# Real-Time Demonstration of Anomalous Vibrations Detection in a Metro-like Environment using a SOP-based Algorithm

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**Abstract:** We demonstrate the real-time applicability of SOP-based anomalous vibrations detection. The proposed demo will engage the audience by showing the time evolution of two proposed metrics, with user-set parameters and different fiber-induced mechanical vibrations. 

## 1. Overview

Fiber sensing over metropolitan optical networks has attracted huge interest over the last few years. The urban scenario is dense with anthropological activities (e.g., construction works), which can severely compromise the health of fiber networks (e.g., fiber cuts). Several recent papers [1,2] demonstrated the possibility to use commercial coherent transceivers to detect human activities in a metropolitan environment, by exploiting information that can be extracted at the receiver DSP, such as the optical phase or the light State of Polarization (SOP). In particular, SOP is a fundamental property for environmental sensing: because of stress-induced birefringence [3,4], it is very sensitive to mechanical stresses. Sensing hazardous conditions would not need additional hardware, because the SOP is already estimated by coherent receiver DSP to demodulate Polarization Division Multiplexing (PDM) coherent signals. Moreover, a typical underground cable installed in a metropolitan environment contains several fiber pairs, which are able to gather information about events happening in the surroundings of the cable. Consequently, a robust monitoring algorithm is needed to process the SOP information and thus detect anomalous conditions rising near the cable, with the goal of delivering early warnings before hazardous events. Therefore, in this work we propose a demo implementation of a real-time algorithm for anomaly detection over metropolitan fiber networks, exploiting the SOP information that may be extracted by standard commercial coherent receivers. In particular, we will mostly focus on automatic detection of anomalous mechanical vibrations hitting a part of the monitored fiber. The demo will show two different approaches to SOP monitoring, particularly focusing on the reaction of both methods to different mechanical stresses applied on the fiber under test. For practical reasons and to reduce the amount of hardware to be transported to the OFC2024 demo room, we will demostrate our real-time algorithms using a polarimeter, and not a coherent receiver. Anyway, as explained in detail in [3,4] when using SOP-based sensing, the two approaches (polarimeters and coherent receivers) are substantially equivalent.

## 2. Innovation

A proper automatic anomaly detection algorithm is necessary for SOP monitoring over metropolitan fibers for anomalous vibrations sensing, to generate warnings/alarms in a telemetry system. Our latest work [5] in this area proposed a blind algorithm able to detect a wide range of different anomalous events, experimentally tested on a metropolitan fiber link using a mechanical shaker to introduce different types of vibrations (changing amplitude and frequency). The main issues addressed in the development of the algorithm were: i) the non-stationary nature of the SOP in an urban environment, which made non-adaptive algorithms struggle with events detection; ii) the detection of weak vibration events; iii) the minimization of false alarms and false positives on the detection systems. A reliable anomaly detection algorithm should adapt to the evolving conditions of the urban environment, due, for example, to the change of traffic and temperature conditions, affecting the SOP. Moreover, the vibrations induced on the fiber by an hazardous event may be very weak because of the cable "mechanical" isolation: it is thus fundamental to achieve a good sensitivity to low intensity events, so that the warning for rising hazardous conditions could be triggered far in advance. The algorithm proposed in Fig. 1 relies on the SOP representation in Stokes space $\mathbf{S} = [S_1,\ S_2,\ S_3]^T$, working on the real-time SOP samples coming from a polarimeter (PM). This is a dedicated device, substituting the coherent receiver DSP in providing the SOP estimate, but we remark that the algorithm is completely agnostic on the method used to extract the SOP. The two approaches shown in Fig. 1 are based on different metrics, but they follow the same steps: i) acquire the discrete time evolution of the Stokes vectors $\mathbf{S}[n]$ from the polarimeter; ii) compute a single-dimensional metric, as described in details in the following (light blue block in Fig. 1a) and yellow block Fig. 1b)); iii) apply a low-pass filter and obtain the alarm signal

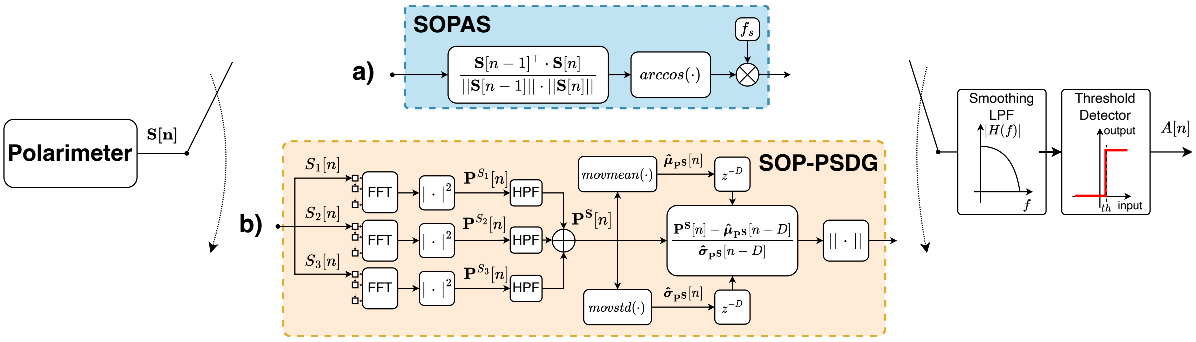


Fig. 1. Anomaly detection algorithm based on a) SOPAS and b) SOP-PSDG computation.

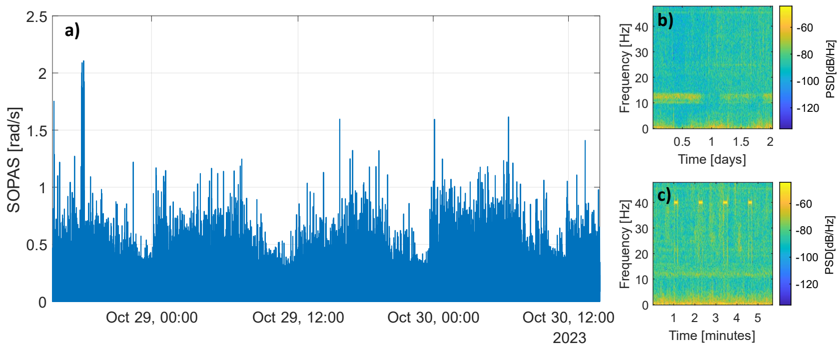


Fig. 2. a) 4 days SOPAS time evolution, b) 2 days $S_3$ spectrogram, c) $S_3$ spectrogram when inducing 40 Hz mechanical vibrations on the fiber. Metropolitan fiber is always considered for these plots.

$A[n]$ through a threshold. Both metrics will be presented in the demo in order to compare a static, non-adaptive, approach and an adaptive one, which we think is the most beneficial way to address the problem. In Fig. 1a), the first metric, called State Of Polarization Angular Speed (SOPAS), is computed. This metric evaluates the angular change rate between two consecutive Stokes vector samples, it thus only needs the $(n-1)$th polarization state, and has no memory of the previous ones. In our SOPAS-based algorithm, we simply apply an amplitude threshold on this signal, giving an alarm when the (low-pass filtered) SOPAS signal goes above it. The key free parameter in this algorithm is the threshold value, which should be selected to find an optimal compromise between high false alarm probability (when the threshold is set too low) or high missed detection probability (when the threshold is set too high). An example of the SOPAS evolution over a few days of Turin metropolitan fiber acquisition is reported in Fig. 2a). It is well noticeable how the metric is highly varying with 12 hours periodicity, due to temperature and traffic variations, and a detection algorithm based on a fixed threshold would struggle to give correct alarms. The second metric, shown in Fig. 1b), is instead called SOP-Power Spectral Density Gap (PSDG). The working principle consists in computing the overall real-time PSDs evolution of the Stokes parameters ($S_1[n]$, $S_2[n]$, $S_3[n]$) $P^S[n]$ and compare it with the average past PSD evolution $\hat{\mu}_{PS}[s]$, computed in the $movmean(\cdot)$ block. The element-wise division is by $\hat{\sigma}(P^S)$, which collects the past PSD standard deviation values, computed in the $movstd(\cdot)$ block. Additionally, the euclidean norm is evaluated to generate the output SOP-PSDG signal. In a nutshell, the key idea of this algorithm is to trigger an alarm when the current PSD is "too far" (from an euclidean distance point of view) from the long-term previous average. This algorithm, thanks to being PSD-based and thus frequency-resolved, has proved to deliver better performances with respect to the SOPAS. As an example, the spectrogram of the $S_3$ parameter evolution over a two days acquisition on a metropolitan fiber is in Fig. 2b). It's clear how some frequency component (for example the one right above 10 Hz) are slowly disappearing and reappearing again, once again underlying the need of having an adaptive metric. Moreover, if inducing an intermittent sinusoidal 40 Hz vibration on the fiber, frequency components are very clearly appearing on the $S_3$ spectrogram, as shown in Fig. 2c). This proves that the spectral information are precious to be used to build a detection metric. The dependency of this metric to the previous SOP conditions allows to make the metric adaptive, and with an enhanced sensitivity to weaker polarization fluctuations. The delay $D$ is instead introduced to avoid short anomalies to be absorbed by the algorithm, thus making the metric less sensitive to them. As previously mentioned, a threshold is applied on the low-pass filtered version of both metrics, in order to generate an alarm signal when the latter is exceeded. We envision that this would be the behavior of a final software version installed in a metropolitan network, while the focus of this live demo will be on showing the real time evolution of the two different metrics on a 20 km long fiber spool and using 1-2 mechanical shakers to induce fiber vibrations.

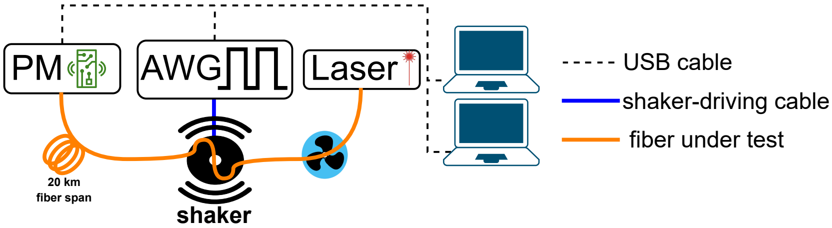


Fig. 3. Demo hardware scheme.

## 3. OFC Relevance

SOP-based optical fiber sensing is a truly challenging field which has had great resonance over the last years, first in the academia and recently in the industry. The growing interest in this subject has lead to incredible works and discoveries but still, to the best of our knowledge, no real-time monitoring algorithm implementation has been presented, particularly for a (very noisy) metropolitan scenario. Moreover, as discussed in Section 2, the choice of a resilient and reliable metric is of fundamental importance to have a secure early warning algorithm. The literature on this specific topic seems to be quite limited even if, in our opinion, having a solid detection algorithm is one of the most important points to be addressed. Presenting a concrete real-time application of two different algorithms could thus be very engaging for the OFC audience, particularly catching the attention of all the people working in polarization-based optical fiber sensing, but also of the more generic fiber sensing and DSP communities. We think that the audience would be engaged in concretely understanding the peculiar challenges of practical real-time polarization monitoring in metropolitan networks, and to see first-hand the capabilities of our SOP-PSDG based algorithm.

## 4. Demo content & implementation

We pictured this demo with the goal of letting the audience not only experience how the proposed metrics react to different solicitations/mechanical vibrations on the fiber, but also to allow them to be able to change parameters and the type of waveform with which the shaker could be driven, i.e. mechanical stress on the fiber. In this way, the potential of the SOP-PSDG based algorithm, compared to the SOPAS based one, could be made clear in a much more concrete and application-oriented way than only seeing the processing scheme or discussing results. We envision to have the hardware organized as in Fig. 3, including: i) one polarimeter (Novoptel PM1000); ii) one laser; iii) one electrical Arbitrary Waveform Generator (AWG) connected to a small mechanical shaker (3B scientific U56001) to generate controlled vibrations with given amplitude and frequency; iv) short span (i.e. few meters) of SMF glued on the mechanical shaker plate, where the vibrations will be induced, followed by a 20km SMF fiber spool; v) two laptops, separately connected with USB cables to the polarimeter and the AWG. A standard small cooling fan will also be placed below the fiber under test to simulate the effect of a constant vibration (which realistically could be generated by coherent transceivers fans) acting over it, showing the resiliency and adaptive behavior of the SOP-PSDG metric. The demo will be presented to the audience as two different Graphical User Interfaces (GUI), on the two laptops. One of the two will drive the type of mechanical vibration induced on the fiber (trough the AWG), allowing the user to change parameters such as intensity (translating in swing amplitude of the shaker, which can range up to 4 mm), vibration frequency (or bandwidth), and waveform type. Among the possible waveforms that the audience would be able to select there would be, for example: sinusoidal wave, Gaussian noise wave, square or triangular wave, frequency chirp. The second computer would instead show a GUI in which the two different metrics, SOPAS and SOP-PSDG will be shown in real-time, in order to see their reaction to the chosen mechanical solicitation. Some parameters of the SOP-PSDG could be tweaked, such as the lengths of moving average and standard deviation, delay and FFT. Once selected the mechanical stress, the user will select all the processing algorithms parameters and start the real-time processing, which outcome could be seen on the laptop screen. The reaction of the algorithms with the chosen vibration could be seen in real time, which we think would be very engaging for the audience.

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