

Overview on the state of polarization sensing: application scenarios and anomaly detection algorithms

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Overview on the state of polarization sensing: application scenarios and anomaly detection algorithms / Pellegrini, S., Minelli, L., Andrenacci, L., Rizzelli, G., Pileri, D., Bosco, G., Della Chiesa, L., Crognale, C., Piciaccia, S., Gaudino, R.. - In: JOURNAL OF OPTICAL COMMUNICATIONS AND NETWORKING. - ISSN 1943-0620. - ELETTRONICO. - 17:2(2025), pp. A196-A209. [10.1364/jocn.537881]

Availability:

This version is available at: 11583/2996903 since: 2025-01-24T06:42:46Z

Publisher:

Optica Publishing Group

Published

DOI:10.1364/jocn.537881

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To be published in Journal of Optical Communications and Networking:

Title: (OFC 2024) Overview on State of Polarization Sensing: Application Scenarios and Anomaly Detection Algorithms

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Accepted: 26 November 24

Posted 06 December 24

DOI: <https://doi.org/10.1364/JOCN.537881>

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Overview on State of Polarization Sensing: Application Scenarios and Anomaly Detection Algorithms

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Abstract: Given the ubiquity of optical fiber networks in both terrestrial and submarine environments, leveraging these facilities for sensing anomalous conditions alongside telecommunications can provide significant added value. In this context, distributed acoustic sensing (DAS) systems have been widely employed and discussed, due to their sensitivity and ability to locate events. However, integrating them within existing networks is complex and expensive. On the other hand, the received state of polarization (SOP) is also sensitive to external factors and it can be used for sensing: in this case, no extra hardware would be required since the SOP is already estimated in coherent receivers for data demodulation. The sensing information is provided “for free” by the already installed hardware, potentially requiring only a software upgrade. In this work, we analyze the feasibility of using polarization-based sensing to detect anomalous conditions in metropolitan environments. A polarimeter was used to evaluate SOP noise induced by urban factors, while a commercial coherent transceiver was employed to assess SOP estimation noise. We propose two algorithms for processing polarization data: a time-based method called SOP angular speed (SOPAS) and an adaptive, frequency-based approach named SOP-Power Spectral Density Gap (SOP-PSDG). These algorithms were compared by processing Stokes vector samples from the polarimeter when different sinusoidal vibrations are applied to the fiber, through a mechanical shaker. Results demonstrate that a sampling rate of just a few tens of Hz is sufficient to effectively identify various hazardous conditions, with SOP-PSDG consistently outperforming SOPAS. Additionally, preliminary findings on the performances of these algorithms using SOP samples from a commercial coherent receiver are discussed.

1. Introduction

In recent years, given the widespread installation of optical fiber networks in terrestrial and submarine scenarios, there has been an increasing research interest in using pre-installed optical fiber infrastructures to monitor the external environment. Various events could pose a risk not only to the fiber cables themselves but also to people’s safety and infrastructure’s integrity. Distributed fiber sensing techniques are experiencing increasing growth, especially in the last years, given their sensitivity to mechanical perturbations coming from the fiber cable’s surroundings, and possibly anticipating dangerous conditions to which early warning would be necessary. For geophysical and civil engineering applications, Brillouin-based sensing and Rayleigh-based Distributed Acoustic Sensing (DAS) are the two main techniques, sensitive to mechanical stresses and temperature variations [1, 2]. The working principle is the same for both of them: light backscattering is exploited to sense and locate any condition generating axial strain on the fiber. Among the two, DAS-based systems are finding the largest appreciation for metropolitan monitoring [3, 4] and earthquake detection [5–7], thanks to their ability to detect dynamic events, such as mechanical vibrations up to the kHz range. DAS systems have proven to deliver

46 outstanding results, particularly among the geophysics community, given the optical fibers'
47 unrivaled spread, especially in submarine environments where they are the only medium lying on
48 the ocean seafloor that can be used as a sensor. For this reason, there is a growing interest in
49 merging their data transmission capabilities with their sensing ones. Monitoring the metropolitan
50 environment is also fundamental in providing early warnings for conditions jeopardizing the
51 optical fiber networks' health status, such as fiber cuts. To ensure good compatibility between
52 telecommunication fiber systems and sensing, DAS can be a viable solution [8, 9], but some
53 concerns need to be addressed. Firstly, DAS is limited in sensing distance by both the amount of
54 backscattered power, which lowers the sensing range to around 100 km, and by the presence of
55 optical amplifiers that include isolators (e.g. EDFAs), which completely block light backscattering.
56 The use of properly engineered "dark fibers" would ease the former, but they do not match the
57 fiber type already installed for telecommunication applications. Secondly, narrow linewidth
58 lasers [10, 11] are not part of the usual commercial coherent transceivers, but are essential for
59 the proper functioning of DAS systems. Additionally, the amount of data generated is huge:
60 since they are resolved in time and space, the stream generated would be complex to manage and
61 could represent an actual bottleneck to real-time early warning for hazardous conditions. For
62 these reasons, integrating DAS with the existing telecommunication infrastructure may not be
63 cost-effective in most cases.

64 In this context, an alternative approach might be to monitor the light's optical phase or
65 state of polarization (SOP) at the receiver side [12]. However, since both techniques are
66 length-integrated and based on forward transmission, they do not rely on backscattering, making
67 accurate event localization more challenging. On the other side, the sensing distance is not
68 limited by low back-reflected power, or by EDFAs isolators, allowing for much higher ranges.
69 Regarding phase sensing, several works demonstrated its reliability in monitoring earthquakes
70 in submarine [13] and terrestrial [14–18] environments, proposing algorithms to resolve events
71 localization, particularly over long-haul links [19]. Research has been conducted to adapt
72 coherent transceivers in processing data for sensing applications [20]. Despite the reliability
73 achieved by optical phase sensing, the system requirements do not match the usual equipment
74 used for telecommunications by coherent transceivers, since phase sensing requires ultra-narrow
75 linewidth lasers. Cost-efficiency would then again be compromised, as the already installed
76 telecommunication hardware could not be exploited as it is.

77 State of polarization monitoring [21–29] can be used as an alternative technique to optical phase
78 monitoring. Geometrical deformations [30, 31], mechanical stresses, and vibrations [32–34], due
79 to the photoelastic effect, change the dielectric tensor of glass [35, 36], inducing fiber birefringence
80 and affecting light polarization at its output. Sensitivity to the agents mentioned above has been
81 demonstrated in various works in both the submarine [37, 38] and the terrestrial [23] environments.
82 Since standard coherent receivers already need to estimate the polarization state to perform data
83 demodulation, the sensing-related information would thus be obtained almost completely "for
84 free" [20, 39, 40], provided that a transceiver input/output monitoring channel delivering SOP
85 data and a software capable of processing them in real-time are made available. Moreover, the
86 amount of data to process is also limited since no space resolution is available, as opposed to the
87 DAS.

88 The work presented in this manuscript is an invited extension of [41], which also builds upon
89 our previous research [42, 43]. We focus on a possible implementation of a polarization-based
90 sensing system in a metropolitan environment, able to provide fast real-time alarms whenever
91 an anomalous condition, possibly due to hazards, is detected. This discussion will cover the
92 practical feasibility of SOP-based sensing, including the required digital signal processing,
93 experimental demonstrations, and resulting detection performance. In Section 2 we will discuss
94 SOP data extraction from coherent receivers, focusing on the accuracy of the estimates and the
95 associated sampling speed. Once we establish the baseline conditions required for polarization

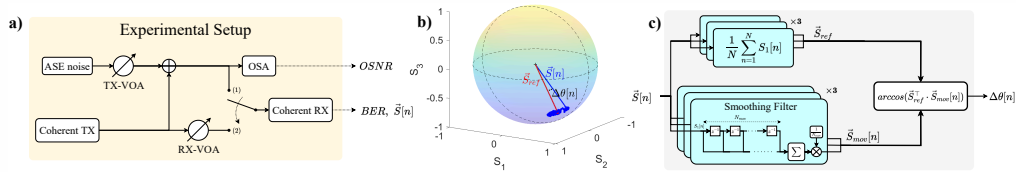


Fig. 1. (a) experimental setup. When connection (1) is selected, the coherent RX considers ASE noise injected in the system. When instead connection (2) is selected, ASE noise is excluded. (b) Poincaré sphere showing the \vec{S}_{ref} (in red) and $\vec{S}[n]$ (in blue) vectors and the angular deviation $\Delta\theta[n]$. (c) Post-processing scheme exploited to compute the angular deviation $\Delta\theta[n]$. A long-term average of N samples over the whole $\vec{S}[n]$ time series is employed to obtain \vec{S}_{ref} vector. A smoothing filter is applied over each single Stokes parameter time evolution to obtain instead $\vec{S}_{mov}[n]$. The last block shows how the angular deviation $\Delta\theta$ is computed.

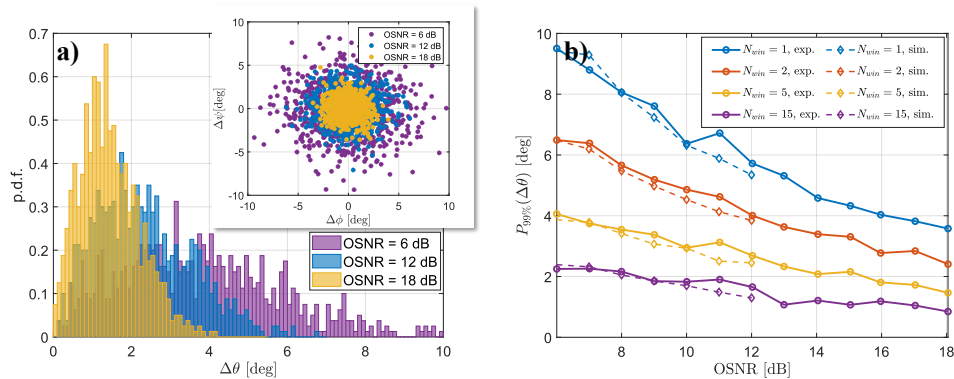


Fig. 2. (a) $\Delta\theta[n]$ histograms at three different OSNR levels. The inset reports the cloud distribution of the SOP points over the Poincaré sphere surface, in angular coordinates. (b) $P_{99\%}(\Delta\theta)$ vs. OSNRs for different moving average windows N_{win} (experiments and numerical simulation).

96 data extraction, Section 3 will detail the state of polarization noise induced by the metropolitan
 97 environment, where the experiments in Section 4 have been carried out, simulating hazardous
 98 conditions that could potentially jeopardize the health of metropolitan fiber networks. Section 5
 99 will introduce and propose SOP-based signal processing algorithms. Section 6 will compare
 100 their detection performance under hazardous conditions. Final observations and conclusions will
 101 be presented in Section 7.

102 2. Accuracy of state of polarization estimate from coherent receivers' DSP

103 This section experimentally examines the physical layer parameters that influence the accuracy of
 104 SOP estimation using standard coherent transceivers. The experiments detailed herein utilize a
 105 commercial transceiver capable of providing the received light SOP estimate through its internal
 106 receiver DSP (a typical scenario for SOP-based sensing). In the following, we assess the accuracy
 107 of the SOP estimate over different system conditions:

- 108 1. **Performance limited by ASE noise:** employing ASE noise loading, this scenario emulates
 109 long-haul optically amplified transmissions with sufficiently high received optical power
 110 (ROP). Results will be presented for different values of optical signal-to-noise ratio (OSNR).

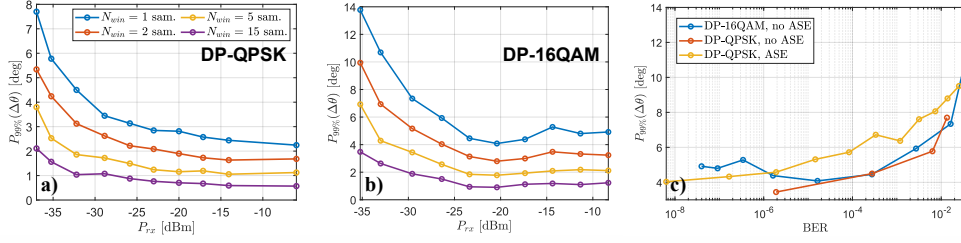


Fig. 3. $P_{99\%}(\Delta\theta)$ vs. ROP for (a) DP-QPSK and (b) DP-16QAM, using different averaging windows. Legend in (a) applies also in (b). (c) $P_{99\%}(\Delta\theta)$ vs. BER levels in all the considered situations, with $N_{\text{win}} = 1$.

111 **2. Performance limited by the ROP:** this scenario emulates short-reach, non-optimally
 112 amplified single-span systems, with no ASE noise and low ROP, using either DP-QPSK or
 113 DP-16QAM modulation.

114 A scheme of the experimental transmission system is shown in Fig. 1(a). To avoid stress-
 115 induced birefringence and geometrical deformations, all the fiber cords were fixed on a stable
 116 optical bench, ensuring a nominally constant received SOP. Conventionally, the Variable Optical
 117 Attenuators (VOA) have been named TX-VOA (transmitter side) and RX-VOA (receiver side).
 118 When performing experiments with ASE noise loading, the coherent receiver (RX) has been
 119 connected to the coherent transmitter (TX) through connection (1) in Fig. 1(a). On the contrary,
 120 in the experiments without ASE noise, the coherent RX has been connected to the coherent TX,
 121 cascaded with the RX-VOA, through connection (2). The commercial transceiver can output
 122 SOP samples at about 20 S/s, and record the related BER during the acquisition.

123 In parallel to the experiments, we also run time-domain simulations of the optical system,
 124 assuming a standard coherent RX [44] operating at 2 Samples/symbol, using an LMS-based
 125 2×2 adaptive equalizer, with $N_{\text{tap}} = 16$ taps. The input signal $x[n]$ and the output signal $y[n]$ at
 126 this stage are related by $y[n] = \mathbf{W}[n] \cdot x[n]$, where n is the discrete time index and $\mathbf{W}[n]$ the
 127 equalization matrix defined in (1):

$$\mathbf{W}[n] = \begin{bmatrix} \mathbf{w}_{11}^{(m)}[n] & \mathbf{w}_{12}^{(m)}[n] \\ \mathbf{w}_{21}^{(m)}[n] & \mathbf{w}_{22}^{(m)}[n] \end{bmatrix}. \quad (1)$$

128 Here, m represents the tap index. Each element of the equalization matrix is an $N_{\text{tap}} \times 1$
 129 vector, whose DC component is equal to $\bar{w}_{ij}^{(m)} = \sum_{m=1}^{N_{\text{tap}}} w_{ij}^{(m)}[n]$ with $i, j = 1, 2$. Note that the
 130 DC component of either column of $\mathbf{W}[n]$ is a Jones vector that can be used to compute the
 131 corresponding Stokes parameters, defined as (considering the first column of the matrix in (1)):

$$\begin{aligned} S_0[n] &= |\bar{w}_{11}[n]|^2 + |\bar{w}_{21}[n]|^2 \\ S_1[n] &= |\bar{w}_{11}[n]|^2 - |\bar{w}_{21}[n]|^2 \\ S_2[n] &= 2 \cdot \text{Re}(\bar{w}_{11}[n] \cdot \bar{w}_{21}^*[n]) \\ S_3[n] &= -2 \cdot \text{Im}(\bar{w}_{11}[n] \cdot \bar{w}_{21}^*[n]). \end{aligned} \quad (2)$$

132 In (2), $(\cdot)^*$, $\text{Re}(\cdot)$ and $\text{Im}(\cdot)$ are the complex conjugation, real part, and imaginary part operators,
 133 respectively. In the following discussion, we will refer to the Stokes parameters using the
 134 normalized Stokes vector $\vec{S}[n] = [S_1[n], S_2[n], S_3[n]]$, where each element is normalized with
 135 respect to $S_0[n]$. We extracted the equalizer tap coefficients every 200 ns while processing a
 136 sequence of 20 million samples, leading to a SOP sampling frequency f_s of 5 MS/s. In all cases,

137 both experiments and simulations, the transmission is operated back-to-back at 34 GBaud (QPSK
 138 line rate is 100 Gbit/s, 16-QAM line rate is 200 Gbit/s), shaped with a square-root raised-cosine
 139 filter with roll-off $\rho = 0.2$.

140 To measure the SOP estimate accuracy, we evaluated the angular deviation of each Stokes
 141 vector with respect to a reference one. Figure 1(b) shows as blue dots the vector $\vec{S}[n]$ time
 142 evolution, extracted from the commercial coherent receiver, or numerical simulation equalizer.
 143 The red \vec{S}_{ref} vector is the reference to compute the angular deviation, denoted as $\Delta\theta$. The
 144 post-processing algorithm is shown in Figure 1(c). Each parameter $S_1[n]$, $S_2[n]$, $S_3[n]$ is passed
 145 through a moving average filter (Smoothing filter in Fig. 1(c)), with filtering window length N_{win}
 146 ($N_{win} = 1$ samples is equivalent to no-filtering). The output of this block is a smoothed version
 147 of the input Stokes vector time evolution, denoted as $\vec{S}_{mov}[n]$. Each Stokes parameter of the
 148 whole $\vec{S}[n]$ acquisition is also averaged over a total number of N samples inside the acquisition
 149 (long-term average in Fig. 1(c)), with N in the order of a few hundred samples. The output
 150 of this block is \vec{S}_{ref} , in red in Fig. 1(b). This represents a “ground-truth” vector, placed at
 151 the center of the noise cloud over the Poincaré sphere surface. We remind that in this specific
 152 experiment, fiber birefringence was intentionally constant over time, thus the SOP variations are
 153 only due to the estimation noise generated inside the coherent receiver. The angular deviation
 154 $\Delta\theta[n] = \arccos(\vec{S}_{ref}^T \cdot \vec{S}_{mov}[n])$ (right-most block in Fig. 1(c)), $(\cdot)^T$ being the transposition
 155 operator, gives an insight into the noise condition, representing the spread of the SOP noise
 156 cloud [45].

157 2.1. Performance in ASE noise

158 In this scenario, the coherent RX goes through connection (1) in the experimental setup (see
 159 Fig. 1(a)), allowing for the TX-VOA to control the injection of ASE noise. The OSNR values,
 160 ranging between 6 dB and 18 dB, have been measured with the OSA, while SOP samples were
 161 returned from a commercial coherent transceiver as Stokes vector time evolution.

162 Fig. 2(a) shows the probability density functions (pdf) of $\Delta\theta[n]$ for three different values of
 163 OSNRs (6, 12 and 18 dB) for DP-QPSK modulation format and $N_{win}=1$. The inset in the Figure
 164 also shows the SOP cloud spread in angular coordinates (i.e., mapped over two orthogonal rotation
 165 axes). As expected, these histograms show that, for higher OSNR values, the statistical spread
 166 on the $\Delta\theta[n]$ pdf is smaller and, in a practical sensing system, mechanical stresses generating
 167 higher deviations would be easier to detect, since less blurred by noise. To quantitatively assess
 168 this consideration, we introduce the 99th percentiles of the angular deviation, i.e. the angle
 169 $P_{99\%}(\Delta\theta)$ at which the probability of $\Delta\theta[n]$ exceeding it is 1%. Since the angular deviation
 170 is always positive and the pdf are not symmetrical, this evaluation metric is more suitable
 171 in assessing the distribution spread than either the mean value and/or the standard deviation.
 172 Fig. 2(b) shows $P_{99\%}(\Delta\theta)$ vs. OSNR for different values of N_{win} . Circle-marked lines represent
 173 the experimental results, while the diamond-marked dashed lines represent the time-domain
 174 simulations, demonstrating an almost complete match between the “ideal” condition used in
 175 simulations and experiments. The presented results seem thus independent from the actual
 176 RX DSP implementation details. The diamond-marked dashed lines are limited to 12 dB, the
 177 highest OSNR value at which we could obtain reliable BER values ($\sim 10^{-4}$) through time-domain
 178 simulations, with a reasonable expense of numerical effort and running time. We observe that
 179 for increasing N_{win} , $P_{99\%}(\Delta\theta)$ decreases, going for instance below 2° for $N_{win}=15$, for all the
 180 measured OSNR values. The moving average introduced to evaluate $\vec{S}_{mov}[n]$ can be implemented
 181 with very limited additional DSP complexity and can thus be used to reduce the impact of SOP
 182 noise significantly. The only trade-off to be considered is that when increasing N_{win} , the effective
 183 sample rate in SOP estimation is reduced. Consider also that the mechanical events to be detected
 184 have quite low-frequency content (few Hz to few tens of Hz) [3, 4, 13, 39, 46]. This eases the need

185 for extremely fast and high-cost processing hardware and also for complex SOP data storage
186 solutions.

187 2.2. Performance limited by low ROP (without ASE noise)

188 In this scenario, referring to the scheme in Fig. 2(a), connection (2) has been selected, thus
189 excluding the ASE noise loading, the TX-VOA, and the OSA. The ROP value $P_{r,x}$ has been
190 varied using the RX-VOA. Experiments have been repeated for DP-QPSK and DP-16QAM, with
191 BER and SOP estimates always recorded at the coherent RX in each situation. The experimental
192 results are shown in Fig. 3(a) and 3(b) in terms of $P_{99\%}(\Delta\theta)$ vs. $P_{r,x}$, and show a similar trend
193 to Fig. 2(b), so that the same system comments can be derived also for this ROP-limited situation
194 and for the two different modulation formats considered here. Once again, averaging controlled
195 by the N_{win} parameter confirms its strong impact on the accuracy, since it allows to lower the
196 percentiles up to around 1° in the best cases.

197 Fig. 3(c) shows $P_{99\%}(\Delta\theta)$ as a function of the BER measured for the different considered ROP
198 values at the output of the coherent receiver, when no smoothing is applied ($N_{\text{win}} = 1$). This
199 represents a practical way to assess the SOP angular accuracy in commercial systems, since
200 given a BER threshold set by the chosen FEC, it indicates the corresponding typical values
201 of $P_{99\%}(\Delta\theta)$. Moreover, in Fig. 3(c), the blue and red curves show a high degree of overlap,
202 suggesting that, in the absence of ASE noise, the relationship between $P_{99\%}(\Delta\theta)$ and BER is
203 quite insensitive to the modulation format. Finally, it can be observed that the yellow $P_{99\%}$ curve
204 in Fig. 3(c), corresponding to the situation in Subsection 2.2.1, is shifted above the others of
205 around 1° , clearly indicating a significant impact of the ASE noise in the system.

206 3. SOP environmental noise in metropolitan fibers

207 When implemented on a metropolitan optical fiber cable, a polarization-based sensing system is
208 inevitably influenced by the urban environment, which causes random SOP fluctuations (referred
209 to in this work as *SOP environmental noise*). External factors such as temperature changes, traffic,
210 and construction activities can induce fiber birefringence, resulting in SOP variations. This
211 section shows how some of these factors can affect the SOP. Differently from Section 2, where a
212 commercial coherent receiver was employed, all the following experiments were conducted using
213 a commercial *polarimeter*. As the SOP sampling frequency of the available coherent receiver is
214 fixed to 20 S/s by the internal telemetry system, it is not suitable to correctly characterize the
215 dynamic metropolitan environment and detect malicious mechanical events producing vibrations
216 at frequencies higher than about 10 Hz. On the other hand, the polarimeter allows for an arbitrary
217 adjustment of the sampling frequency up to the MHz range and thus enables a more complete
218 analysis of the proposed algorithms.

219 Figure 4 illustrates the experimental setup, which utilizes fiber cables deployed in the Turin
220 metropolitan area, with their endpoints located in our laboratory. Specifically, we primarily
221 used a 35-km fiber (green line in Fig. 4), while some experiments in Section 6 will also involve
222 the 10-km fiber (red line in Fig. 4). The setup comprises an external cavity laser operating in
223 continuous wave (CW) mode, with 0 dBm launch power and 100 kHz linewidth, and a Novoptel
224 PM1000 polarimeter for acquiring the SOP at the other endpoint. The sampling frequency is set
225 to 95.4 S/s, one of the f_s values available from the device, which is suitable for our purposes
226 given the low-frequency ranges typically excited by the urban environment [4]. The SOP data are
227 provided as the time evolution of normalized Stokes vectors.

228 To characterize the SOP environmental noise, we acquired the SOP evolution over the 35
229 km long metropolitan fiber in quiet conditions, without generating any external event. Figure
230 5(a) shows the evolution of the Stokes vector acquired for two days, starting from March 4th,
231 2023. At first glance, the statistics of the Stokes parameters exhibit gradual hourly changes.
232 These slow SOP variations generally exhibit a daily pattern: as shown in Figure 5(a), during

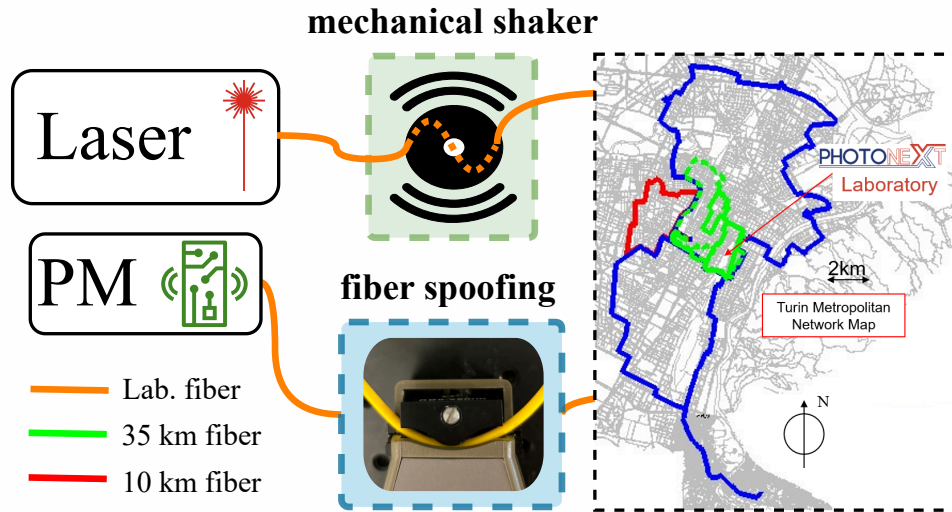


Fig. 4. Experimental set-up used for the experiments. The laboratory fiber is represented by the orange line. A mechanical shaker is applied to it (green-dashed block) before it enters the metropolitan ring while spoofing attempts (blue-dashed block) are generated just before the polarimeter. Green and red lines depict the fibers used for the experiments, running around Turin, measuring 35 km and 10 km, respectively. Blue line depicts a fiber that was not used for the experiments.

233 both March 4th and 5th, the SOP remains relatively stable around midnight, starting to deviate
 234 only a few hours before noon, likely due to increased human activities in the urban environment.
 235 When examining a shorter time window of a few tens of seconds (insets in Figure 5(a)), the SOP
 236 environmental noise becomes evident: the Stokes parameters display random fluctuations around
 237 their hourly-varying average values. On average, the recorded $P_{99\%}(\Delta\theta)$ value is 0.23° , which is
 238 lower than the ones obtained using a coherent receiver and discussed in Section 2.

239 The SOP fluctuation can be analyzed through the evaluation of the power spectral density
 240 (PSD) of S_1 , S_2 , and S_3 . Figure 5(b-d) shows the evolution of the PSDs (i.e., the spectrogram)
 241 of the three Stokes parameters. The three PSDs exhibit several common features: a high-
 242 magnitude zero-frequency component (red lines at $f = 0$), consistently high magnitudes in the
 243 frequency range between 5 and 15 Hz, and an intense pure frequency component at 46 Hz. To
 244 comprehensively observe all the frequency components in the SOP noise, Figure 6 illustrates the
 245 spectrogram corresponding to the sum of the three PSDs over the same time window as in Figure
 246 5(a). It can be clearly observed that this representation effectively captures the characteristics of
 247 the SOP noise, giving equal weight to each Stokes parameter and incorporating all the frequency
 248 components present in their relative spectra in Figure 5(b-d). Environmental agents indeed affect
 249 the Stokes parameters arbitrarily, depending on the current SOP. However, their contribution
 250 to the SOP spectrum remains consistent at specific frequencies, regardless of the direction the
 251 Stokes vector takes on the Poincaré sphere. This characteristic is exploited in the SOP-PSDG
 252 algorithm [42], which we will illustrate in Section 5.5.2. Additionally, as shown in Figure 6,
 253 certain intense low-frequency components (below 5 Hz) tend to be more intense around noon,
 254 corresponding with the daytime Stokes fluctuations observed in Figure 5(a). Conversely, the
 255 frequency range becomes less intense when reaching the nighttime hours.

256 Regarding the frequency components with significant magnitudes between 5 and 15 Hz, as

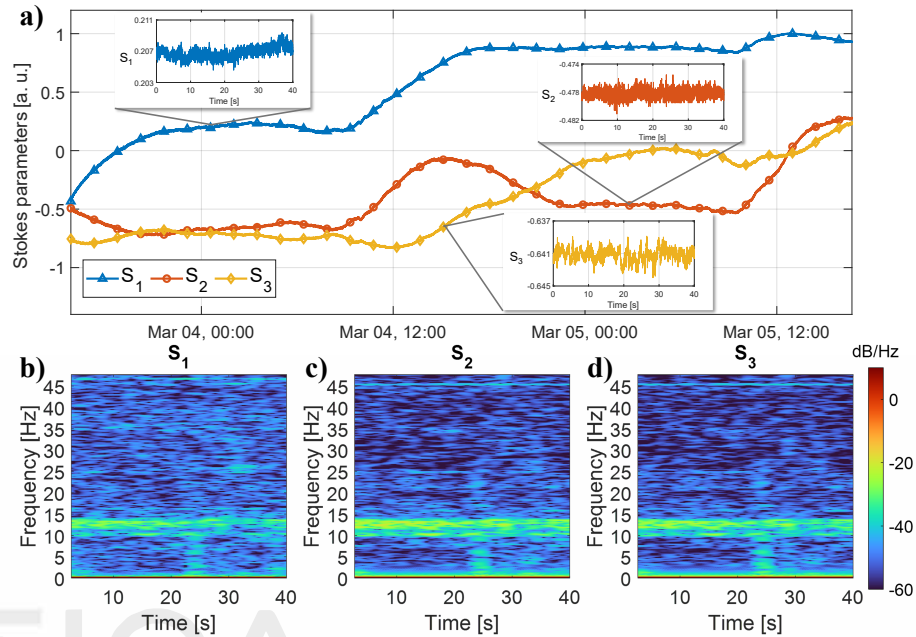


Fig. 5. (a) Stokes parameters time evolution over a two-days-long acquisition considering the 35 km long metropolitan fiber, started on March 4th 2023. Insets provide a 40 seconds zoom on one Stokes parameter, in different portions of the acquisition. (b-d) 40 seconds long spectrogram of the single Stokes parameters.

257 well as other higher-frequency tones that are less intense but almost perfectly constant, these
 258 do not appear to be caused by the urban environment. These frequency components are also
 259 observed when the metropolitan fiber is not part of the setup (i.e. when acquiring the SOP using
 260 only the optical fiber within the laboratory). The likely cause of this effect in the SOP spectrum
 261 is the presence of cooling fans near the optical fiber path, such as those in our laboratory. This
 262 condition is common in practical scenarios, such as central offices and data centers.

263 4. Anomalous conditions characterization

264 On top of the SOP environmental noise, characterized in the previous section, anomalous events
 265 affecting the optical fiber health status can generate SOP variations which can be analyzed both
 266 through angular deviation and SOP spectral analysis. These conditions will be discussed in the
 267 following subsections.

268 4.1. Mechanical vibrations

269 In the metropolitan scenario, fiber cuts and physical network infrastructure damages represent
 270 the most typical hazards. Maintenance or construction works, which usually employ excavators
 271 and jackhammers, can jeopardize the health of the underground fiber cables, with consequent
 272 re-installation costs and inconveniences for the vendors controlling the network services. Since
 273 the SOP is sensitive to mechanical stresses and geometrical deformations, the vibrations induced
 274 on the fiber before the occurrence of the actual damages could be used as an immediate early
 275 warning for potentially hazardous conditions.

276 In this analysis, we use a mechanical shaker to generate vibrations (green-dashed block in Fig.
 277 4) over a portion of the laboratory fiber (in orange in Fig. 4), assuming that no abnormal condition

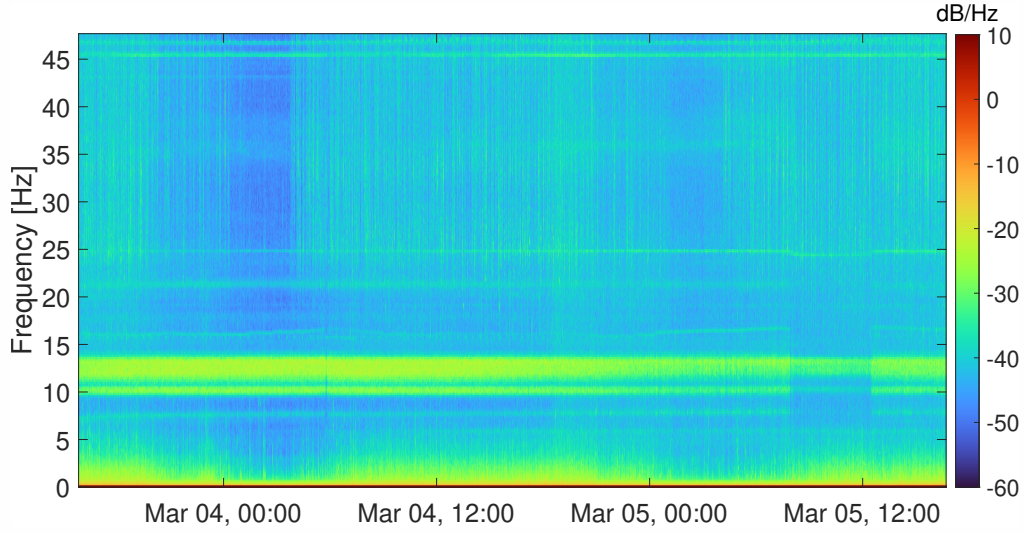


Fig. 6. Spectrogram of a 2-days acquisition over the 35 km long metropolitan fiber, obtained as the sum of the PSDs of the three Stokes parameters.

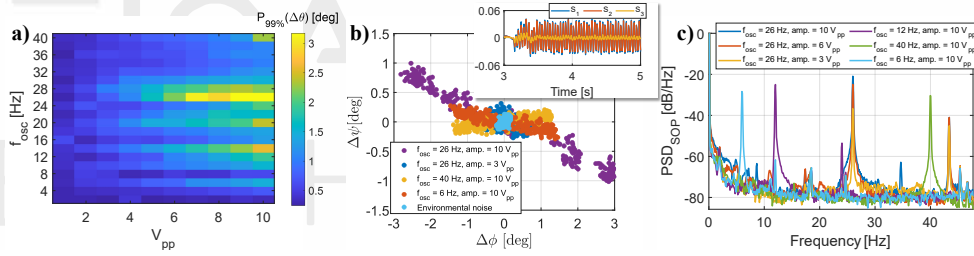


Fig. 7. (a) $P_{99\%}(\Delta\theta)$ values for different vibrations induced on the fiber, changing f_{osc} and V_{pp} . (b) angular coordinates plot showing the SOP cloud on the Poincaré sphere surface for different vibrations (purple, blue, yellow, orange dots), and for the environmental noise only (light blue dots), on the 35 km long metropolitan fiber. Inset shows the effect that vibration with $f_{osc} = 26$ Hz and amp. = $10 V_{pp}$ has on the Stokes parameters. (c) SOP PSDs for different vibrations induced on the fiber.

278 occurs on the 35-km metropolitan fiber during our tests. The laboratory fiber cable is a simplex
 279 standard single mode G.652 fiber patchcord with LSZH coating and 2mm diameter, while the rest
 280 of the metropolitan fiber uses standard telecom fiber cables, for which we do not have detailed
 281 information. Since fiber displacements, geometrical deformations, and stresses are generated
 282 during the experiments, they can be used to assess the effects that different vibrations of different
 283 intensities would have on the SOP. It should be pointed out that we will not accurately reproduce
 284 the effects that real-life maintenance works, jackhammers, or excavators [20] would have on the
 285 fiber before generating damages or cuts. The precise modeling of how they would couple on the
 286 fiber cable after ground propagation is out of the scope of this work. The mechanical shaker is
 287 driven by sinusoid signals generated by an analog waveform generator (AWG) and consists of a
 288 vibrating rectangular plastic plate, where one meter of fiber has been glued, oscillating in the
 289 vertical direction and generating a maximum displacement of 4mm. The oscillation frequency
 290 f_{osc} can be changed from the AWG, as well as its amplitude, expressed in peak-to-peak voltages,
 291 to which we will refer as V_{pp} units.

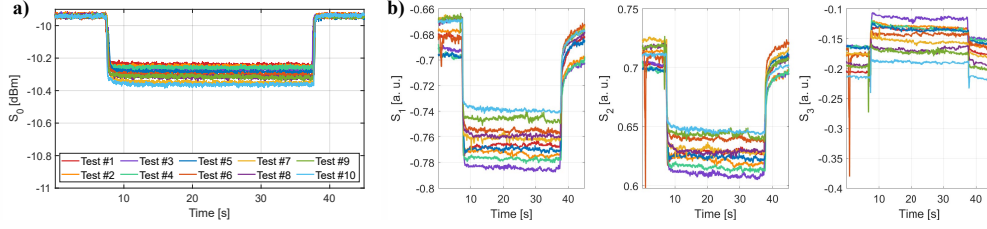


Fig. 8. Effect of fiber clamping on (a) the instantaneous power S_0 , and (b) the SOP as Stokes parameters S_1 , S_2 , S_3 . Legend in (a) applies also to all the plots reported in this figure.

292 We first characterize the vibrations by computing the angular deviation $\Delta\theta$ (consistently with
 293 what has been done in Section 2, but no smoothing has been applied in this case) of the SOP
 294 captured from the polarimeter, when the vibration is turned on. The map in Fig. 7(a) shows the
 295 values of $P_{99\%}(\Delta\theta)$ versus f_{osc} and V_{pp} . As previously mentioned in Section 3, the average
 296 value of $P_{99\%}(\Delta\theta)$ in quiet conditions is around 0.23° , thus shaker-induced angular deviations
 297 with similar values correspond to SOP variations comparable with environmental noise. In
 298 general, vibrations having amplitude higher than $6 V_{pp}$ and f_{osc} from around 12 Hz to 32 Hz
 299 seem to have non-negligible consequences on the SOP. The one generating the largest SOP
 300 variation occurs for f_{osc} values around 26 Hz with an amplitude of $10 V_{pp}$. However, it should
 301 be noted that the intensity of mechanical vibrations on the attached fiber depends not only on the
 302 oscillation frequency and amplitude but also on the geometry and material properties of the plate.
 303 To better observe the effects of the vibration on the SOP, Fig. 7(b) shows a scatter plot of the
 304 Stokes vector angular coordinates for different vibrations. The light blue cloud at the center of
 305 the graph represents SOP environmental noise only. When a vibration with $f_{osc} = 26$ Hz and 10
 306 V_{pp} is applied, it generates the largest spread (purple points in Fig. 7(b)), with a deviation of
 307 around 3° from the initial noise cloud, consistent with Fig. 7(a). Testing different f_{osc} and V_{pp}
 308 pairs results in reduced vibration-induced cloud spread (blue, yellow, orange).

309 Comparing these results to the ones illustrated in Section 2, it should be noted that mechanical
 310 oscillations yielding $P_{99\%}(\Delta\theta)$ values of 3° , i.e. the most intense generated in this case, would be
 311 difficult to be detected in that scenario. As observed in Figures 2 and 3, the $P_{99\%}(\Delta\theta)$ can reach
 312 as high as 8° to 14° when using commercial transceivers, although being strongly reduced to
 313 around 2° when filtering is applied. As a result, the mechanical vibrations considered in this study
 314 would be obscured by noise in most cases (at different ROPs, OSNRs and N_{win}). The inset of Fig.
 315 7(b) shows the high-pass filtered (HPF) time evolution of the Stokes vector when a vibration
 316 with $f_{osc} = 26$ Hz and amplitude $10 V_{pp}$ is applied. The HPF with a 3 Hz cut-off frequency is used
 317 to enhance visualization, eliminating the DC component and preserving the mechanical ones.
 318 Depending on the specific fiber displacement, geometrical deformations, and induced stresses,
 319 S_3 oscillates more weakly compared to the other Stokes parameters. Consequently, relying on
 320 a single Stokes parameter for event detection could be misleading, potentially resulting in a
 321 misinterpretation of the overall picture.

322 Regarding the frequency components, Fig. 7(c) shows the PSDs for various induced vibrations
 323 on the fiber. Similarly to the spectrograms in Figures 5(b-d) and 6, these PSDs have been obtained
 324 by summing up the single PSDs of the three Stokes parameters. The 26 Hz event generates the
 325 strongest component, which attenuates as the vibration amplitude is reduced from $10 V_{pp}$ (blue
 326 curve) to 6 (orange curve) and $3 V_{pp}$ (yellow curve), while the other two components at 6 Hz and
 327 40 Hz (green and light blue curves) are of comparable intensity. This picture provides valuable
 328 insights for the detection algorithms that will be discussed later, demonstrating that frequency
 329 content can be extremely useful for event detection.

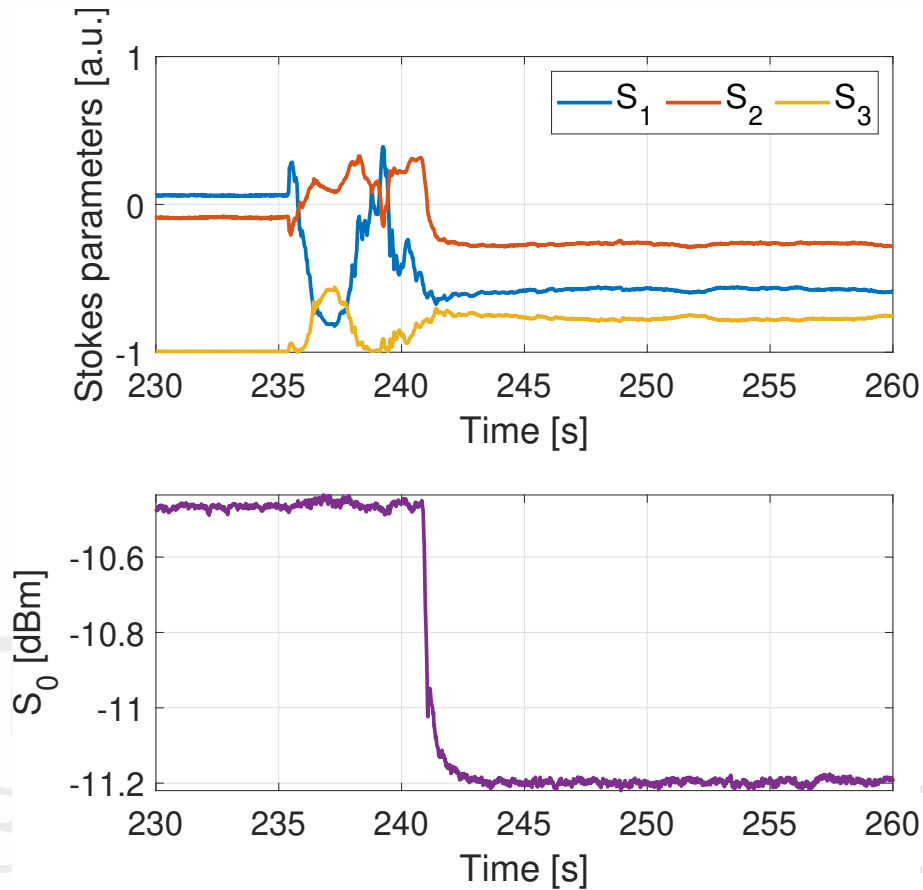


Fig. 9. Effect of hacker-like fiber spoofing on the Stokes parameters and on the instantaneous power S_0

330 4.2. Fiber spoofing

331 A malicious person, a hacker, could act on the telecommunication system's physical layer to
 332 eavesdrop on sensitive data and cause damage to the vendors. Among the different fiber-tampering
 333 techniques that have been identified [47], the most common one is fiber spoofing, which consists
 334 in macro-bending the fiber cable at a low curvature radius so that the total internal reflection
 335 condition allowing for light propagation is compromised and, in the bending point, light leaks from
 336 the fiber and can thus be captured by an eavesdropping device. One of the consequences for the
 337 communication system is a small received power drop [48, 49], in parallel with a bending-induced
 338 SOP variation [50], both of which can be detected by a SOP-sensing system.

339 In order to emulate this kind of event, we employed a commercial optical fiber identifier (OFI)
 340 tool which, as shown in Fig. 4 in the dashed-blue block, clamps the laboratory fiber (in orange
 341 in Fig. 4), connected to the 35 km metropolitan ring (in green in Fig. 4), and heavily bends
 342 it [51]. The clamping is controlled by a handgrip, which is tightened to bend the fiber inside the
 343 instrument. When the device detects light leakage, a fiber spoofing event is generated.

344 To characterize the signature that the macro-bends have on the SOP, initial experiments were
 345 carried out with OFI firmly secured to the optical bench, isolating it from external agents. The
 346 fiber was gently clamped for 30 seconds and then released. The polarimeter outputs the complete
 347 Stokes vector, with the S_0 component recording instantaneous power. The results of ten tests are

348 shown in Fig. 8(a). The closing/opening of the clamp (around 7 and 37 seconds, respectively)
349 cause the instantaneous power to transition gradually between levels over approximately one
350 second. When the clamp is instead completely closed and pressing on the fiber, S_0 remains
351 constant. To gain a more comprehensive understanding of S_0 's response, the fiber spoofing tests
352 were repeated about 120 times, revealing an average power drop of 0.3 dB.

353 Fig. 8(b) reports the behavior of the three Stokes parameters for the same ten tests, showing a
354 strong impact of the macro-bends on the SOP. To quantify the impact of macro-bends on the
355 polarization state [33], we computed the angular deviation as described in Fig. 1(c). Here the
356 reference Stokes vector \vec{S}_{ref} is the average Stokes vector measured a few seconds before the fiber
357 spoofing, while $\vec{S}[n]$ represents the time evolution of the Stokes vector when the clamp is closed.
358 For the 120 measured events, the average angular deviation $\Delta\theta$ was found to be 9° , which is three
359 times greater than the deviation caused by the most intense vibration discussed in the previous
360 subsection (see Fig. 7(a-b)).

361 In a real-life scenario, a malicious individual would likely manipulate the fiber before inserting
362 it into the device, rather than keeping it completely firm over a surface. Additionally, the device
363 would probably remain closed on the cable for several hours to intercept as much data as possible,
364 rather than just for a few seconds. This more realistic hacking situation is depicted in Fig. 9. In
365 this case, beyond the SOP angular deviation caused by clamping, the manipulation of the fiber
366 before bending it is also considered. The Stokes parameters in Fig. 9 show abrupt changes just
367 before the S_0 parameter drops, starting from second 235, when the fiber is handled to be inserted
368 in the OFI. The power drop itself occurs at the 241st second, when the macro-bend is introduced.
369 It is noteworthy that S_0 remains completely unaffected by any manipulation prior to clamping, as
370 no power leakage is generated. The same applies to the induced vibrations discussed in Section
371 4.4.1. Given these characteristics of fiber spoofing, a possible detection algorithm could jointly
372 monitor the Stokes vector and instantaneous power, triggering alerts only when both metrics
373 exhibit significant changes. This approach would help differentiate malicious activities from
374 generic power fluctuations or SOP variations caused by accidental, non-hazardous touches to the
375 fiber.

376 4.3. Lightning strikes

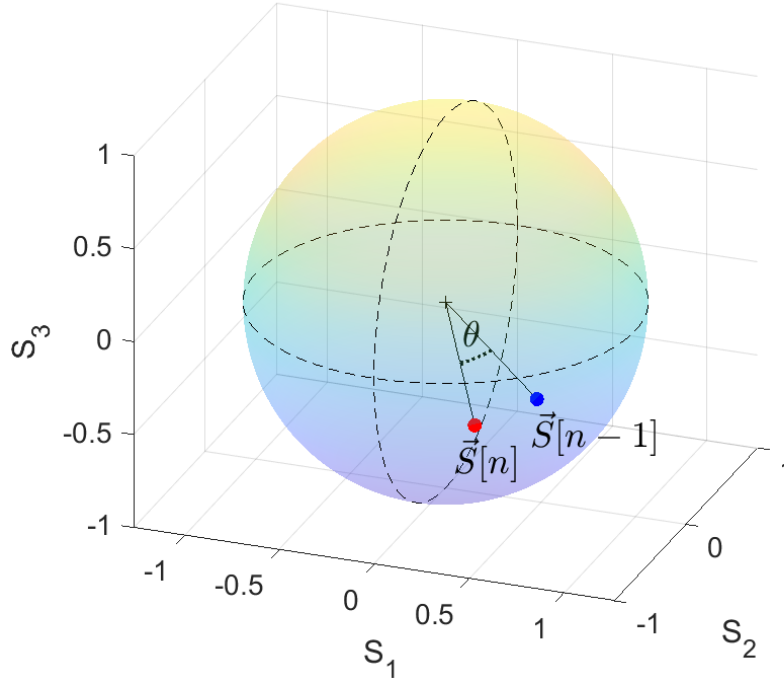
377 Lightning strikes occurring near underground fiber cables or hitting aerial fibers can induce
378 extremely rapid (krad/s to Mrad/s) polarization rotations due to the Faraday effect [52]. This
379 can cause a loss of polarization tracking and potentially disrupt communications [40]. Although
380 these events significantly impact the SOP, their duration is very brief, ranging from about 20 to
381 $60 \mu\text{s}$, as discussed in [53]. Therefore, lightning strikes are impossible to characterize and, most
382 importantly, detect at the sampling rate discussed until now in this work. One potential solution
383 for detecting such events could be to process the data stream directly from the coherent receiver
384 equalizer without any decimation, targeting an SOP sampling frequency in the tens of MS/s
385 range. However, managing the vast amount of data generated in this manner would be extremely
386 complex and requires further careful consideration. Since this detection scenario is completely
387 different from slow mechanical events, lightning strike occurrences will not be discussed further
388 in this work.

389 5. SOP-based Algorithms for automatic detection of anomalous events

390 The scenarios and events discussed in the previous Section have highlighted various types of
391 perturbations affecting the state of polarization. This suggests that by analyzing the time evolution
392 of the SOP, it is possible to detect harmful and anomalous events occurring along the deployed
393 optical fiber path.

394 In this Section, we describe two DSP algorithms that we proposed in our previous works
395 [21, 22, 41, 42]. The first method evaluates the SOP angular speed (SOPAS, see Subsection

a)



b)

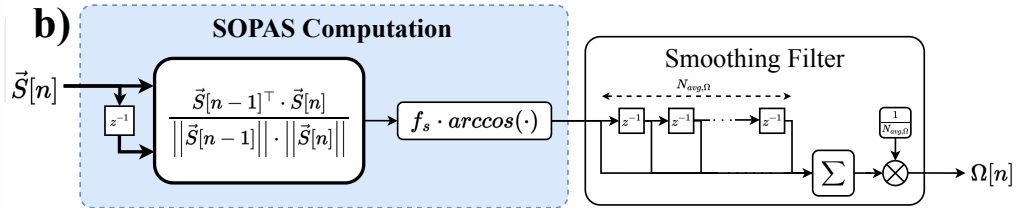


Fig. 10. (a) Poincaré sphere where an example of two consecutive Stokes vectors (blue dot $\vec{S}[n-1]$, red dot $\vec{S}[n]$), and the angle θ in between them has been reported, to make the scheme in (b) more clear. (b) DSP scheme for the SOPAS anomaly detection algorithm, where $\Omega[n]$ is the SOPAS post-smoothing filter. $\vec{S}[n]$ is the input Stokes vector time series.

396 5.5.1) using a simple, non-adaptive, time-domain solution. The second method (SOP-PSDG,
 397 see Subsection 5.5.2) employs a more advanced, frequency-based scheme capable of adaptively
 398 tracking the non-stationarity of the SOP fluctuations that typically occur in the deployed optical
 399 fiber scenario. Both methods detect anomalous events by raising an alarm when a processed
 400 signal, derived from the SOP evolution, exceeds a given threshold.

401 5.1. Time-based solution: the SOPAS algorithm

402 A straightforward method for detecting anomalies using a threshold-based approach involves
 403 monitoring the rate at which the SOP varies over time. This can be achieved by evaluating its
 404 angular speed, i.e. measuring the variation over time of the angle between two consecutive Stokes
 405 vectors over the Poincaré sphere (illustrated as θ in Figure 10(a)). The SOPAS signal $\Omega[n]$ can

406 be computed from the Stokes vector $\vec{S}[n]$, according to (3):

$$\Omega[n] = f_s \cdot \arccos \left(\frac{\vec{S}[n-1]^T \cdot \vec{S}[n]}{\|\vec{S}[n-1]\| \cdot \|\vec{S}[n]\|} \right). \quad (3)$$

407 Figure 10(b) illustrates the DSP scheme used to compute the SOPAS. The scheme includes also a
 408 smoothing filter, implemented as a moving average, to attenuate the SOPAS fluctuations caused
 409 by the SOP environmental noise, discussed in previous sections.

410 This metric requires only the current and previous SOP samples, making it extremely simple
 411 to compute, even in real-time scenarios. However, it is not adaptive to slow daily urban changes
 412 of the SOP, as they require more consecutive SOP samples in order to be effectively monitored.
 413 This characteristic makes it suitable for scenarios where anomalous conditions are well-defined
 414 and cause polarization rotations significantly faster than those generated by the surrounding
 415 environment.

416 Additionally, the SOPAS has an upper limit bounded by the employed sampling frequency f_s ,
 417 since the arc length drawn over the Poincaré sphere surface cannot exceed π without resulting in
 418 undersampling, as stated in [53]. This means that the maximum measurable SOPAS is given
 419 by the relationship $\Omega_{max} = \pi \cdot f_s$ [rad/s], which is anyway usually sufficient if considering
 420 mechanical vibrations and stresses.

421 5.2. Adaptive and spectrally-resolved solution: the SOP-PSDG algorithm

422 When environmental agents surrounding the fiber induce polarization rotations at speeds
 423 comparable to those caused by anomalous events, the SOPAS algorithm may become ineffective.
 424 However, as observed in the SOP spectrograms in Section 3, SOP environmental noise contributes
 425 to the spectrum at specific (though not static) frequencies, which can significantly differ from the
 426 frequencies excited during an anomalous event. Consequently, an alternative approach to process
 427 the SOP evolution for anomaly detection can be to compute a metric based on the analysis of the
 428 evolution of Stokes parameters in the frequency domain, i.e. studying how the SOP PSD changes
 429 over time.

430 The method we propose, simple yet effective, involves comparing historical values of the SOP
 431 PSD (i.e., the time-domain average of the SOP PSD spectrogram) with current SOP PSD values
 432 computed in real-time from the Stokes vector time series. The main idea is that anomalies are
 433 likely to occur when the current SOP PSD deviates significantly from its historical average. This
 434 concept is illustrated in the spectrogram in Figure 11, where a mechanical vibration is induced
 435 by a shaker on the experimental setup (with an oscillation frequency of $f_{osc} = 40$ Hz). By
 436 examining the spectrogram, the anomalous event can be easily identified by simply comparing
 437 the time-domain average PSD of the SOP in a quiescent condition (e.g., the area within the solid
 438 violet rectangle in Figure 11) against the PSD computed when the anomaly affects the SOP
 439 (dashed violet line in Figure 11). By quantifying this discrepancy, unexpected PSD patterns
 440 can be identified as anomalies, leading us to the design of the SOP-Power Spectral Density Gap
 441 (SOP-PSDG) algorithm.

442 The DSP scheme for SOP-PSDG-based anomaly detection is illustrated in Figure 12. The
 443 proposed algorithm extends the DSP scheme we proposed in [42], including implementation
 444 details on its real-time adaptive capabilities. The real-time SOP-PSDG is calculated as follows.
 445 First, each of the three $\vec{S}[n]$ components (where n represents the discrete-time index), $S_1[n]$,
 446 $S_2[n]$ and $S_3[n]$, is stored into a tapped delay line of N_{FFT} consecutive samples, from which, at
 447 each sampling time a one-sided PSD is evaluated: its computation is implemented by means
 448 of real-valued Fast Fourier Transform (FFT) [54], followed by the computation of the square
 449 magnitude of the FFT points. The evolution of the PSDs of the three Stokes parameters is

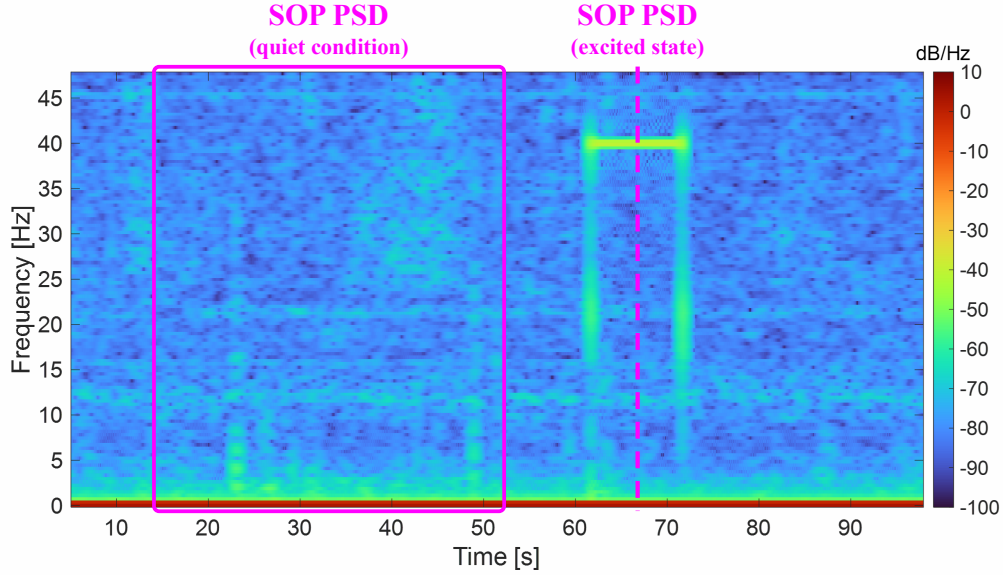


Fig. 11. SOP spectrogram, computed as the sum of the three Stokes parameters PSDs, acquired over the 35 km metropolitan fiber when inducing a mechanical vibration ($f_{osc} = 40$ Hz) for 10 seconds. The area within the solid violet rectangle is the SOP PSD in a quiescent condition, while the dashed violet line is the SOP PSD when the anomaly affects the fiber.

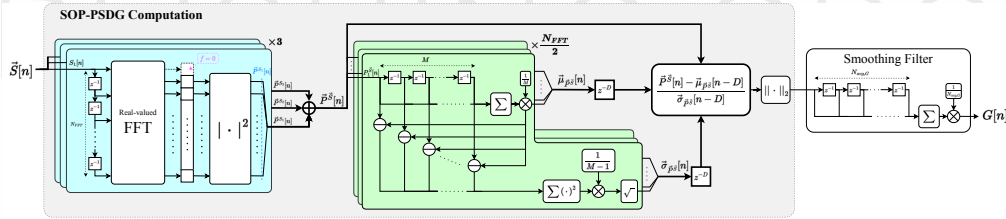


Fig. 12. DSP scheme for the SOP-PSDG anomaly detection algorithm. Light-blue DSP blocks indicate operations on individual Stokes vector parameters, while light-green DSP blocks denote operations on individual SOP PSD frequency components. Thick lines represent element-wise operations on vector signals.

450 represented by the signal vectors $\vec{P}^{S_1}[n]$, $\vec{P}^{S_2}[n]$ and $\vec{P}^{S_3}[n]$, defined as follows:

$$\vec{P}^{S_i}[n] = \left[P_1^{S_i}[n], P_2^{S_i}[n], \dots, P_{\frac{N_{FFT}}{2}}^{S_i}[n] \right], \quad i = 1, 2, 3 \quad (4)$$

451 where $P_k^{S_i}[n]$ represents the value of the k -th PSD point at the time index n relative to the i -th
 452 Stokes parameter. For practical reasons, in the computed PSDs, we discard the FFT point relative
 453 to the lowest frequency bin ($f = 0$), as shown in Fig.12. This removal helps exclude discrepancies
 454 relative to the “stationary” SOP (i.e., the average value of the Stokes Parameters) from the metric
 455 computation, as they are not relevant for anomaly detection purposes. The stationary SOP can
 456 indeed slowly vary over time, encompassing the entire Poincaré sphere even in the absence of
 457 anomalies.

458 The three computed PSDs are then summed together element-wise, to form the vector

459 $\vec{P}^{\vec{S}}[n] = \vec{P}^{S_1}[n] + \vec{P}^{S_2}[n] + \vec{P}^{S_3}[n]$ (as done in Section 3 when analyzing the SOP spectra). This
 460 single SOP PSD constitutes an “isotropic” representation of the SOP power spectral content:
 461 indeed, $\vec{P}^{\vec{S}}[n]$ provides information on the fluctuations of the SOP over the Poincaré sphere
 462 regardless of the direction of these variations.

463 Finally, the SOP-PSDG signal $G[n]$ is obtained as the Euclidean norm of the difference between
 464 the current SOP-PSD vector $\vec{P}^{\vec{S}}[n]$ and its moving average $\vec{\mu}_{\vec{P}^{\vec{S}}}[n] = [\mu_{P_1^{\vec{S}}}[n], \mu_{P_2^{\vec{S}}}[n], \dots]$
 465 delayed by D sample-times (referred to as *margin delay*), as follows:

$$G[n] = \sqrt{\sum_{k=1}^{\frac{N_{FFT}}{2}} \frac{1}{\sigma_{P_k^{\vec{S}}}[n-D]^2} \left(P_k^{\vec{S}}[n] - \mu_{P_k^{\vec{S}}}[n-D] \right)^2}, \quad (5)$$

466 where $\vec{\sigma}_{\vec{P}^{\vec{S}}}[n] = [\sigma_{P_1^{\vec{S}}}[n], \sigma_{P_2^{\vec{S}}}[n], \dots]$ represent the moving standard deviation of the elements
 467 in $\vec{P}^{\vec{S}}[n]$. As done for the SOPAS, the SOP-PSDG scheme also incorporates a smoothing filter
 468 applied to attenuate the $G[n]$ fluctuations. In (5), the normalization of both the current and
 469 average SOP-PSD values with respect to their standard deviation allows the algorithm to account
 470 for variability in the intensity of the frequency components in the SOP spectrum. In this way,
 471 frequency components with more unstable or variable intensities are appropriately weighted,
 472 preventing random increases in $G[n]$ values under normal conditions (and thereby enhancing
 473 anomaly detection performance).

474 As shown in Figure 12, the moving averages and standard deviations of the spectral elements
 475 of the SOP PSD are continuously computed over $N_{FFT}/2$ separated tapped delay lines, each
 476 with a *memory* of M consecutive samples. This approach provides a DSP scheme with adaptive
 477 capability, able to memorize and track the pattern and variability of the SOP PSD in real-time.
 478 Consequently, the algorithm can adapt to the non-stationary behavior of the SOP PSD, which
 479 varies on an hourly basis (as observed in Section 3).

480 Moreover, as illustrated in Figure 12 and (5), both $\vec{\mu}_{\vec{P}^{\vec{S}}}$ and $\vec{\sigma}_{\vec{P}^{\vec{S}}}$ are delayed by D samples with
 481 respect to the current SOP PSD $\vec{P}^{\vec{S}}[n]$: this ensures that anomalies are not memorized by the
 482 DSP-scheme immediately upon their occurrence, which would degrade the detection capability
 483 of the algorithm. In fact, a margin delay $D > N_{FFT}$ is sufficient to prevent this issue, since in
 484 this way $D - N_{FFT}$ samples are required to be processed before the SOP-PSDG scheme starts to
 485 adapt its statistics to the anomaly.

486 Compared to SOPAS, this metric is clearly more complex, requiring the storage of more SOP
 487 samples and the accumulation of statistics on the SOP spectrum. Nevertheless, its ability to adapt
 488 to slow variations in the SOP provides a significant advantage in detecting anomalous events, as
 489 we will illustrate in the next section.

490 6. Experimental results using SOP-based algorithms.

491 The two DSP schemes illustrated in the previous section will now be evaluated based on their
 492 responses to the anomalous events described in Section 4. To ensure a fair comparison of the two
 493 methods in terms of detection delay induced by the DSP scheme, the smoothing filter length
 494 employed to compute the SOPAS has been set to $N_{avg,\Omega} = 287$ samples (corresponding to 3
 495 seconds with $f_s=95.4$ Hz) [42]. For the SOP-PSDG, the smoothing filter length is adjusted
 496 to $N_{avg,G} = N_{avg,\Omega} - N_{FFT}$ samples, to account for the delay induced by FFT input tapped
 497 delay line (see Figures 10 and 12). Unless stated otherwise, all subsequent results will use these
 498 parameters with $N_{FFT} = 128$ points.

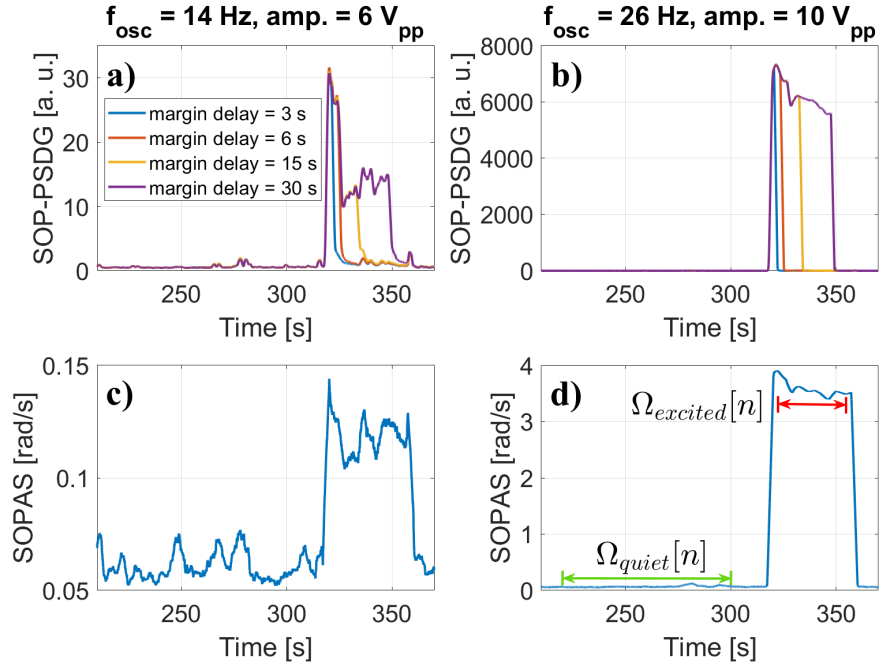


Fig. 13. (a-b) SOP-PSDG signal when $f_{osc} = 14$ Hz, amp. = $6 V_{pp}$ and $f_{osc} = 26$ Hz, amp. = $10 V_{pp}$, for different values of margin delay. Legend in (a) applies also to (b). (c-d) SOPAS signal when $f_{osc} = 14$ Hz, amp. = $6 V_{pp}$ and $f_{osc} = 26$ Hz, amp. = $10 V_{pp}$.

499 6.1. Mechanical vibrations detection using SOPAS and SOP-PSDG

500 Figure 13 illustrates the evolutions of the SOP-PSDG and SOPAS under two different vibration
 501 scenarios induced by a mechanical shaker in the experimental setup described in Fig. 4),
 502 considering the 35 km long fiber. In the first scenario, the setup was configured to produce an
 503 angular deviation of approximately 1° (see Figure 7(a)), with an oscillation frequency of 14 Hz
 504 and a peak-to-peak voltage of $6 V_{pp}$ (Figures 13(a) and (c)). The second scenario, character-
 505 ized by a more intense vibration, induced an angular deviation of approximately 3° , with an oscillation
 506 frequency of 26 Hz and a peak-to-peak voltage of $10 V_{pp}$ (Figures 13(b) and (d)). For this
 507 analysis, the memory duration was set to 180 seconds (i.e. M around $17 \cdot 10^3$ samples), while
 508 various margin delays were tested, ranging from 3 to 30 seconds.

509 In Figure 13, both the SOPAS and SOP-PSDG methods detect anomalies at approximately 320
 510 seconds for the induced vibrations. However, the SOP-PSDG signal demonstrates a key advantage:
 511 after the specified margin delay has been surpassed, it quickly returns to its pre-detection levels.
 512 This indicates that the SOP-PSDG can rapidly adapt to changing conditions once the margin
 513 delay has been exceeded. Furthermore, comparing Figures 13(a) and (c) reveals that, during
 514 detection, the SOP-PSDG signal shows a significantly larger relative increase (up to one order of
 515 magnitude) compared to the SOPAS, which only shows a doubling of its pre-detection values.
 516 This difference highlights the superior sensitivity of the frequency-based SOP-PSDG algorithm.

517 In order to quantitatively compare the sensitivity of the two algorithms, we define a detection
 518 Signal-to-Noise Ratio (SNR) as the ratio between the average squared values of the detection
 519 signal in excited and quiet conditions. For instance, the SNR of the SOPAS signal is defined as

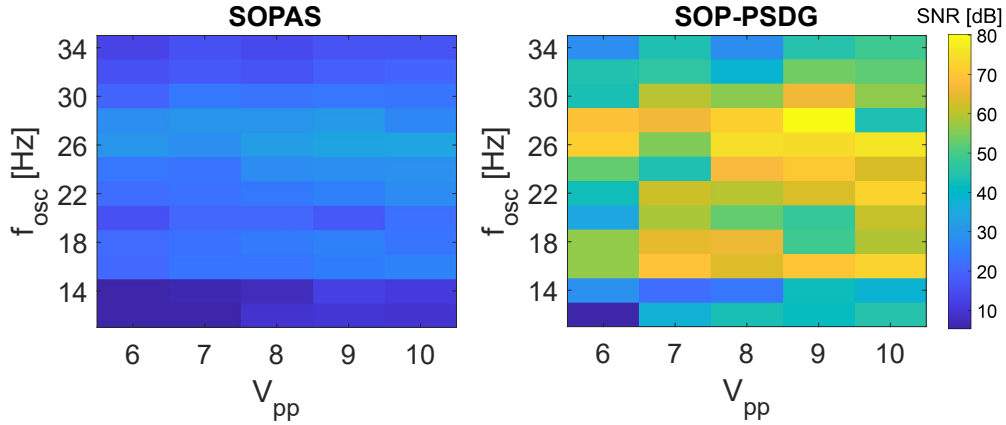


Fig. 14. SNRs computed for SOPAS and SOP-PSDG at different f_{osc} and V_{pp} .

520 follows:

$$SNR_{SOPAS} = \frac{\mathbb{E}[(\Omega_{excited}[n])^2]}{\mathbb{E}[(\Omega_{quiet}[n])^2]}. \quad (6)$$

521 As shown in Fig. 13(c), $\Omega_{quiet}[n]$ refers to a few tens of seconds before the vibration is activated.
 522 $\Omega_{excited}[n]$ refers instead to the samples related to the event acting on the fiber, neglecting the
 523 transients due to the smoothing filter. The same windowing of Fig. 13(c) and (6) has been applied
 524 on the SOP-PSDG, considering $G_{quiet}[n]$ and $G_{excited}[n]$. The latter refers to the SOP-PSDG
 525 samples when the vibration is activated, up to the margin delay value, neglecting the transients
 526 due to the smoothing filter and FFT. Figure 14 displays the evolution of the detection SNR over
 527 a subset of the cases considered in Section 4.4.1 (refer to Fig. 7(a)). For this analysis, the
 528 SOP-PSDG margin delay was set to 10 seconds. For all the combinations of f_{osc} and V_{pp} , the
 529 SOP-PSDG exhibits a consistently higher SNR (50 dB-70 dB) than the SOPAS (20 dB-40 dB).

530 6.2. Fiber-spoofing detection using SOPAS and SOP-PSDG

531 As outlined in Subsection 4.4.2, fiber spoofing events have been simulated through an OFI over
 532 the 35 km long fiber. Each spoofing event was replicated 100 times, with each occurrence lasting
 533 30 seconds and separated by 60 seconds. The relevant phase of each event was the closing of the
 534 fiber insertion clamp, rather than its release. This means that spoofing detection needs to occur
 535 promptly after the clamp starts closing.

536 Figure 15 illustrates the responses of the SOP-PSDG and SOPAS to several fiber spoofing
 537 events. For the SOP-PSDG algorithm, the memory M has been set to 30 seconds (i.e. M around
 538 $2.8 \cdot 10^3$ samples), while the margin delay has been fixed at 5 seconds. The insertion of the fiber
 539 into the clamp causes a noticeable increase in both SOPAS and SOP-PSDG signals, occurring
 540 about 7-8 seconds before the S_0 drop. This early rise highlights the superior responsiveness of the
 541 SOP-based DSP schemes, which is crucial for minimizing the data leakage during a fiber spoofing
 542 attack. Notably, the SOP-PSDG signal drops after 5 seconds, coherently with the imposed margin
 543 delay, while the SOPAS signal remains in its excited state until the fiber stabilizes within the OFI
 544 device.

545 6.3. SOPAS and SOP-PSDG methods on SOP data from a coherent receiver

546 As a final discussion, we present preliminary results using both methods on SOP data collected
 547 from the commercial coherent transceiver described in Section 2, which replaces the laser

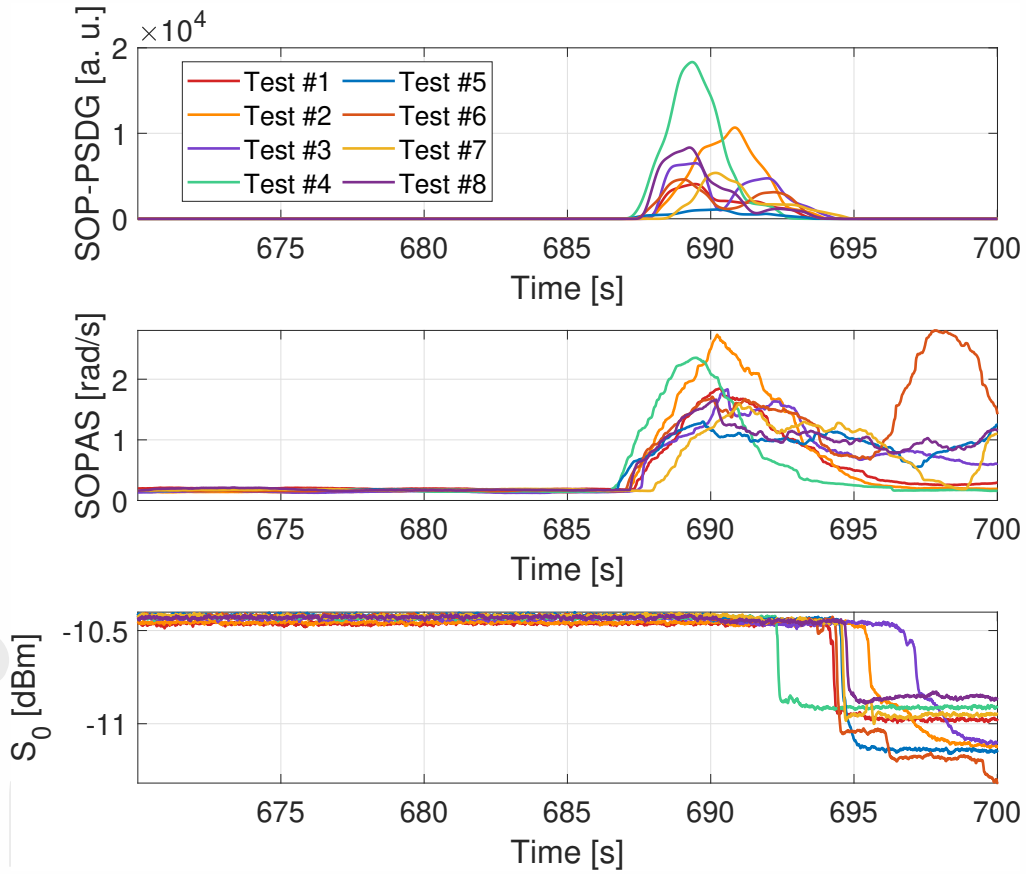


Fig. 15. Hacker-like spoofing effect on SOP-PSDG, SOPAS and S_0 .

548 and polarimeter depicted in Fig. 4. For this experiment, to further change the scenario and
549 demonstrate how the two algorithms work and compare in a completely different condition, we
550 exploited the 10 km long metropolitan fiber (indicated red line in Fig. 4). Given the significant
551 SOP estimation noise in this scenario, as detailed in Section 2 (see Fig. 3), we introduced strong
552 mechanical vibrations using a mechanical shaker. For this purpose, the vibrating plate has been
553 substituted with a circular metallic one, which is most intense on the fiber for an oscillation
554 frequency of 20 Hz and a peak-to-peak voltage of $10 V_{pp}$. The $P_{99\%}(\Delta\theta)$ is around 2° in the
555 absence of vibration and increases to 4° when vibrations are applied. 130 vibrational events
556 lasting 5 seconds each have been periodically induced in the experimental setup. Fig. 16 shows
557 the corresponding SOP-PSDG and SOPAS evolutions for each event. The SOPAS scheme used
558 a smoothing filter with $N_{avg,\Omega} = 76$ samples (corresponding to approximately 4 seconds) and
559 sampled at $f_s = 19$ S/s. To achieve a similar detection delay with the SOP-PSDG, N_{FFT} was
560 set to 64 points and $N_{avg,G}$ to 12. The SOP-PSDG memory was set to 180 seconds, with a
561 margin of 3 seconds. As shown in Fig. 16, the SOP-PSDG seems to effectively react to the
562 induced anomaly events: during detection, the PSDG values increase by around one order of
563 magnitude compared to pre-detection levels. In contrast, due to the smoothing filter, the SOPAS
564 signal stays high and nearly constant before detection, with peak intensities only doubling when
565 an event occurs. In summary, preliminary results indicate that SOP-PSDG outperforms SOPAS
566 for threshold-based detection even when using commercial coherent receivers.

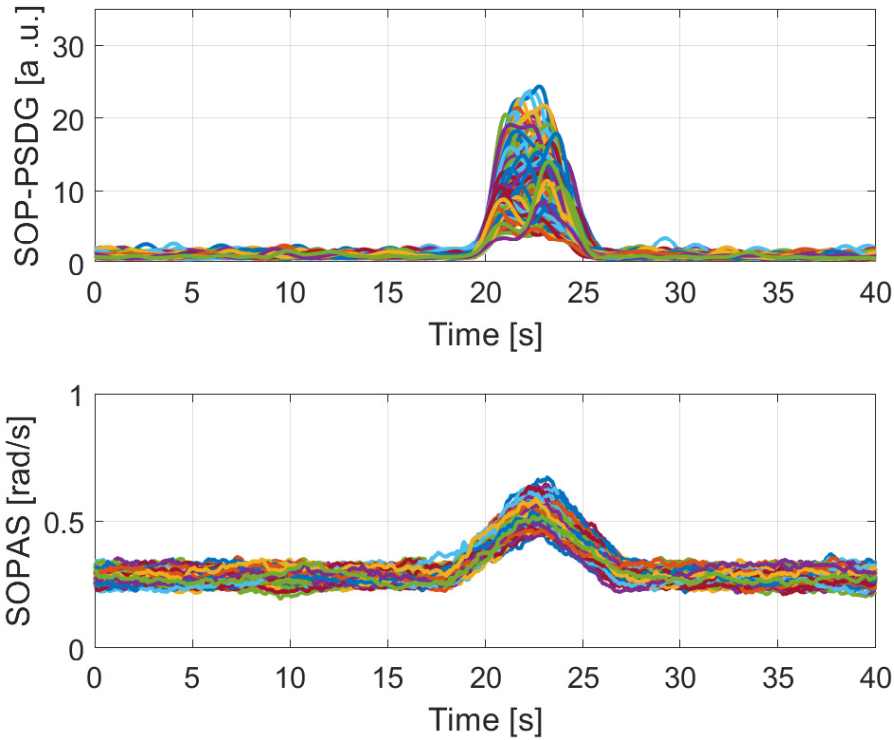


Fig. 16. Several occurrences of SOP-PSDG and SOPAS signals considering SOP data extracted from the commercial transceiver, when a vibration having $f_{osc} = 20$ Hz and amplitude $10 V_{pp}$ is induced on the fiber.

567 7. Discussions and Conclusions

568 In this work, we analyzed polarization sensing in an urban environment, employing metropolitan
 569 fibers running around Turin, in Italy. We first characterized the accuracy of the SOP data
 570 provided by a commercial coherent transceiver (able to output the SOP samples at around 20
 571 S/s), evaluating the estimation noise cloud spread over the Poincaré sphere surface. The results
 572 obtained in both an ASE noise-limited scenario and ROP-limited one underline the possibility of
 573 enhancing the accuracy, which was originally quite low. $P_{99\%}(\Delta\theta)$ values can reach 8° to 14°
 574 in the worst cases. Using a simple low-pass filter improves accuracy even by a factor of four, using a
 575 window length of $N_{win} = 15$ samples (see Figures 2 and 3). The matching between experimental
 576 and numerical simulation results also suggests that the SOP data stream, sampled at sampling
 577 frequencies of the order of the symbol rate, could be low-passed and then decimated, keeping the
 578 SOP estimate accuracy fixed. Due to the low-frequency components generated by mechanical
 579 vibrations, a sampling frequency of around a few tens of Hz could also be suitable to reduce
 580 processing and data storage complexity.

581 A characterization of the SOP fluctuations generated by the urban scenario, which we called
 582 SOP environmental noise, has been provided, showing different agents that could impinge on
 583 the cable and enhance the noise. Experiments have been carried out exploiting a polarimeter so
 584 that the sampling frequency could be tweaked for our purposes, and set to 95.4 S/s. Specifically,
 585 time-varying external conditions to which the fiber is subject generate SOP fluctuations, making

586 it non-stationary. This represents an issue for any anomaly detection algorithms. On top of this
587 scenario, we have shown the effect of different mechanical vibrations on the SOP, characterizing
588 the effect that they have on the cloud of points on the surface of the Poincaré sphere, as Stokes
589 vector time evolution and frequency content. This analysis showed that different vibrations have
590 particularly strong or weak effects on the fiber cable, which translates to SOP angular deviation.
591 Fiber spoofing has also been characterized, showing a strong effect on the SOP variation and
592 instantaneous power drop.

593 Two different algorithms have then been proposed to process the data and allow for anomaly
594 detection, based on threshold application. The SOPAS method is time-resolved and non-adaptive,
595 whereas the SOP-PSDG is frequency-resolved and adaptive. Especially for the SOPAS algorithm,
596 baseline noise characterization is fundamental in understanding which anomalies can be revealed.
597 The surrounding environment may present different SOP noise levels depending on non-harmful
598 external agents acting on the fiber. Due to its ability to adapt to changing conditions, the
599 SOP-PSDG method is more suitable for use in environments such as metropolitan areas, where it
600 demonstrated enhanced sensitivity compared to the SOPAS method under all tested conditions.
601 Both the SOP-PSDG and SOPAS methods can be combined with a threshold on the instantaneous
602 power to detect fiber spoofing. However, once the memory and margin delay are set, the SOP-
603 PSDG method appears to outperform the SOPAS approach. Results employing a commercial
604 coherent transceiver connected to a metropolitan fiber have also been shown. The two methods
605 have been compared when a vibration is induced on the fiber. Despite the disadvantageous
606 conditions due to the low sampling frequency and very high SOP estimation noise, SOP-PSDG
607 demonstrated to outperform the SOPAS method even in this condition.

608 The latest research on anomaly detection of hazardous conditions within the optical network's
609 physical layer broadly employs machine learning techniques [55–57], particularly for fiber
610 spoofing events, earthquakes [6,58], but also for traffic monitoring [59]. Nevertheless, a DSP
611 algorithm that can output a signal indicating an anomalous condition without requiring prior
612 training could be extremely useful. When used in conjunction with neural networks, this approach
613 could enable much more reliable detection of potentially hazardous events. Key features such as
614 event duration and signature over the Poincaré sphere surface could be used as further detection
615 parameters. This would enhance the resilience of optical networks to fiber cuts in metropolitan
616 environments, robustness against eavesdropping, and potentially offer early warnings for a wide
617 range of anomalous conditions not only limited to the urban scenario.

618 8. Acknowledgments

619 Saverio Pellegrini, Giuseppe Rizzelli and Roberto Gaudino are also sponsored by the SURENET
620 project – funded by European Union – Next Generation EU within the PRIN 2022 program (D.D.
621 104 - 02/02/2022 Ministero dell'Università e della Ricerca). This manuscript reflects only the
622 authors' views and opinions and the Ministry cannot be considered responsible for them.
623 The authors wish to express their gratitude to Novoptel GmbH, who co-authored the OFC2024
624 paper [41] from which this Journal article is derived. Novoptel GmbH played a pivotal role in
625 facilitating the demo session at OFC2024, by providing the necessary hardware (polarimeter
626 PM1000 and laser LU1000) and offering technical support.

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