOP change rate time evolution for 4x simulated birefringence orientation random realizations. (c) SOP change rate cross-correlation of the 4x realizations' possible combinations.

seismologists to simulate a seismogram accounting for detailed soil propagation. After setting the desired earthquake source and intensity, the software solves the Green functions [4] to obtain the ground motion time signal on a set of spatial point at a distance R from the source describing the position of the sensing optical fiber. In the second step the simulated ground motion is translated to the corresponding fiber strain, considering the fiber material response to the impacting seismic wave [1], thus obtaining a seismogram as in Fig.1. Alternatively to these two steps, one may employ a prerecorded fiber strain seismogram obtained from a real DAS interrogation. In the following results, we have used this approach using the DAS dataset of [5] rof Fig.1. The synthetic earthquake generation will be addressed in future papers. In the third step the SOP time evolution corresponding to the fiber strain is estimated using the well-known waveplate model [6]. In this paper we assume that the probe signal is linearly polarized at 45 degrees and that such input SOP variation over time is negligible and slow with respect to the earthquake effect. The waveplate model splits the fiber into N segments of length dz whose length is smaller or equal to the fiber correlation length L_c. Each waveplate has its own birefringence principal axes rotated by a random angle θ with respect to the input polarization frame, uniformly distributed in $[0, \pi]$. The i-th waveplate effect is modelled by its the Jones rotation matrix $J_{rot,i}(\theta_i, \Delta_i) = R(-\theta_i) \cdot M(\Delta_i) \cdot R(\theta_i)$, where $R(\theta_i)$ rotates the SOP to the local birefringence axes and $M(\Delta_i)$ applies a phase shift $\Delta_i = 2\pi \left({dz_i + \Delta L_i}/{L_b} \right)$, dependent on the fiber strain ΔL_i and the fiber beat length L_b. The output SOP time evolution is thus obtained multiplying the input SOP by the sequence of waveplate rotation matrices and repeating the process for all the strain sampling times. We have performed a Montecarlo simulation campaign with 30 different random realizations of the birefringence orientation, keeping fixed the input SOP. The output Stokes vectors are reported Fig.2 for a subset of 4 realizations. We notice that different θ orientation sequences yield different Stokes, but still following the earthquake strain evolution of Fig.1 The SOP change rate $\Delta SOP = \sqrt{dS_1^2 + dS_2^2 + dS_3^2}$ (Fig.2), (the sum of each squared Stokes vector variation), can be then considered as reference signal, since it aggregates the Stokes peak variations which may be observed alternatively in S_1, S_2 or S_3 dependently on the coupling between the fiber strain birefringence effect and the orientation realization. ΔSOP is not invariant because of the birefringence fast variations, but the the P-Wave and S-Wave can be still recognized in average. Hence, one could measure the cross-correlation between different realizations' SOP change rate to test if the information about fiber strain is preserved. If yes, all the cross-correlations should yield maximum similarity at zero lag. This has been done for all the 30 realizations' combinations and it always confirmed the hypothesis. A subset of them is plotted in Fig.2, clearly showing maximum similarity always at zero lag, although with a limited peak intensity.

3. Conclusions

We have proposed a method to simulate the SOP evolution due to the fiber strain of a seismic wave impacting an optical fiber. This can be done starting from a real earthquake fiber strain DAS measure or by generating synthetic data using well tested seismological software. This data will be employed in future studies to develop and test techniques able to detect reliably the characteristic waveform corresponding to P-Waves and S-Waves.

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