Seismic detection through state-of-polarization analysis in optical fiber networks

Invited Paper

Seismic Detection through State of Polarization Analysis in Optical Fiber Networks

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ABSTRACT

The existing optical fiber terrestrial network can be leveraged to serve as a wide distributed network of sensors, especially to detect mechanical stresses as the optical signal polarization is significantly influenced by external disturbances. Exploiting this trend, paves the way for employing the optical fiber network in environmental sensing, like detecting earthquakes or tracking anthropic activities. The purpose is to examine the changes in the state of light polarization caused by birefringence induced by seismic events. Consequently, we have developed a Python-based Waveplate Model to track state of light polarization changes in buried optical fiber cables. This model integrates real ground motion data from a 4.9 magnitude earthquake that occurred southwest Marradi city in Italy, and converts it into strain values along the fiber cable. To further investigate the effects of this particular seismic activity, we propose a centralized smart grid fiber network approach based on a neural network model with an attention mechanism for earthquake early warnings. Along with the aforementioned Waveplate Model, numerous sets of polarization evolution were produced on two distinct sensing points with different distances from the epicenter in two different cities, enabling earthquake early detection upon P-wave arrivals that precede the earthquake's destructive surface waves and allowing for a swift initiation of emergency plans including early warning alerts and earthquake countermeasures.

Keywords: Sensing, Polarization, Earthquakes, Terrestrial, Optical-Fiber-Networks, Machine-Learning

1. INTRODUCTION

The mechanical and optical properties of an optical fiber, as well as the physical properties of the light wave propagating inside it, change due to applied mechanical stresses and external disturbances. This trend opens the perspective of using the optical networks as a wide distributed network of sensors for environmental sensing, such as earthquake detection or anthropic activities monitoring [1],[2]. Essentially, there are two types of seismic waves, body waves (Primary, P waves and Secondary, S waves) that propagate through the earth's interior and Surface waves that propagate along the earth's surface. Surface waves carry the greatest amount of energy and are usually the primary cause of destruction [3]. Detecting P waves that precede earthquake's destructive waves allows swift initiation of emergency plans. Recently, we have witnessed the rise of distributed fiber optic sensors like Distributed Acoustic Sensing (DAS) [4],[5], that has usable range of less than 100 km. Frequency metrology interferometric techniques came to overcome DAS usable range limitations [6], but still interferometric techniques considered to be using dedicated and expensive hardware. In this manuscript, we present a novel technique that employs light polarization sensing, analyzed by a machine learning model and aimed at producing early anomaly warnings by identifying the presence of earthquake's P waves without adding expensive equipment to the network, and ensure long-range measurements with high efficiency. In this paper, section II introduce the fiber optic network smart grid approach, Section III covers the Waveplate Model empowered by a neural network algorithm implemented to monitor state of polarization (SOP) changes due to birefringence induced by a real seismic event. The paper concludes with the neural network model explanations with related results and discussions in Section IV, and a conclusion in Section V.

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2. FIBER NETWORK SMART GRID APPROACH

On the 18th of September 2023, an earthquake of 4.9 magnitude struck in the region of Marradi in Central Italy. The earthquake was located by the italian National Institute of Geophysics and Volcanology (INGV) with a seismic wave velocity of 7.10 km/s according to the Central Italian Appennines (CIA) velocity model. This speed is determined based on the characteristics of the Earth's interior in the specific region [7].

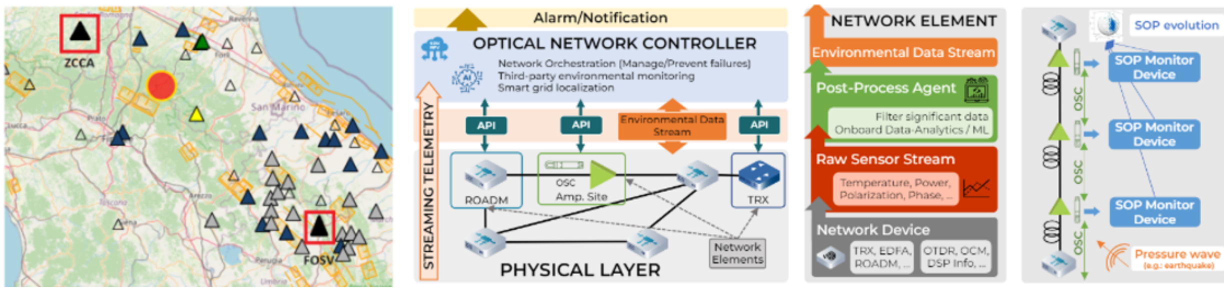

Figure 1. Left - Earthquake Epicenter and Nearby Seismic Stations; Right - Network Smart Grid Approach

Instead of the two seismic stations located in Zocca (ZCCA) and Fassato di Vico (FOSV), left of Fig. 1, we propose to exploit the existing optical fiber terrestrial network as a centralized smart grid approach empowered by machine learning for analyzing State of Polarization (SOP) variation along the fiber cables, right of Fig. 1. The methodology to extract SOP variations is detailed in the next section. ZCCA and FOSV are located in two different municipalities around Marradi city with 58.5 km and 126.9 kilometers distances far from the earthquake epicenter, respectively. The reason we chose two sensing points, is first to train and test a deep learning algorithm on SOP data extracted from two different sensing points in the network; secondly, to determine the time available for each municipality to implement earthquake countermeasures, considering the varying distances of the two cities from the epicenter, which result in different P wave arrival times. We propose to expand the existing network into streaming telemetry paradigm to integrate earthquake prediction services. The streaming telemetry paradigm involves continuous data transmission from network elements (NEs) to the Optical Network Controller (ONC) by means of Application Programming Interfaces (API) to facilitate network management and control. Devices like coherent transceivers (TRX) include changes in the phase and the state of polarization (SOP) of optical signals. Indeed, external strain affects the phase and SOP of the propagating signal, thus, these SOP changes could be used for sensing as they already contain environmental information [8],[9]. Additionally, a post processing agent within the NEs analyse, filters and forwards only essential information to the ONC. Since, coherent transceiver's data is often inaccessible due to vendor lock, although cheaper intensity modulated direct detected (IM-DD) TRX are still popular in the metro and access network with lower data rates or functioning as slower optical supervisory channels (OSCs) [10]. Typically, OSCs terminate at every amplification site. Thanks to the polarized nature of IM-DD signals that enables the detection of OSC SOP changes caused by external strains by extracting small amount of power to supply SOP monitoring device like a simple polarimeter or a simpler Polarization beam Splitter (PBS) as in right of Fig. 1. As a post processing agent, we propose to train a deep learning model that can be implemented within NEs, provide earthquake predictions based on SOP variation, and leverage NEs edge-computing capabilities. In [11], we have experimentally tested this approach on a deployed fiber ring in the city of Turin, Italy, using commercial IMDD TRX and polarimeters as SOP sensing devices, in order to detect and localize passage of cars from observing SOP variations footprint. In [12], the author showed as well, the implementation of machine learning based algorithms for car passage count by means of fiber optics sensing.

3. WAVEPLATE MODEL EMPOWERED BY DEEP LEARNING ALGORITHM

Instead of using SOP monitoring devices, we propose to use a Waveplate Model [13],[14]. In reality, optical fibers are often birefringent due to construction imperfections that disrupt the fiber's cylindrical symmetry, thus affecting the polarization. This means that, in a fiber section small enough, the perturbation or the internal birefringence from construction imperfections can be assumed spatially uniform [15]. Seismic waves are another form of disturbances that cause external birefringence in the fiber and can also affect the polarization. To isolate and study the external disturbances on the light's polarization within the fiber, it is crucial to understand the influence of internal birefringence. Here, adopting the Waveplate model is essential to well define the effect of internal birefringence by dividing the fiber into numerous small segments, referred to as 'plates' to ensure a uniform internal perturbed medium across each section[15]. Consequently, any deviation from this established internal behaviour can be attributed to external perturbations, as they would introduce unexpected changes in the state of polarization of light. However, by nature, these plates have a random orientation, which can not be controlled, adding complexity to the analysis of external effects. To overcome this challenge, a large amount of polarization evolution dataset for a given seismic event was gathered where each SOP evolution corresponds to a different set of random angles. These SOP evolutions should contain invariant information as they are affected by the same earthquake. This is where the neural network model becomes valuable or the post processing agent presented earlier in the smart grid network section, as it is trained to detect and interpret the patterns of SOP evolutions due to external seismic impact on the fiber. Instead of analysing the changes in three stokes parameters that describe each SOP evolution and add higher complexity, we propose to calculate for each SOP evolution from their stokes parameters, the State of Polarization Angular Speed (SOPAS) [16], thus analyzing one variable instead of three. Moreover, one of the main functions of our python based Waveplate model, is to convert earthquake ground displacement values into nano-strain values according to the conventional iDAS conversion presented in [17] where each 116 nano-meters of ground displacement corresponds to 11.6 nano-strain along the fiber.

4. NEURAL NETWORK ALGORITHM AND RELATED RESULTS

Through the INGV website, we managed to get the ground motion time series experienced by two seismic stations (ZCCA and FOSV) located within distinct distances from the epicenter, 58,5 km and 126.9 km respectively. Leveraging the Waveplate model, we extracted the first two plots of Fig. 2, the strain plots corresponding to two fiber cables at the same stations' position as in the right plot of Fig. 2.

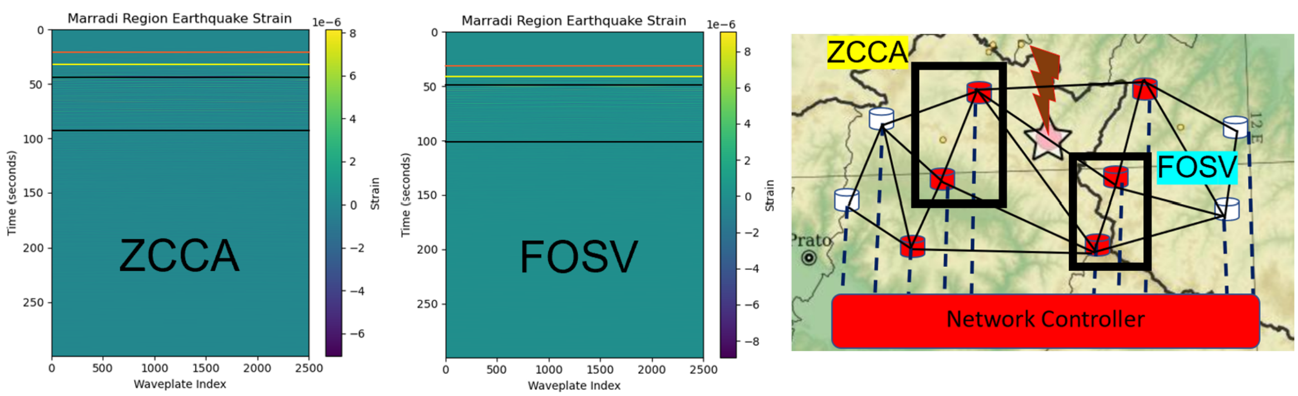

Figure 2. Left and Middle, Strain Values Plots Experienced by Fiber Cables instead of ZCCA and FOSV - Right, Demonstration for Network Exploitation instead of Seismic Stations

The strain plots show varying P wave arrival times, highlighted in orange for both fibers placed at the same position corresponding to each station. Due to the varying distances from the epicenter, the P wave for the fiber replacing ZCCA, arrive at 20 seconds, occurring 10 seconds earlier from the P wave for the fiber replacing FOSV, which arrive at 30 seconds. The yellow line indicates the S wave's arrival, occurring at 30 seconds for ZCCA substitute fiber and 40 seconds for FOSV substitute. The black line represents the arrival of the more destructive Surface waves, which reach the ZCCA substitute at 40 seconds and the FOSV substitute at 50 seconds. Consequently, with a 10 seconds interval between the P wave and the Surface waves, and accounting for the seismic wave propagation time from the epicenter to both locations at 7.10 km/h speed as per the CIA model [7], the municipality of Zocca has 18 seconds to implement its emergency plan and countermeasures. In contrast, Fassato di Vico has 27 seconds to execute similar actions. The two fiber cables considered in this scenario are two 10 kilometers of fibers, segmented into 2500 waveplates each of 4 meters. The beat length chosen was 20 meters. Due to the random orientation of plates, we intend to simulate 100 runs for both locations with 300 seconds of measurement time, extract their SOP stokes parameters and calculate their state of polarization angular speed (SOPAS). The SOPAS data extracted from the waveplate model for both location was used as an input to the neural network model to be trained, validated and tested. Examples on SOPAS we get for both station substitutes is depicted in the Fig. 3 below.

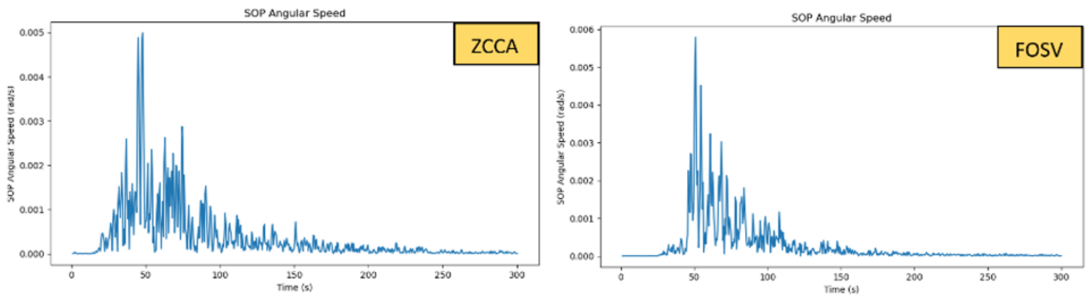

Figure 3. ZCCA - FOSV SOPAS real examples

We employ a neural network model using Long Short-Term Memory (LSTM) layers [18], with an attention mechanism for early detection for forthcoming earthquakes. The model is detailed in the left of Fig. 4. The output layer is a full connected dense layer with 4 units (assuming it's a multi class classification problem, detecting No Earthquake, P waves, S waves, and Surface waves) and Softmax activation, generating class probability [19]. The output visible in the left of Fig. 4 is just a demonstration for the expected results we see on the right of Fig. 4 with the right SOPAS plot example.

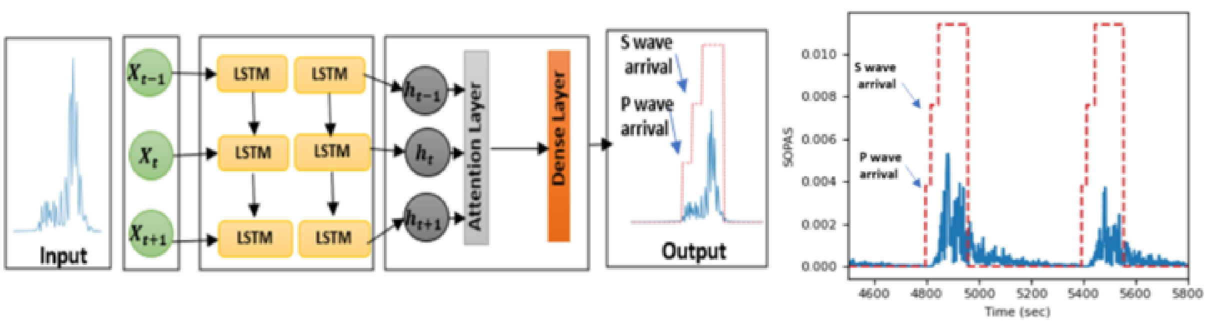

Figure 4. Left: Neural Network based LSTM layers ; Right: Real Results

The model is trained on 60% of all the previous data, 20% used for validation, and the rest 20% for testing. For testing purposes, we used two SOPAS to better visualize the model prediction showing P wave detecting in one second as depicted in the right of Fig. 4. Consequently, the municipality of Zocca still have 17 seconds for counter actions and 26 seconds for the municipality of Fassato di Vico.

5. CONCLUSION

In conclusion, the study utilized a Waveplate Model to analyze state of polarization (SOP) changes in optical fibers due to seismic events. The neural network model successfully identified P-wave arrivals, enabling timely initiation of emergency response measures. This approach offers a promising, cost-effective method for leveraging existing optical fiber networks for environmental sensing and earthquake prediction, enhancing public safety.

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