Detection, Localization and Emulation of Environmental Activities Using SOP Monitoring of IMDD Optical Data Channels

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Detection, Localization and Emulation of Environmental Activities Using SOP Monitoring of IMDD Optical Data Channels

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Abstract: Optical telecommunications networks have become pervasive to satisfy the continuously growing internet traffic demand. At the same time, there's a huge interest in deploying a wide sensor network for in order to offer enhanced network services for environmental monitoring, such as early detection of earthquakes. In this context, there's a large interest in using the large infrastructure deployed for telecommunications also for environmental sensing. In this paper we employ the state of polarization (SOP) monitoring of intensity modulated channels, still widely deployed in metro and access network. We show experimental demonstration of environmental events' detection and localization and propose a waveplate model-based simulative tool aimed at emulating the SOP variation induced by seismic waves propagated along fiber network segments, to test their detection and localization in presence of further SOP noise induced by anthropic activities.

1. Introduction

In order to cope with the increasing capacity demand, optical data networks have been extensively deployed forming a capillary infrastructure covering entire geographical areas of hundreds to thousand of kilometers. Moreover, in the need to cope with rapidly changing traffic matrices, optical networks are evolving towards dynamically reconfigurable, autonomous systems orchestrated by a centralized optical network controller (ONC), which communicates with the network elements (NE)s by means of application programming interfaces (API). In this context, the ONC makes use of several quantities monitored by each NEs, constituting the streaming telemetry, for network management purposes [1] and exposes differentiated services to the upper network layer. At the same time, optical fibers are know to behave excellently as mechanical stress sensors [2], and they have been employed in dedicated environmental sensing

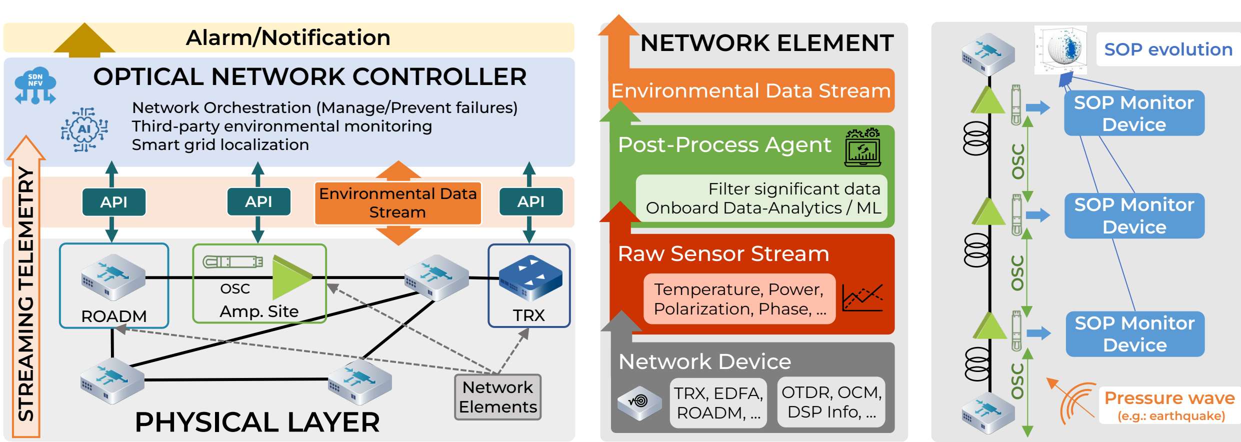


Fig. 1: (Left) Sensing network architecture; (Center) NE with embedded post processing. (Right) Closeup of OSC sensing OLS.

systems, such as the distributed acoustic sensing (DAS) leveraging on the backscattered light for events detection [3]. Although this technology provides large accuracy it requires dedicated fibers and hardware and it has a limited reach, thus preventing a wide deployment. There is thus a increasing interest in exploiting the already deployed pervasive fiber infrastructure for telecommunications as a wide distributed environmental sensing networks, with several application fields: from anthropic activities monitoring to earthquake detection [4, 5]. In this paper we propose to expand the streaming telemetry paradigm to integrate environmental sensing services into the existing networks, leveraging on already monitored quantities or accountable with additional sensors. We review experimental activities demonstrating the feasibility of environmental activities' detection and localization by means of state of polarization (SOP) monitoring. We then focus on tools for studying feasibility of earthquake detection, proposing a waveplate model-based tool to emulate the SOP variations caused by seismic waves.

2. Streaming Telemetry Sensing Network Architecture and Experimental Activities

Fig.1 represents the architecture of the proposed sensing/data network architecture. The streaming telemetry is a set of data continuously sent from the NEs to the ONC for network control and management, which includes, for example, power and temperature evolution from reconfigurable add/drop multiplexers (ROADM) and amplifiers or phase on the received data signal [1]. Indeed, external strains affects also the phase and SOP of the data signals propagating through the OLSs, which can be used for sensing as they already contain environmental information [5, 6]. Moreover, NEs can be equipped with additional sensors to enrich the streaming telemetry. Hence, the ONC functions can be integrated with software modules exploiting the streaming telemetry diversity to detect and localize events, thus forming a sensing smart grid capable of constantly monitoring vast regions and responding with timely warning signals for potential disasters, or preparing for redirecting traffic. Moreover, as in Fig.1, a post-processing agent can use the computational capabilities available in the NEs to filter out only significant information to the ONC. As previously mentioned, coherent transceivers (TRX) already track signals' phase and SOP evolution, however, access to this data is not straightforward due to vendor lock. While these TRX dominate the core segment, in the metro and access cheaper intensity modulated-direct detected (IMDD) TRX are still popular, with data rates of 10Gbps or as slower optical supervisory channels (OSC) [7]. OSCs can provide plenty of sensing sources as they are usually terminated at every amplification site, thus enabling the sensing smart grid paradigm. Hence, since IMDD signals are inherently polarized, it is possible to detect OSC SOP variations caused by external strain by extracting a small amount of power to supply a SOP monitoring device, as outlined in Fig.1. In [8] we have experimentally tested this technique on a deployed test fiber ring in the city of Turin using commercial IMDD TRX and polarimeters as SOP sensing devices. We detected and counted the SOP variation footprint induced by the passage of cars, validated w.r.t. public GPS databases. In [9] we have proposed a lower cost implementation based on a simpler polarization beam splitter (PBS) followed by two photodetectors, trans-impedance amplifiers and a 14 bit ADCs allowing for local processing in the NEs. In [10] we have also shown the implementation of machine learning-based algorithms for car passage count. These encouraging results suggest the feasibility of events' detection and local post processing in the NEs with minimum addition to the existing network infrastructure. We prosecute here the experimental investigation by adding the localization capability, which requires bidirectional transmission, thus doubling the SOP monitoring devices count as per Fig.1. To focus on the detection and localization of a predetermined event knowing its SOP time-varying footprint, we built single span link connecting two nodes in the laboratory, as if the link in Fig.1) (right) has only two sensing endpoints. The setup is described in Fig.2. Each node is composed by a commercial DWDM card and a ROADM, the former equipped

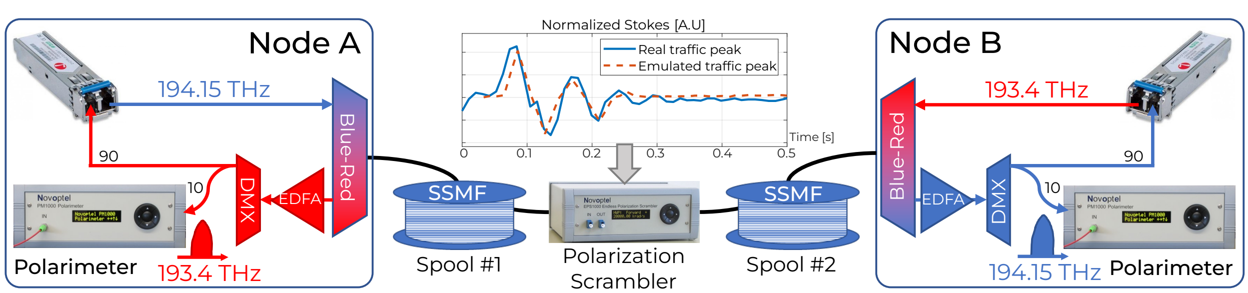


Fig. 2: Experimental setup. On both ends an IMDD TRX and a polarimeter are present, opposite flows are separated with blue/red filters. SSMF: standard single-mode fiber; EDFA: fiber amplifier; DMX + Blue-Red: channel/flows multiplexer/demultiplexer.

Test	OTDR Method [km]		SOP Method [km]		Error
	Spool 1	Spool 2	Spool 1	Spool 2	[km]
1	20.006	0.957	19.938	1.025	0.068
2	20.006	6.045	20.083	5.968	0.077
3	20.006	9.515	19.934	9.587	0.072
4	20.006	10.473	20.105	10.374	0.099
5	20.006	15.560	20.079	15.487	0.073
6	20.006	16.518	20.044	16.480	0.038

Table 1: Spool lengths measured using OTDR and SOP method.

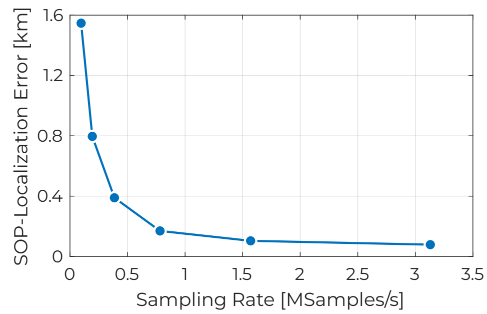
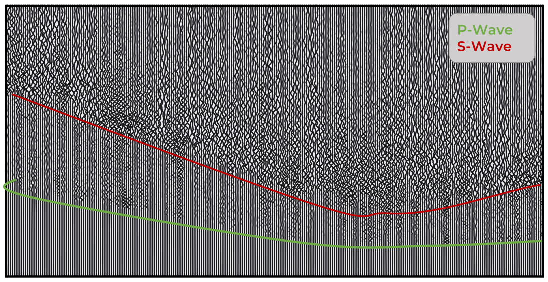


Fig. 3: Localization error vs the polarimeter sampling rate.

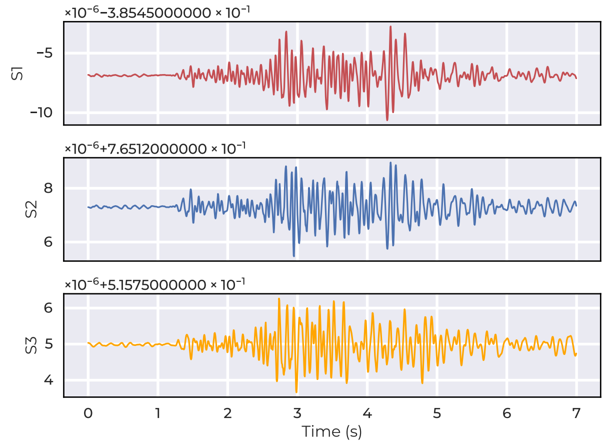
with a 10 Gbps IMDD SFP+ TRX pluggable carrying data. The ROADM consists of two DWDM filters (MUX and DMX) used as add/drop nodes integrating two EDFAs, serving as a booster and pre-amplifier. The two bidirectional signal transmitted by opposite nodes are separated by blue-red filters. After the receiver DMX, a 10/90 splitter is used to extract a small amount of power (-20 dBm) to feed a commercial polarimeter (Novoptel PM1000) monitoring the Stokes parameters evolution, while the rest is used to receive data at the SFP+ module. The bidirectional link is made of two standard single mode fiber (SMF) spools with a polarization scrambler (Novoptel EPS1000) between them. While the first spool has a fixed length, the second has been varied to simulate an event happening in six different positions in the overall span length. The scrambler is used in to emulate the fast Stokes parameters variations similar to the one caused by the local birefringence modulation induced by an external pressure wave. In this experiment we emulate the SOP footprint due to the passage of the front and rear car's axle across the mini/micro trenches for fiber cable installation on the roadway. Fig.2 report the comparison between the Stokes evolution recorded on the metropolitan ring [8] (blue) and the scrambler emulated (red). The considered Stokes waveform propagates towards both nodes and can be detected [8, 10] by the SOP monitoring device (the polarimeter) after proper filtering of the acquired Stokes. The polarimeters, operating at 3.1 Msamples/s (about 64 meters of spatial resolution), are interconnected by a BNC cable sharing the same time axis reference. The time difference in the stokes waveform detection can be translated in a spatial difference, so that the localization problem coincide with the spool length estimation using the counter-propagating Stokes cross-correlation. Table 1 reports the SOP estimations varying the 2nd spool length, compared to the precise length characterization obtained with an optical time-domain reflectometer (OTDR) and the consequent error (the difference). In all the cases we obtained a localization accuracy below 100 meters, although in this setup we do not have any cause of additional SOP variations acting as noise. A crucial aspect is related to the required sampling rate to obtain a certain accuracy, as it impacts the system cost and complexity. We thus focused on the 6th case with spool 2 of 16.518 km, varied the sample rate from 0.1 MSamples/s to 3.1 MSamples/s and plotted the localization error in Fig.3, showing that it decreases from around 1.5 km to less than 100 m at 3.1 MSamples/s, although it reaches similar low values at 1.0-1.5 MSamples/s. This result suggests that acceptable estimation errors can be obtained with reasonably low cost/complexity ADC circuits. A simpler PBS-based system can be also used to estimate the SOP variation [9], whose accuracy will be verified in future works. Finally, another important aspect is the time synchronization accuracy between the SOP monitoring devices, as the BNC cable connection method cannot scale outside the laboratory. We found out that the required synchronization should be of the tens of microseconds order, so that timing protocols such as the Precision Time Protocol (PTP) [11] or the white rabbit [12] can be used, whose accuracy scales down to the sub-microsecond regime. Alternatively, equipping the NEs with GPS modules would go to the nanoseconds [13] range and also provide additional accurate node geographical localization.

3. Waveplate Model-based Earthquake Stokes Simulator

There's a lot of interest in using fiber sensing for early disaster warning as in the case of earthquakes. DAS systems are very accurate as distributed seismic sensor, but costly and with a limited range. A DAS system is capable to measure the small fiber elongation due to a seismic wave crossing the DAS fiber. Fig.4(a) shows 4 seconds of DAS traces along 10 km of fiber of an earthquake recorded in Iceland in 2015 [14]. Each vertical trace represents the fiber elongation during the considered timespan at a fixed fiber point. Traces are acquired every 4 meters at 200 Hz sampling frequency. Typically, the so called earthquake S-wave of an earthquake is anticipated by a weaker P-wave of around 1 or 2 seconds [14], which can be seen to start at around 0.5-1 second in Fig.4(a). Hence, a reliable earthquake sensing implementation in data networks would greatly expand the capability to raise timely warning signals. In the previous experiment we have emulated the SOP footprint due to car passages over a deployed fiber, easy to capture in urban areas. It would



(a)



(b)

Fig. 4: (a) DAS measured earthquake seismogram [14]. (b) Stokes parameters evolution simulated from DAS measurement.

be more useful to emulate the SOP evolution waveform of an earthquake, since it is not a common to observe it directly. It can be then replicated in the laboratory using a polarization scrambler to test the detection and localization of synthetic earthquakes. We have thus developed a simulator which produces the Stokes parameters footprint of a test-earthquake given its fiber strain versus time and fiber length as recorded by a DAS system. The simulator is based on the waveplate model as in [15], thus modelling the optical fiber as a sequence of linear birefringent elements. At this development stage, the circular birefringence is neglected. The simulator subdivides the fiber in segments equal to the fiber correlation length (around 20 meters) and for each segment generates a random orientation of the birefringence principal axes. The retardation between the fast and slow axis for each segment is instead obtained from the DAS strain measurement. By iteratively multiplying the input state of polarization and the rotation/retardation matrices of each segment we obtain the output SOP at a given time instant and thus for the whole timespan measured by the DAS. Fig.4(b) reports the stokes parameters evolution using the strain of Fig.4(a) as input. The obtained SOP evolution can be then propagated even through a deployed metropolitan fiber segment to test the detection in presence of other source of SOP variations.

4. Conclusions

We have proposed a network architecture for sensing requiring limited hardware addition to the existing telecommunication networks. We demonstrated the detection and localization of events by means of SOP monitoring technique on IMDD channels and proposed a method to emulate SOP variations caused by real earthquakes. Next investigation will test the synthetic events emulation to assess the earthquake detection performance in presence of additional SOP noise caused by anthropic activities in urban environemnt.

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