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Sensing and Communication Coexistence in Optical Networks

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2026

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

I would like to dedicate this thesis to my inspiring, supportive, and loving family.

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Abstract

The widespread deployment of optical fiber networks has drawn significant attention to a new research topic called “integrated sensing and communications” (ISAC), concerning the investigation of various solutions to enable sensing capabilities within telecommunication infrastructures. This thesis will address, in this context, the following main research questions and related contributions.

- **Integrating state of polarization (SOP) sensing into the optical telecommunication networks.** Coherent communication systems encode data on light’s SOP, tracked at the receiver side. Since SOP is inherently sensitive to strain and temperature, sensing can be enabled without extra hardware, but with no event localization capability. We experimentally demonstrated SOP data retrieval from commercial transceivers, evaluated their estimation accuracy, and proposed algorithms to identify anomalous events. We proposed a non-adaptive and time-resolved algorithm, based on the SOP angular speed (SOPAS) computation, and a more sophisticated one, adaptive and frequency-resolved, called SOP-power spectral density gap (SOP-PSDG). The latter delivered enhanced detection capabilities in a metropolitan environment with respect to the SOPAS in all the cases tested.
- **SOP-based hazards detection in a mountain environment.** We investigated the use of SOP to monitor the mountain scenario, often subject to hazards (e.g., debris flow, rockfalls), through a standalone system (i.e., not connected to any telecommunication infrastructure) to deliver timely warnings. We studied the monitoring system on a reduced-scale model of a real mountain gully, and then scaled it up to a real environment. We demonstrated how the SOPAS-based detection algorithm can be reliable in this context, with lower costs compared to legacy geotechnical sensors.

- **Distributed acoustic sensing (DAS) and telecommunication systems co-existence.** The DAS technology is capable of precise strain/temperature measurements, and event localization along the fiber. We investigated intensity-modulated and direct-detected (IM-DD) data channels co-propagating with chirped-pulse DAS, a more advanced DAS technology. Our discoveries, confirmed by experiments and numerical simulations, found modulation instability (MI) to be the primary cause of crosstalk in telecommunication channels, which can be mitigated by increasing the frequency spacing between the sensing signal and the telecommunication channels, reducing the in-band DAS pulse noise level, or employing lower DAS pulse peak powers. For coherent telecommunication systems, we experimentally investigated a standard (non-chirped) DAS signal co-propagating with data combs in both the C- and L- bands. Our results indicate that C-band channels are affected by Kerr nonlinearities, primarily cross-phase modulation, also mitigated by increasing spectral separation. Moreover, we discovered that the Raman effect seems to compromise data integrity in the L-band. Telecommunication channels were never compromised if counterpropagated with the DAS pulse.

This thesis analyzes sensing techniques compatibility and coexistence with optical telecommunication systems, focusing specifically on state of polarization monitoring and distributed acoustic sensing. Rather than comparing these technologies to determine which is the better fit, this research provides a comprehensive characterization of both systems to facilitate their integration or addition into the existing infrastructure. By examining various deployment contexts, the study demonstrates how SOP and DAS can coexist, under different conditions, within the telecommunication infrastructure.

Contents

List of Figures	xi
List of Tables	xx
Nomenclature	xxi
1 Introduction	1
1.1 PhD Thesis Motivation	1
1.2 State of the Art of Telecommunication and Sensing System Integration	4
1.2.1 Length-integrated sensing techniques	5
1.2.2 Length-resolved sensing techniques	8
1.3 Outlook of This PhD Thesis	11
1.4 List of Publications of the PhD Candidate	12
2 Theoretical Background of the Sensing Techniques Addressed in this Thesis	16
2.1 Light State of Polarization Theory Background	16
2.1.1 General polarization theory	16
2.1.2 Birefringence, Jones calculus and hints on coherent receivers polarization compensation	21
2.2 Distributed Acoustic Sensing Theory Background	25
2.2.1 Optical time domain reflectometry and standard DAS	26

2.2.2	Chirped-pulse DAS working principle	30
3	Polarization Sensing over Coherent Telecommunication Systems	33
3.1	Accuracy of State of Polarization Estimate from Coherent Receivers' DSP	34
3.1.1	Performance in ASE noise	38
3.1.2	Performance limited by low ROP (without ASE noise) . . .	39
3.1.3	Discussions and conclusions	41
3.2	Anomaly Detection Algorithms over a Metropolitan Fiber Link . . .	41
3.2.1	SOP environmental noise in metropolitan fibers	42
3.2.2	Anomalous conditions characterization	45
3.2.3	SOP-based algorithms for automatic detection of anomalous events	52
3.2.4	Experimental results using SOP-based algorithms.	58
3.2.5	Discussions and conclusions	62
3.3	Comparison Between Phase and Polarization Sensing Using Coherent Transceivers Over Deployed Metropolitan Fibers	64
3.3.1	Experimental setup and results	64
3.3.2	Discussions and conclusions	68
3.4	Chapter Conclusions and Hints on Localization	68
4	Polarization Sensing in Mountain Areas	72
4.1	Algorithm Optimization for Rockfalls Alarm System Based on Fiber Polarization Sensing	74
4.1.1	Small-scale experimental setup of the SOP-based detection system	75
4.1.2	SOPAS algorithm for anomalous vibrations detection	77
4.1.3	Experimental results and assessment of system performance	80
4.1.4	Localization using spatially separated fibers	82

4.1.5	Discussions and conclusions	84
4.2	Polarization-Based Fiber Optic System for Debris Flow Early Warning: On-Field Demonstration	86
4.2.1	On-field setup	86
4.2.2	Environment-induced noise analysis	88
4.2.3	Anomalous events detection analysis	92
4.2.4	Discussions and conclusions	98
4.3	Experimental Characterization of a Deployed Early-Warning System for SOP-Based Monitoring of Debris Flows in Mountain Scenarios	99
4.3.1	Experimental setup and processing algorithm	100
4.3.2	System detection results	103
4.3.3	Discussions and conclusions	107
4.4	Chapter Conclusions	107
5	Distributed Acoustic Sensing Coexistence with Telecommunication Systems	111
5.1	Experimental and Simulative Study on IM-DD Transmission and Large Chirped-Pulse DAS Coexistence	112
5.1.1	Experimental setup	114
5.1.2	Experimental results	117
5.1.3	Numerical simulations	128
5.1.4	Discussions and conclusions	133
5.2	Experimental Investigation on Pulsed DAS Coexistence with DWDM High-Speed Coherent Transmission in C and L-bands	135
5.2.1	Experimental setup and results	136
5.2.2	Discussions and conclusions	140
5.3	Chapter Conclusions	141
6	Thesis Conclusions	144

References	150
Appendix A Polarization	165
A.1 Polarization Ellipse Equation Derivation	165
A.2 Stokes Parameters Fundamental Condition	167
A.3 Stokes Parameters Relationship with Ellipticity and Orientation . . .	168
Appendix B Hints on Localization Using SOP over a Bidirectional Link	169

List of Figures

1.1	Landline internet subscriptions per 100 people versus time, for different countries (data taken from [1]).	1
1.2	a) Terrestrial and b) submarine optical fiber network spread all over the world (picture taken from [2]).	2
1.3	Distributed fiber optic sensor market, divided by technology, through the years. Figure is taken from [3].	3
1.4	Backscattered signal spectrum, with highlighted the different bandwidths used for sensing. The plot is qualitative, on both axes, and meant for further explanation in the text. Picture taken from [38]. . .	9
2.1	a) $E_x(t)$ (upper plot) and $E_y(t)$ (lower plot) components time evolutions with amplitudes (E_1 and E_2 , respectively) and phase difference δ highlighted. b) shows as a black line the resulting electric field vector tip time-evolution.	18
2.2	Polarization ellipse.	19
2.3	Poincaré sphere space, showing generic Stokes vector $\vec{S}$, ellipticity χ and orientation ψ angles geometrical representation. Image taken from [52].	20
2.4	Schematic representation of a fiber with highlighted the cascade of M waveplates, showing the effect on input $\vec{E}_{in}$ polarization.	23
2.5	Fast time and slow time visualization, versus pulse occurrences and backscattered traces amplitude. Picture taken from [5].	26

2.6	Graphical representation of DAS pulse propagation in the fiber, highlighting the scattering area Δz and the m -th scatterers.	27
2.7	Graphical explanation of CP- ϕ OTDR. The left part of the figure shows what happens to the backscattered trace time evolution when a strain is applied to the fiber. On the right side, the frequency-to-time conversion induced by the chirp shows the relationship with strain. Picture inspired from [61, 69]	31
3.1	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) 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.	35
3.2	Poincaré sphere showing the $\vec{S}_{ref}$ (in red) and $\vec{S}[n]$ (in blue) vectors and the angular deviation $\Delta\theta[n]$	36
3.3	a) $\Delta\theta$ 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).	38
3.4	$P_{99\%}(\Delta\theta)$ 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 $N_{win} = 1$	40

3.5	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 (PM, in the scheme). The pictures of the two mechanical shakers are shown, of different geometrical shapes, materials, and fiber wrappings layouts. Green and red lines depict the metropolitan fibers used for the experiments, running around Turin (Italy), measuring 35 km and 10 km, respectively. The blue line depicts a fiber that was not used for the experiments.	43
3.6	a) Stokes parameters time evolution over a two-days-long acquisition considering the 35 km long metropolitan fiber, started on March 4 th 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.	44
3.7	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.	45
3.8	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.	47
3.9	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.	49
3.10	Effect of hacker-like fiber spoofing on a) the Stokes parameters and on b) the instantaneous power S_0	51
3.11	Scrambler-generated lightning strikes effect on the three normalized Stokes parameters time-evolution.	52

- 3.12 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) clearer. 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. 53
- 3.13 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. 55
- 3.14 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. 56
- 3.15 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. = $10 V_{pp}$ 58
- 3.16 SNRs computed for SOPAS and SOP-PSDG at different f_{osc} and V_{pp} . 59
- 3.17 Hacker-like spoofing effect on SOP-PSDG, SOPAS and S_0 60
- 3.18 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. 62
- 3.19 Experimental setup. AWG: arbitrary waveform generator, MZM: Mach-Zehnder modulator, LO: local oscillator, SMF: single-mode fiber, BPD: balanced photodetector, RTO: real-time oscilloscope, DSP: digital signal processing, VOA: variable optical attenuator. . . 64
- 3.20 Measured BER for the first 1000 data bursts in back-to-back and after metropolitan transmission. 66

3.21	PSD in back-to-back configuration for the a) optical phase and b) SOP with a 15 Hz shaking.	66
3.22	Power spectral density after metropolitan transmission of a) optical phase and b) SOP for 15 Hz shaking, c) optical phase and d) SOP for a shaking frequency swept from 10 Hz up to 20 Hz every 5 seconds.	67
4.1	Scheme of the monitoring system showing the T (red line), Uc (green line), and Ul (yellow line) fibers configuration. The same layouts exist at different depths.	75
4.2	a) Experimental model with no geotextile showing the most superficial (and not yet buried) fiber configuration, b) slide covered in geotextile.	76
4.3	a) Picture of the cylinder and the single rock used to generate C and SR events. b) Example of rockfalls event occurring on the slide.	77
4.4	Ten different runs of RF and one of background noise on fiber T3, represented with different colors. The inset shows an example of SOPAS traces for the three tested events. T_{mov} used is 1 second.	78
4.5	a) Rockfalls SOPAS on fiber T3, ω_{th} and alarm signal using $T_{mov} = 1$ second. b) SOPAS time evolution of an RF event generated on T3 for different T_{mov} values.	79
4.6	SOPAS spectrogram of an RF event in linear, normalized to the maximum value.	80
4.7	Detection maps for a) T configuration, b) Uc configuration, c) Ul configuration.	81
4.8	Experimental setup of the two-fibers system. The blue line represents Fiber A (with highlighted 10 km spool), while the red line represents fiber B.	83
4.9	a) Cross-correlation curves and centroids (red dots) between SOPAS on fiber A and B for five SR events. The inset shows the SOPAS curves for one of the five SR events. b) Table of delays τ of the five cross-correlation curves.	84

4.10	a) Schematic representation of the monitored site with fiber layout. b) View of the gully from manhole #2 and c) from manhole #1. The dashed blue and violet lines are the fibers selected for the round-trip, contained inside the black dashed cylinder representing the underground cable. The green line shows the fiber configuration on the surface. Footsteps indicate a semi-exposed portion of the cable in a passageway in the woods. The red line shows the bottom limit of the fiber installation. The black dotted lines in b) and c) show the lateral edges of the gully.	87
4.11	Distribution of SOPAS samples for the walking (W) and quiet (Q) case, normalized to show probability density functions. The red-dashed line shows the theoretical Rician pdf fit on the Q distribution. The inset shows the corresponding SOPAS evolution in time.	89
4.12	a) Distribution of SOPAS samples in the walking (orange) and quiet (blue) case with RT fibers only, in the quiet state with 40 m gully fiber (purple), and in the quiet state with 80 m gully fiber (green). b) SOPAS time evolution over 12 hours in the configuration with 80 m gully fiber.	90
4.13	SOPAS traces acquired during the crossing of RT fibers of 0, 1, 2, 3, 5 vehicles. The fiber configuration considers the 40 m gully fiber. . .	91
4.14	Eight different SOPAS traces associated with out-of-the-ordinary events generated over the 40 m long gully fiber.	93
4.15	Seconds of FA over the 12 hours SOPAS acquisition as a function of the threshold value. The red curve has been obtained considering the whole 80 m fiber overnight acquisition, the blue one has been obtained neglecting the two highest spurious spikes.	94
4.16	Two-fiber detection system setup showing the top (blue) and the bottom (orange) fiber.	95
4.17	SOPAS measured during four different launches in the two-fiber configuration.	96
4.18	Bar plot showing on the y-axis the delays computed by means of cross-correlation in between the SOPAS traces acquired on the two fibers. The related events are identified just as numbers on the x-axis. . .	97

4.19	Experimental setup of the monitored gully, including photos of the actual fiber installations, interrogator, and solar panels. Red, green, purple, yellow, and blue lines refer to circuits #4, #3, #2, #1, and common fiber cable.	101
4.20	a) Simplified interrogator scheme. b) Proposed processing and alarming algorithm running on the card connected to the polarimeter. . . .	102
4.21	a) pdfs of consecutive 12 hours acquired, per circuit. b) SOPAS evolution recorded during anomalous noisy hours for circuits #3 and #4.	103
4.22	Exceedances detection maps for circuits #3 and #4.	105
4.23	a) The upper photo shows the gully on circuit #2 with a snow layer in quiet conditions, the lower photo shows the occurrence of an intense snowfall on the same spot. b) SOPAS evolution recorded on circuit #2 during an intense snowfall.	105
4.24	a) Exceedances detection map for circuit #2. b) Simulated flowing mass event response on SOPAS, non-smoothed (blue line, “no smth”) and smoothed (orange dashed line, “smth”).	106
5.1	a) Experimental setup used for the coexistence analysis of the DAS pulse with data channels propagating in a 10 km SSMF. The inset shows the real (green) and imaginary (purple) parts of the complex chirp, driving the I/Q MZM. The black line is the Super-Gaussian intensity envelope. b) Transmitted spectrum of the large chirped-pulse DAS alone, normalized to its maximum.	115
5.2	a) Theoretical MI gain curve [63, 140] generated by a single frequency source, considering $\gamma = 1.3 \text{ W}^{-1}/\text{km}$, $\beta_2 = -22 \text{ ps}^2/\text{km}$ and a 10 km SSMF fiber. b) Received spectra obtained after fiber propagation versus different P_{DAS} , when the chirped pulse alone is propagated. The graph is normalized to the maximum value among all the measured spectra.	118
5.3	Average spectra of the co-propagating large chirped-pulse DAS and $\Delta f = 100 \text{ GHz}$ spaced data channel recorded by the OSA right after fiber propagation for different P_{DAS}	120

- 5.4 Data signal average intensity $\langle I \rangle$ evolution along the pulse co-propagation for $B_{rx} = 14$ GHz when a) $\Delta f = 50$ GHz, b) $\Delta f = 100$ GHz and c) $\Delta f = 200$ GHz, versus P_{DAS} . Different colors are only used to provide contrast between lines and enhance readability. Inset in a) represents the non-averaged intensity I evolution for the case with $\Delta f = 50$ GHz, $B_{rx} = 14$ GHz and $P_{DAS} = 23.5$ dBm. 121
- 5.5 Instantaneous BER time-evolution along the pulse co-propagation with data for $B_{rx} = 14$ GHz, when a) $\Delta f = 50$ GHz and b) $\Delta f = 100$ GHz, versus P_{DAS} . Different colors are only used to provide contrast between lines and enhance readability. 123
- 5.6 BER curve versus P_{DAS} values when co-propagating data and chirped pulse, for $\Delta f = 50$ GHz and $\Delta f = 100$ GHz. Four different optical filter bandwidths have been tested for both cases. 124
- 5.7 BER curve versus increasing P_{DAS} values when co-propagating data and chirped pulse, for a) $\Delta f = 200$ GHz and b) $\Delta f = 400$ GHz. Four different optical filter bandwidths have been tested for the former, while only two for the latter. Legend is shared between a) and b). . . 125
- 5.8 BER curve versus increasing P_{DAS} values when counter-propagating data and chirped pulse, for different Δf and same optical filter bandwidth B_{rx} 126
- 5.9 Spectra of transmitted DAS pulse + data a) before and b) after fiber propagation with $\Delta f = 50$ GHz data channel, when considering different OSNR values, for $P_{DAS} = 25$ dBm. All spectra have been normalized to the maximum value when transmitting $P_{DAS} = 25$ dBm. Graph c) shows the BER as a function of the P_{DAS} for both experiments and numerical simulations for different OSNR values. 129
- 5.10 BER curves versus P_{DAS} for a) $\Delta f = 50$ GHz and 100 GHz with $B_{rx} = 14$ GHz for both experiments, and simulations. Inset shows the simulated BER versus fiber length, when $P_{DAS} = 24$ dBm and $\Delta f = 100$ GHz. Simulation-only BER curves for increasing Δf values from 50 GHz to 150 GHz in steps of 25 GHz are shown in b) for the PAM2 and c) for the PAM4 modulation formats. All the simulations have been obtained setting OSNR = 16 dB. 131

5.11	Spectra of the received DAS + 100 GHz spaced data channel when considering $P_{DAS} = 28$ dBm and varying B_{tx} . The yellow curve refers to the reference case with 100 GHz wide noise bandwidth employed to emulate the DWDM.	132
5.12	BER curves versus P_{DAS} obtained in numerical simulations, when employing narrower optical filter bandwidths B_{tx} at the transmitter side, around the DAS channel. The yellow curve refers to the reference 100 GHz wide noise bandwidth employed to emulate the experimental DWDM.	133
5.13	a) Experimental setup and b) transmitted optical spectrum.	136
5.14	Co-propagation case. a) BER vs OSNR for 400G DP-QPSK CCUT and different spectral spacings Δf when $P_{DAS} = 20.5$ dBm (solid) and without DAS (dashed), and corresponding FEC errors vs OSNR for CCUT when P_{DAS} is b) 19.5 dBm and c) 20.5 dBm. d) BER vs OSNR for three 200G DP-QPSK LCUT when $P_{DAS} = 25.5$ dBm (solid) and without DAS (dashed), and corresponding FEC errors vs OSNR for all LCUT when P_{DAS} is e) 23.5 dBm and f) 25.5 dBm. . .	137
5.15	a) Three BER vs OSNR measurements for 800G DP-16QAM CCUT in the counter-propagation case, and b) corresponding FEC errors when $P_{DAS} = 27.5$ dBm. Runs #1, #2, #3 refer to 1-second-long consecutive acquisitions.	139
B.1	Schematic representation of a coherent transceiver's bidirectional link. East and West side quantities have been highlighted in red and blue, respectively.	170

List of Tables

1.1	Length-integrated sensing techniques: summary and comparison. . .	5
1.2	Length-resolved sensing techniques: summary and comparison. . .	10
4.1	Comparison of mountain engineering monitoring systems with optical fiber sensing.	73
4.2	Comparison between the proposed monitoring system and existing solutions [106–109, 120, 102, 105].	109
5.1	P_{th} and $P_{FECfail}$ values for co-/counter-propagating signals, considering all the tested B_{rx} and Δf . N.C. is short for “no consequences” recorded on the BER, for those parameters.	127
5.2	Table summarizing all the obtained results. We depicted with green circles the cases where no FEC errors were recorded at any OSNR level, and with red crosses when at least one FEC error was measured. Specifically, four Δf values from 200 GHz to 400 GHz for the C-band, and the three LCUT central wavelengths (1593.37 nm, 1600.17 nm, and 1608.76 nm) for the L-band (separated by “/”). The acronym BUT stands for band under test.	140
6.1	Comparison of the main characteristics of SOP and DAS sensing techniques.	147

Nomenclature

Acronyms / Abbreviations

ϕ OTDR Phase Optical Time Domain Reflectometer

ADC Analog-to-Digital Converter

ASE Amplified Spontaneous Emission

AWG Analog Waveform Generator

BER Bit Error Ratio

BPF Band-Pass Filter

C Cylinder

CCUT C-band Channel Under Test

CD Correct Detection

CDC Chromatic Dispersion Compensation

CP- ϕ OTDR Chirped-Pulse-Phase Optical Time Domain Reflectometer

CPR Carrier Phase Recovery

CW Continuous Wave

DAS Distributed Acoustic Sensing

DD Direct Detected

DFB Distributed Feedback Laser

DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
ECL	External Cavity Laser
EDFA	Erbium-Doped Fiber Amplifiers
FA	False Alarm
FBG	Fiber Bragg Grating
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FOC	Frequency Offset Compensation
FRM	Faraday Rotating Mirror
FWHM	Full-Width-Half-Minimum
HPF	High-Pass Filter
I/Q	In-phase/Quadrature
IM-DD	Intensity-Modulated and Direct-Detected
ISAC	Integrated Sensing And Communications
LCUT	L-band Channel Under Test
LI	Length Integrated
LMS	Least Mean Square
LP	Linearly Polarized
LR	Length Resolved
LSZH	Low Smoke Zero Halogen
MD	Missed Detection
MF	Matched Filtering

MI	Modulation Instability
MZM	Mach-Zehnder Modulator
NRZ	Non-Return-To-Zero
OFI	Optical Fiber Identifier
OSA	Optical Spectrum Analyzer
OSC	Optical Supervisory Channel
OSNR	Optical Signal-to-Noise Ratio
OTDR	Optical Time Domain Reflectometer
PD	PhotoDiode
pdf	Probability Density Function
PDL	Polarization Dispersion Loss
PG	Parametric Gain
PON	Passive Optical Networks
PRBS	Pseudo-Random Bit Sequence
PSD	Power Spectral Density
Q	Quiet
RF	RockFall
ROADM	Reconfigurable Optical Add-Drop Multiplexer
ROP	Received Optical Power
RT	Round-Trip
RTO	Real-Time Oscilloscope
RX	Receiver
RX-VOA	Receiver side-Variable Optical Attenuator

SNR	Signal-to-Noise Ratio
SOP	State Of Polarization
SOP-PSDG	State Of Polarization-Power Spectral Density Gap
SOPAS	State Of Polarization Angular Speed
SR	Single Rock
SRS	Stimulated Raman Scattering
SSMF	Standard Single-Mode Fiber
T _x	T-shaped fiber layout, at depth x
TIA	TransImpedance Amplifier
TOF	Time Of Flight
TX	Transmitter
TX-VOA	Transmitter side-Variable Optical Attenuator
U _c x	U-shaped central fiber layout, at depth x
U _l x	U-shaped lateral fiber layout, at depth x
VOA	Variable Optical Attenuator
W	Walking

Chapter 1

Introduction

1.1 PhD Thesis Motivation

Technological advancements, together with the growing prevalence of data-intensive applications, have played a crucial role, particularly in recent years, in the deployment and expansion of fixed landline networks. Owing to their transmission capabilities, such as large bandwidth and low latency, as well as their significant installation advantages compared to legacy copper telephone lines, optical fibers have emerged as one of the most impactful technological innovations of the past two decades. Following this trend, the legacy telecommunication infrastructure has, over the years, been replaced by optical fiber cables, which were commercially deployed beginning in 1990. These considerations are supported by the data plotted in Fig. 1.1, depicting

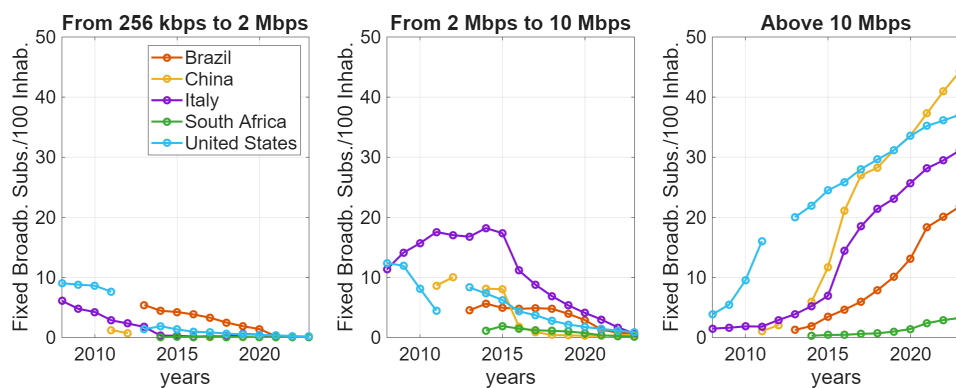


Fig. 1.1 Landline internet subscriptions per 100 people versus time, for different countries (data taken from [1]).

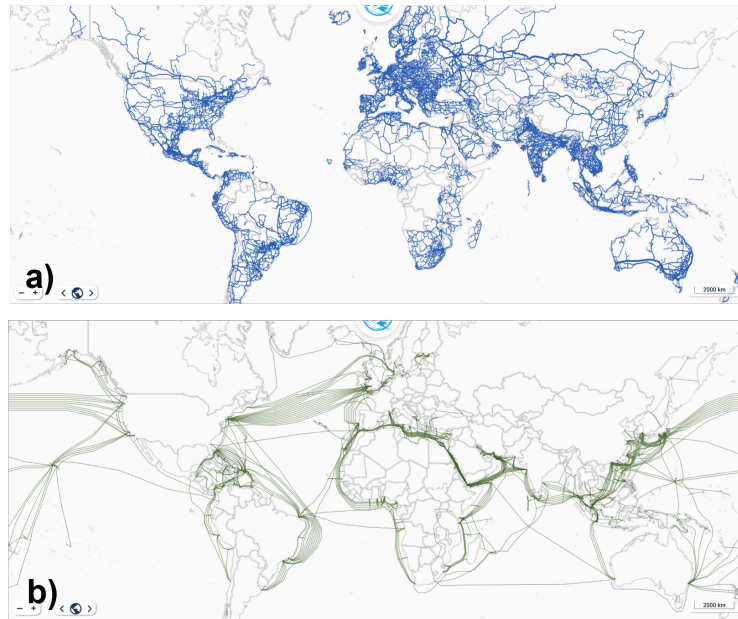


Fig. 1.2 a) Terrestrial and b) submarine optical fiber network spread all over the world (picture taken from [2]).

the time evolution of the landline broadband internet subscriptions per 100 people, for different speed ranges [1]. The countries considered are presented as examples, illustrating the global average trend in those years. The (now) slowest technologies, offering speeds from 256 kbps to 2 Mbps, which dominated the years pre-2010, began to decline, leaving room for mixed (copper + fiber) technologies, with speeds from 2 Mbps to 10 Mbps. From 2012-2015, the optical fiber technology, which is capable of providing speeds well above 10 Mbits per user, began to dominate the market and continues to grow. For what concerns the geographical spread of optical fibers, the core transport network is illustrated in Figure 1.2, showcasing a highly complex infrastructure of connections that link cities, nations, and continents. As optical fibers have become the primary medium for data transmission in fixed landline networks, their distribution is dense in both terrestrial (Fig. 1.2a)) and submarine (1.2b)) areas.

Optical fibers have also been used since the late 60s [4] for sensing, with a wide range of applications, and have demonstrated excellent performance in detecting and measuring mechanical and temperature-related events [5]. As with telecommunications, the lightweight nature of these sensors facilitates installation and exhibits exceptional capacity to withstand extreme conditions, including radiation and strong

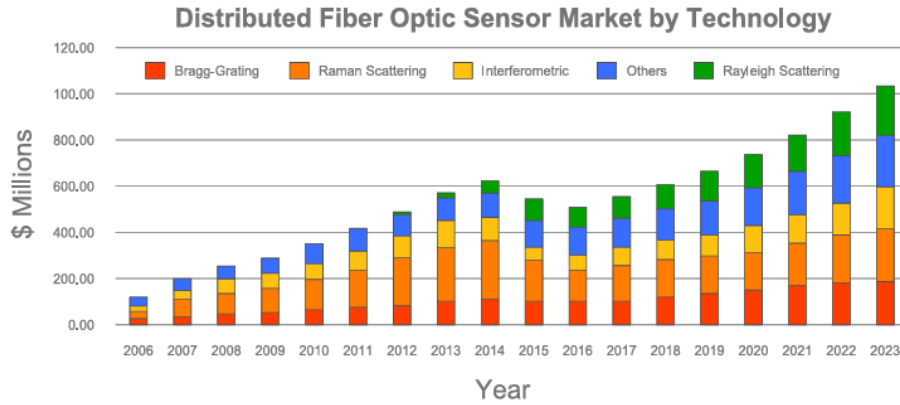


Fig. 1.3 Distributed fiber optic sensor market, divided by technology, through the years. Figure is taken from [3].

electromagnetic interference [6]. These characteristics render them a distinctive and valuable solution for monitoring external environmental events. Despite having been around for decades, distributed fiber sensing techniques [5] experienced significant growth only in the last few years, as shown in Fig. 1.3 (taken from [3]), employing dedicated fibers installed solely for sensing.

The joined ubiquity of the optical fiber networks, and the capability of the transmission medium to be sensitive to surrounding agents, recently opened up a completely new research topic, concerning integration and coexistence of different sensing techniques over the already deployed fiber network [7], better known as “integrated sensing and communications” (ISAC). Note that the latter is a topic of significant interest also for 5G and 6G wireless networks; this thesis will only treat optics-related ISAC. The main idea would be to make the whole telecommunication optical network able to record surrounding events, possibly mining the health status of the fibers or, more importantly, be precursors of dangerous events endangering people’s lives and the integrity of infrastructures. A major advantage of employing the optical network as a sensor is that the fibers can be installed in remote locations, such as at the bottom of the sea, where legacy geophysical sensors are too complex and costly to deploy intentionally. This technology would also enable sensing in ubiquitous and pervasive optical access networks. Several studies already demonstrated the fiber network sensitivity to all sorts of natural [8–13] and anthropological events [14–17], even involving earthquakes or tsunamis detection, for which ISAC would be a game changer. The rise of this recent research branch is probably the reason why the distributed optical fiber sensing techniques, which were mostly used

in the specific contexts of structural health monitoring and oil and gas safety [3], underwent a notable increase starting from the year 2018, as shown in Fig. 1.3. Notice also how the different technologies occupy, in 2023, approximately the same share of the market.

One of the main reasons why the coexistence of sensing techniques over telecommunication infrastructures has gained great visibility over the last few years, both in academia and industry, is because, in coherent communication systems, data are encoded in the state of polarization (SOP) of light, other than the phase and intensity. The whole receiver equalization and data demodulation process [18, 19] provides then for an SOP estimate, with near-zero additional effort. As it is very well known from literature, SOP is sensitive to mechanical stresses and temperature variations [20–24], resulting in an already installed system which, even if employed for telecommunication purposes, records for surrounding agents acting on the fiber. In this regard, some of the very first research demonstrating the feasibility of this idea are reported in [25, 16], which employed submarine and terrestrial telecommunication infrastructure to retrieve SOP samples. Nevertheless, one of the very first large-scale experimental demonstrations of using deployed optical fibers to detect events (earthquakes in particular) is in [26], which employed a dedicated sensing system based on optical phase retrieval.

While SOP-based sensing is likely the simplest method to implement, due to its integration within coherent communication systems, it does have significant drawbacks when compared to other techniques. This thesis will primarily focus on SOP sensing, but before diving into the specific results of this PhD research, we believe it is essential to present a comprehensive overview of the current available sensing solutions.

1.2 State of the Art of Telecommunication and Sensing System Integration

Fiber sensing is not confined to SOP monitoring alone: it encompasses a wide range of techniques that exploit different physical phenomena to make the medium sensitive to external agents. In this section, we review the main approaches, focusing on those that enable coexistence with communication systems. Here, coexistence refers to the ability of sensing and telecommunication functionalities to operate

Table 1.1 Length-integrated sensing techniques: summary and comparison.

Technique	Required backprop.	Max distance	Temp./strain sens.	Laser linewidth	Optical source power	Required optical bandw.	Telecom. compat.
Interf. technique [27–30, 26, 31, 32]	Yes or loop configuration	Tens–thousands km	Yes/Yes	~ Hz–kHz	~ 10 dBm (CW)	~ linewidth	Demonstrated
SOP [9, 14, 15, 12, 16]	No	Thousands km	Yes/Yes (qual.)	Not relevant	Few dBm (CW)	~ linewidth	Demonstrated
Forward optical phase [33, 34, 10, 35]	No	Thousands km	Yes/Yes	~ Hz	Few dBm (CW)	~ linewidth	Demonstrated

simultaneously over the same transmission medium and, in some cases, even using the same hardware.

Inspired by the formalisms in [5], this thesis will discuss *length-integrated* (LI) and *length-resolved* (LR) sensing systems. In the following, we will use the term *measurand* to refer to the actual physical quantity that the sensor measures (e.g., phase, see further), which is then translated to what is actually happening on the fiber (e.g., strain, see further). For both LI and LR cases, the whole fiber length is continuously sensitive to perturbations. Stresses acting on whatever point of the link will result in a time change of the measurand. The main difference between the two concerns the inherent capability of localizing external events, which is usually impossible to achieve for length-integrated systems, unless some proper configuration is employed. Discrete sensing techniques such as fiber Bragg gratings (FBGs, mentioned in Fig.1.3), which viceversa make the fiber sensitive only at specific points along its length, are excluded from our following analysis.

1.2.1 Length-integrated sensing techniques

With LI sensing, we refer to all techniques that deliver an integrated, non-spatially localized measurand. In this case, since perturbations happening on the whole fiber length, at whatever point, generate a change in the measurand time evolution, it is not possible to resolve the spatial position of the single perturbation acting on the fiber. The three main LI techniques that have been studied in the optical ISAC context

are interferometric, SOP, and forward optical phase-based. A final, non-exhaustive, summary of the main characteristics is depicted in Table 1.1.

Interferometric techniques

The interferometric techniques will not be addressed in any of the works in this thesis; however, they have been extensively studied by various research groups. We will not here explore the specifics, as these techniques cover a broad range of subgroups with different characteristics.

Light optical phase is sensitive to axial strains, which are directly related to a change in the optical path length. Its value is then critical to retrieve the perturbation happening on the fiber. The measurand is the phase difference between the sensing signal and a reference one, obtained by interference at the receiver. In general, signal backpropagation through Faraday rotating mirrors (FRM) [27, 28] and looped configurations [29] can be exploited to allow for this kind of sensing. In the first case, the phase of the FRM-reflected signal is compared to a reference one. In the second case, the loop back to the transmitter allows for the actual signal phase to be compared to the reference. The latter is usually the transmitter laser, which needs to have a narrow linewidth: any phase drift would be translated into an apparent length variation (i.e., strain); it is thus important to keep the phase noise low. These kinds of techniques are largely used for basic physics experiments, as variants of the well-known Michelson interferometer [30]. For metropolitan networks, usually in the tens of km range, a few kHz linewidth allows for the necessary coherence. For longer distances, with a range of hundreds of km [26], ultra-stable lasers are required. On a suboceanic link (thousands of km), a similar approach has also been employed [31]. The sensing signal is usually in continuous wave (CW) and with power ~ 10 dBm. A higher power is sometimes needed for the FRM case. Coexistence with telecommunication data channels has been demonstrated in various scenarios [27, 32], despite the need to add the entire sensing system, including the transmission of the sensing signal and the retrieval of the resulting interference, which is clearly not part of the installed telecommunication hardware.

State of polarization sensing

Light SOP is sensitive to fiber external perturbations. As this is one of the main techniques that will be studied in this thesis, the mechanisms underlying the SOP changes induced by temperature and/or strain will be mentioned in the next chapter. SOP can be measured by ad hoc instruments, polarimeters [36], or by coherent receivers [18], which already estimate it as part of their internal digital signal processing (DSP), since it is needed for data demodulation. Notice that the latter is a recent approach, slowly becoming a standard: in this case, there would be no need to install dedicated sensing hardware, easing costs and complexity.

Despite the light polarization being largely insensitive to laser linewidth, there are some other limitations that should be accounted for. For short distances (mainly metropolitan networks, a few tens of km) where no amplifiers, typically erbium-doped fiber amplifiers (EDFA), are employed, the main limitation is on the received optical power, relating to the sensitivity of the instrument (polarimeter or coherent receiver) employed. If it is too low, the measured state of polarization may become too noisy or even unmeasurable. For long, amplified, optical links, the main problem would be related to the amplified spontaneous emission (ASE) noise, generated by the EDFAs in the link. Similarly, this would distort the measured SOP if the ASE noise is too high. A detailed characterization will be provided in Chapter 3. Note that the light being measured should always be polarized. SOP-based sensing systems can thus extend to thousands of km (e.g., submarine environments [9]), but work even in shorter distances (e.g., terrestrial environments [12, 14]).

The measurand SOP delivers a qualitative estimate of the actual physical event occurring on the fiber, which is also one of the limits of this technique. When used to sense events, it is never used to quantify them in terms of strain or temperature, but rather as a detector of changing conditions.

With respect to interferometric techniques, in coherent telecommunication systems, the actual telecommunication signals' SOP can be retrieved and used to sense external events, without the need to add external probes.

Forward optical phase sensing

As discussed above, any phase change can be traced back to an axial strain. In the absolute forward optical phase-based technique, no interferometry is involved and

only the forward signal is considered. With respect to interferometric techniques, integrating forward optical phase sensing with communication systems could be more efficient. As for the polarization, the data channels' phase information encodes the data and needs to be recovered anyway by the DSP. There is no need to employ FRM or specific loopback configurations. Nevertheless, the external perturbations need to induce stronger phase changes than the ones intrinsically generated by the laser phase noise. This means that low-linewidth ($\sim$ Hz) lasers are required. Their integration with the communication systems is then complicated, as the need for laboratory-grade lasers is outside the requirements (and costs) for typical telecommunication hardware [33, 34, 10, 35]. Some research discussed an enhanced forward phase events detection capability with respect to SOP, further investigation will be provided in Chapter 3.

1.2.2 Length-resolved sensing techniques

Distributed, length-resolved, fiber sensing techniques are experiencing increasing growth, especially in recent years, given their sensitivity in measuring and localizing mechanical and temperature perturbations coming from the fiber cable's surroundings, possibly anticipating dangerous conditions to which early warning would be necessary. A short ($\sim$ tens of ns) high-power (i.e., peak power of 30-33 dBm) pulse is sent to the fiber, and the backscattered trace is analyzed. The backpropagated pulse flight time is exploited to localize the events, with space resolution depending on the pulse time width (usually of some meters). This working principle, typical of optical time domain reflectometer (OTDR) systems, will be further discussed in Section 2.2, in the next chapter. Despite the "pulsed" approach being the most common, some others based on pulse coding are increasingly being studied [37].

The main distributed sensing techniques are based on Brillouin, Raman, or Rayleigh light backscattering, which translate into different working principles of the sensing system and, in turn, into diverse scenarios for coexistence with data. Specifically, Fig. 1.4, taken from [38], shows the typical backscattered spectrum components, highlighting the ones that are used for the specific approach mentioned above.

In this thesis, we will only study coexistence with distributed acoustic sensing (DAS) systems, based on Rayleigh backscattering. Nevertheless, we provide in the following a full picture of the state of the art [39].

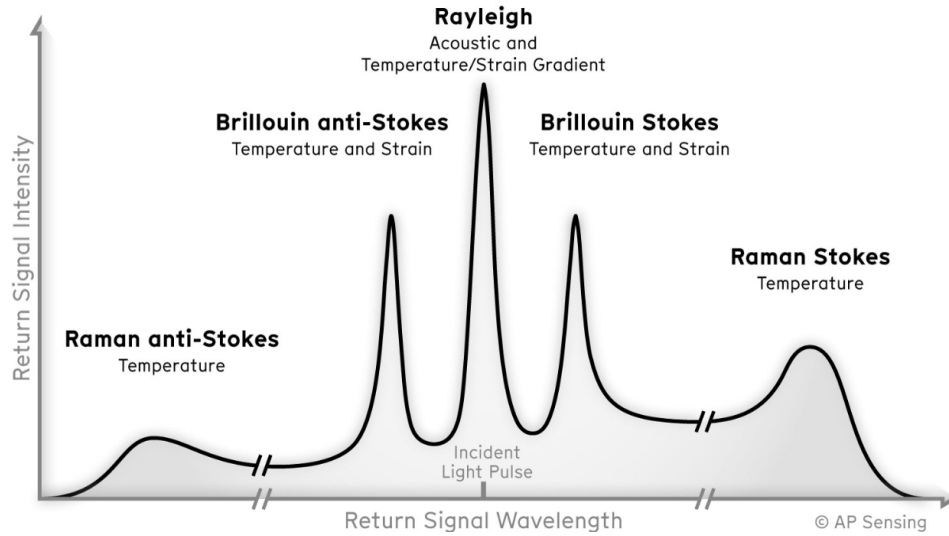


Fig. 1.4 Backscattered signal spectrum, with highlighted the different bandwidths used for sensing. The plot is qualitative, on both axes, and meant for further explanation in the text. Picture taken from [38].

Raman-based sensing

The Raman phenomenon has extensive application scenarios, including telecommunication channels amplification in optical fiber communications systems. When used for sensing, the backscattered Raman-induced anti-Stokes gain is the measurand. It is spaced about 13 THz from the pulsed pump (see Fig. 1.4), and has temperature-dependent intensity. The usual approach consists of evaluating the ratio between the intensity of the gain in the anti-Stokes with that in the Stokes side, insensitive to strain, to get rid of fiber losses, and recover the temperature variation. This technique only allows for temperature sensing. Concerning the coexistence with telecommunication data, precise wavelength positioning in the dense wavelength division multiplexing (DWDM) spectrum is required, also avoiding proximity to the pump due to the nonlinear Kerr effect and ensuring sufficient separation from the very weak anti-Stokes sensing signal. The typical pulse peak power are very high, around 30 dBm to 33 dBm. Two completely different optical bands should be used, such as the C-band for Raman sensing and the O-band for data transmission (or vice-versa). For these reasons, huge peak power and bandwidth requirements, Raman-based sensing coexistence with telecommunication systems is complex to deploy. To our knowledge, few to no works have addressed this scenario so far.

Table 1.2 Length-resolved sensing techniques: summary and comparison.

Technique	Response time	Temp. /Strain sens.	Laser linewidth	Optical source power	Required optical BW	DWDM compat.
Raman	Slow (tens of seconds)	Yes/No	~MHz	30-33 dBm	13 THz	No
Brillouin	Slow (tens of seconds/minutes)	Yes/Yes	~MHz	27 dBm	~ 11 GHz	To be studied
DAS	Real-time	Yes/Yes	$\leq$ kHz	up to 30 dBm, most commonly ~ 23 dBm	~linewidth	Conditioned

Brillouin-based sensing

Distributed fiber sensors based on the Brillouin phenomenon rely on the detection of a backscattered signal spaced approximately 11 GHz from the pump (see Fig. 1.4). At this offset, a several GHz frequency shift in the backscattered trace can be used as a measurable parameter, as it quantifies any changes in strain or temperature. The Brillouin backscattering effect is quite weak, which means that the interrogating system must time-average over a large number of backscattered traces, adding to the processing time. Compared to the Raman, it is anyway stronger, especially in the stimulated version. The frequency shift search makes the sensor accurate but also quite complex and time-consuming. Consequently, Brillouin systems have quite slow response times, sometimes reaching a few minutes, and thus are not suited to sense fast mechanical vibration happening along the fiber, but only slow effects, such as temperature drift and almost-static fiber strains. Concerning their coexistence with telecommunication systems, the pulses have high power (around 27 dBm), which results in Kerr nonlinearities for nearby channels. As for Raman, the optical bandwidth required is less critical, but still concerning. Coexistence with a Brillouin-based sensing system is to be studied, but it seems complex to deploy.

Distributed acoustic sensing

Particularly for geophysical applications, concerning, for example, metropolitan monitoring [40, 41] and earthquake detection [42, 43, 8], DAS systems are finding the largest appreciation, thanks to their ability to detect dynamic events, such as mechanical vibrations up to the kHz range, and extremely slow ones, such as

temperature changes [44]. The basic working principle is based on processing the Rayleigh backscattered trace, which contains information on the fiber axial strain and temperature [45]. Unlike Brillouin and Raman-based techniques, the laser linewidth and stability are important constraints to allow the DAS system to function correctly. The coexistence with optical telecommunication systems is currently studied and seems possible, under certain conditions. The main problem of DAS pulses and telecommunication channels co-propagation is always related to the Kerr effect, which, with pulse peak powers reaching even 30 dBm, would be non-negligible on nearby channels. Nevertheless, the usual power range employed never usually exceeds 23 dBm [46]. On a larger scale, we must also consider the scalability of the integration of this system to deployed telecommunication optical infrastructure. Since this expensive sensing-dedicated hardware [37, 47] is not part of the usual commercial coherent transceivers, the installation cost and complexity would be non-negligible, over a large scale. Additionally, the amount of data generated is huge: since they are resolved in time and space, the data stream generated would be complex to manage and could represent an actual bottleneck to real-time early warning for hazardous conditions. DAS integration with the telecommunication system is extremely powerful, as it would efficiently exploit the same medium to sense for hazards, with demonstrated localization accuracy. Nevertheless, having strict hardware requirements and mostly opposite characteristics to the telecommunication side, the coexistence is conditioned to some specific cases, which we will study in Chapter 5.

1.3 Outlook of This PhD Thesis

This thesis is divided into a total of 6 chapters, the next 5 will be organized as follows:

- **Chapter 2.** We discuss and provide the general theoretical background for the reader to be able to understand the content of the following chapters. The main focus will be on the SOP, as the main technique that has been studied, for which we provided a whole framework for the different mathematical derivations. Some theoretical background concerning DAS is also provided.

- **Chapter 3.** Since one of the main application scenarios for SOP sensing is the metropolitan network, we provide here a complete analysis concerning the SOP extraction from coherent transceivers, proposing and comparing some DSP algorithms to process it. Some phase versus SOP experiments are proposed to understand the main differences between the two measurands when integrated in a telecommunication system. In this chapter's conclusion section, we also provide some hints concerning events positioning through SOP.
- **Chapter 4.** Despite the application range being mostly confined to telecommunication systems, for the reasons explained above, SOP sensing can be employed in some standalone mode, using only the hardware needed to allow for SOP retrieval (e.g., polarimeters). In this context, we studied first in a scale model and later in a real mountain gully the development and installation of a debris flow detection system that completely relies on SOP processing. This chapter shows the main related results and outcomes.
- **Chapter 5.** Distributed acoustic sensing delivers outstanding strain and temperature detection capabilities, with accurate space localization. Nevertheless, the requirements that these systems have are opposite with respect to the telecommunication side. In this chapter, we show the main results we obtained when studying the coexistence of the two systems, showing the final working conditions where they both can work properly.
- **Chapter 6.** Conclusions, providing a complete picture, based on the obtained results, of the main sensing technique performances when integrated into the optical fiber telecommunication system.

1.4 List of Publications of the PhD Candidate

The publications of the PhD candidate are listed below and consist of: 5 journal papers (4 as the first author), and 10 conference proceedings (6 as the first author).

1. S. Pellegrini, L. Minelli, L. Andrenacci, G. Rizzelli, D. Pilori, G. Bosco, L. Della Chiesa, C. Crognale, S. Piciaccia, R. Gaudino, "Overview on the state of polarization sensing: application scenarios and anomaly detection algorithms,"

- Journal of Optical Communications and Networking*, vol. 17, no. 2, pp. A196–A209, 2025, Optica Publishing Group.
2. S. Pellegrini, G. Rizzelli, M. Barla, R. Gaudino, “Algorithm optimization for rockfalls alarm system based on fiber polarization sensing,” *IEEE Photonics Journal*, vol. 15, no. 3, pp. 1–9, 2023, IEEE.
 3. S. Pellegrini, G. Rizzelli, M. Barla, R. Gaudino, “Polarization-based fiber optic system for debris flow early warning: on-field demonstration,” *IEEE Photonics Journal*, vol. 16, no. 3, pp. 1–8, 2024, IEEE.
 4. M. Barla, S. Aiassa, F. Antolini, A. Insana, R. Gaudino, G. Rizzelli Martella, S. Pellegrini, “A new real-time debris flow and snow avalanche detection system based on optical fiber sensing,” *Landslides*, vol. 22, no. 5, pp. 1367–1382, 2025, Springer Berlin Heidelberg.
 5. S. Pellegrini, L. Hernández-Martin, A. M. Rosa Brusin, G. Rizzelli, J. D. Ania-Castañón, G. Bosco, R. Gaudino, H. F. Martins, “Experimental and Simulative Study on IM-DD Transmission and Large Chirped-Pulse DAS Coexistence,” *Journal of Lightwave Technology*, 2025, doi: 10.1109/JLT.2025.3644664.
 6. S. Pellegrini, R. Gaudino, C. Crognale, “Experimental demonstration of vibration sensing and positioning on multiple metropolitan fibers,” 2023 IEEE Photonics Society Summer Topicals Meeting Series (SUM), pp. 1–2, 2023, IEEE.
 7. S. Pellegrini, L. Andrenacci, L. Minelli, D. Piori, G. Bosco, L. Della Chiesa, R. Gaudino, “Estimation accuracy of polarization state from coherent receivers for sensing applications,” 2023 IEEE Photonics Conference (IPC), pp. 1–2, 2023, IEEE.
 8. L. Minelli, S. Pellegrini, L. Andrenacci, D. Piori, G. Bosco, L. Della Chiesa, A. Tanzi, C. Crognale, R. Gaudino, “SOP-based DSP blind anomaly detection for sensing on deployed metropolitan fibers,” 49th European Conference on Optical Communications (ECOC 2023), vol. 2023, pp. 519–522, 2023, IET.
 9. L. Andrenacci, D. Piori, S. Pellegrini, L. Minelli, G. Bosco, C. Crognale, S. Piciaccia, R. Gaudino, “Comparison between phase and polarization sensing using coherent transceivers over deployed metro fibers,” Optical Fiber Communication Conference, pp. M2K.2, 2024, Optica Publishing Group.

10. S. Pellegrini, L. Minelli, L. Andrenacci, D. Piori, G. Bosco, B. Koch, R. Noé, C. Crognale, S. Piciaccia, R. Gaudino, “Real-time demonstration of anomalous vibrations detection in a metro-like environment using a SOP-based algorithm,” 2024 Optical Fiber Communications Conference and Exhibition (OFC), pp. 1–3, 2024, IEEE.
11. A. M. Rosa Brusin, G. Rizzelli, M. Fasano, J. Morosi, S. Pellegrini, V. Ferrero, G. Bosco, D. Piori, P. Parolari, A. Madaschi, “Overview and analysis of optical sensing techniques over deployed telecom networks,” 2024 24th International Conference on Transparent Optical Networks (ICTON), pp. 1–4, 2024, IEEE.
12. S. Pellegrini, G. Rizzelli, L. Minelli, L. Andrenacci, D. Piori, G. Bosco, C. Crognale, S. Piciaccia, R. Gaudino, “SOP-based Sensing for Detecting Different Anomalous Events: Practical Implementation Considerations,” ECOC 2024; 50th European Conference on Optical Communication, pp. 1952–1955, 2024, VDE.
13. S. Pellegrini, L. Hernández-Martin, A. M. Rosa Brusin, G. Rizzelli, J. D. Ania-Castañón, G. Bosco, R. Gaudino, H. F. Martins, “On the Coexistence of DAS and IMDD Systems on the Same Fiber,” 2025 25th Anniversary International Conference on Transparent Optical Networks (ICTON), pp. 1–4, 2025, IEEE.
14. S. Pellegrini, D. El Hak Daamouche, R. Gaudino, G. Rizzelli, “Experimental Characterization of a Deployed Early-Warning System for SOP Based Monitoring of Debris Flows in Mountain Scenarios,” 2025 25th Anniversary International Conference on Transparent Optical Networks (ICTON), pp. 1–4, 2025, IEEE.
15. M. Olivero, G. Rizzelli, C. Bellezza Prinsi, S. Pellegrini, A. Quattrone, F. Tondolo, D. Sabia, G. Perrone, R. Gaudino, “Real-framework comparison of optical fiber distributed sensing techniques for Building Information Modeling,” IMEKO TC2 PhotoMet 2025, pp. 25–26, 2025, IMEKO.

At this time, we also plan the following submissions:

- One IEEE Photonics Journal, one ECOC, and one ICTON paper on the DAS coexistence with coherent telecommunication data.

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- One Journal of Optical Communications and Networking and one ECOC paper on state of polarization estimate over passive optical networks.

Chapter 2

Theoretical Background of the Sensing Techniques Addressed in this Thesis

This chapter discusses the theoretical background for the main sensing techniques discussed throughout this thesis, aiming to provide a strong foundation for out-of-field readers and to set the baseline for notations. The content of the following sections has been inspired by [48, 49, 24, 50, 51].

2.1 Light State of Polarization Theory Background

Prior to understanding how and why the light state of polarization can be used to sense external perturbations, the baseline theory needs to be addressed. Note that the following is not an absolutely comprehensive theoretical approach to polarization, and will mainly address the necessary concepts that the reader will need to understand this PhD research work.

2.1.1 General polarization theory

As light is an electromagnetic wave, polarization in optical fibers refers to the orientation of the electric field vector in the transverse x - y plane, which evolves in

space and time as the wave propagates over z . As is well known from basic optics theory [24], when considering a standard single-mode fiber (SSMF), the fundamental linearly polarized (LP) $LP_{0,1}$ mode includes the $LP_{0,1}^x$ and the $LP_{0,1}^y$. Consequently, on the most general and simplified mathematical (instantaneous) form, the electric field $\vec{E}(t)$ can be expressed as in Eq. 2.1.

$$\begin{aligned}\vec{E}(z, t) = \text{Re}[(\hat{x}E_1e^{j(2\pi ft + \varphi_1)} + \hat{y}E_2e^{j(2\pi ft + \varphi_2)})e^{-jkz}] = \\ \hat{x}E_1 \cos(2\pi ft - kz + \varphi_1) + \hat{y}E_2 \cos(2\pi ft - kz + \varphi_2)\end{aligned}\quad (2.1)$$

Here, E_1 , E_2 are the electrical field amplitudes with related φ_1 , φ_2 phases, on the x - and y -components. The frequency and wavenumber are represented by f and k , while t and z represent time and space, respectively. Notice that, as a first approximation, $LP_{0,1}^x$ and $LP_{0,1}^y$ are considered to be perfectly degenerate, meaning that their wavenumber is identical, $k_x = k_y = k$. Having constant or varying z is thus not really relevant, as the same (constant) quantity would be subtracted from the phases φ_1 and φ_2 on the two polarizations, making the phase difference $\delta = \varphi_2 - \varphi_1$ between the x and y polarization, constant over z . For this reason and for the sake of simplicity, in the following part of this subsection, the space propagation has been neglected, as if it were $z = 0$, and thus the time-only evolution of the single x - y electric field component $E_x(t)$ and $E_y(t)$, would be as in Eq. 2.2,

$$\vec{E}(t) = \hat{x}E_1 \cos(2\pi ft + \varphi_1) + \hat{y}E_2 \cos(2\pi ft + \varphi_2) = E_x(t) + E_y(t) \quad (2.2)$$

and thus leading to Eq. 2.3.

$$\begin{aligned}E_x(t) &= \hat{x}E_1 \cos(2\pi ft + \varphi_1) \\ E_y(t) &= \hat{y}E_2 \cos(2\pi ft + \varphi_2)\end{aligned}\quad (2.3)$$

In particular, Fig. 2.1a) shows the two single components' time evolution. In general, the amplitudes are different (i.e., $E_1 \neq E_2$), but for this example we chose $E_1 < E_2$ with phase difference δ . The time evolution of the tip of the resulting $\vec{E}(t)$ vector is also shown as the black line in Fig. 2.1b). Considering $E_x(t)$ and $E_y(t)$ as basis functions, the resulting shape described by the tip of the electric field vector $\vec{E}(t)$ is described by the formula in Eq. 2.4

$$\left(\frac{E_x(t)}{E_1}\right)^2 + \left(\frac{E_y(t)}{E_2}\right)^2 - 2\frac{E_x(t)E_y(t)}{E_1E_2}\cos(\delta) = \sin^2(\delta) \quad (2.4)$$

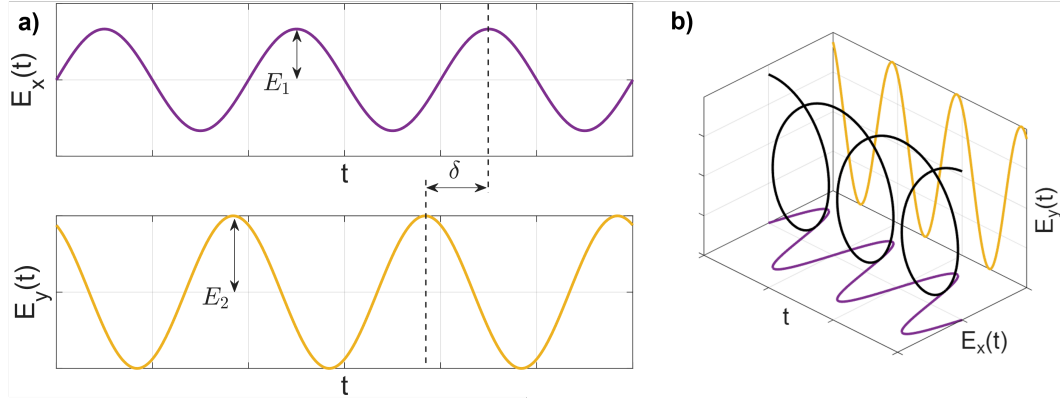


Fig. 2.1 a) $E_x(t)$ (upper plot) and $E_y(t)$ (lower plot) components time evolutions with amplitudes (E_1 and E_2 , respectively) and phase difference δ highlighted. b) shows as a black line the resulting electric field vector tip time-evolution.

which demonstration is in the Appendix A.1. Eq. 2.4 states that the tip of the electrical field vector, seen as projected over the $E_x(t)$ - $E_y(t)$ plane, describes, in the most general case, an ellipse. For this reason, this is called *elliptic polarization*. Among all the states of polarization, the ellipse could degenerate to a line (if $\delta = n\pi$, see Appendix A.1) or a circle (if $\delta = n(\pi/2)$ and $E_1 = E_2$, see Appendix A.1), corresponding to *linear* and *circular polarizations*. The polarization ellipse has been reported, for the same case shown in Fig. 2.1, in Fig. 2.2. This corresponds to looking at Fig. 2.1b) through the $E_x(t)$ and $E_y(t)$ plane only.

Following the considerations discussed up to now, the SOP can be expressed through three parameters: E_1 , E_2 and δ , which completely define the polarization ellipse (see Eq. 2.4 and Fig. 2.2). Nevertheless, the ellipticity angle χ and orientation (or tilt) ψ can also be used to define the shape of the ellipse in Fig. 2.2. Their relationships with the previously defined parameters are reported in Eq. 2.5, where $R = E_2/E_1$.

$$\begin{aligned}\tan(2\psi) &= \frac{2E_1E_2}{E_1^2 - E_2^2} \cos(\delta) = \frac{2R}{1 - R^2} \cos(\delta) \\ \sin(2\chi) &= \frac{2E_1E_2}{E_1^2 + E_2^2} \cos(\delta) = \frac{2R}{1 + R^2} \sin(\delta)\end{aligned}\tag{2.5}$$

If the optical power is known, the knowledge of R and δ completely defines the SOP, as well as χ and ψ .

In this thesis, unless specified, the Stokes formalism has always been employed to represent the SOP. Mathematically, it can be derived starting from the ellipse in Eq. 2.4, and connects E_1 , E_2 , δ , χ , ψ discussed above to the *Stokes parameters*.

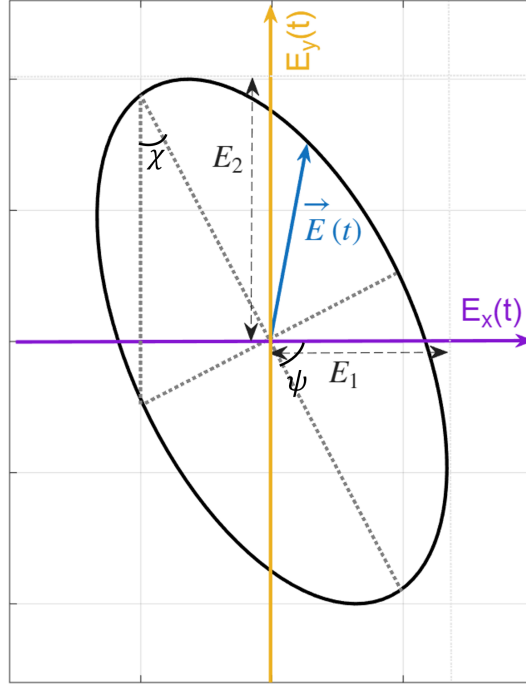


Fig. 2.2 Polarization ellipse.

Since, under perfectly ideal conditions, the ellipse is defined when both $E_x(t)$ and $E_y(t)$ are considered (at least) within a single time period T of the sinusoids in Fig. 2.1a), Eq. 2.4 could be considered as an average over a single period, as in Eq. 2.6.

$$\frac{\langle E_x(t)^2 \rangle}{E_1^2} + \frac{\langle E_y(t)^2 \rangle}{E_2^2} - 2 \frac{\langle E_x(t)E_y(t) \rangle}{E_1E_2} \cos(\delta) = \sin^2(\delta) \quad (2.6)$$

By unwrapping all the averaged terms, in Eq. 2.6, one obtains Eq. 2.7.

$$\begin{aligned} \langle E_x^2(t) \rangle &= \frac{E_1^2}{T} \int_0^T \cos^2(2\pi ft + \phi_1) dt = \frac{E_1^2}{2} \\ \langle E_y^2(t) \rangle &= \frac{E_2^2}{T} \int_0^T \cos^2(2\pi ft + \phi_2) dt = \frac{E_2^2}{2} \\ \langle E_y(t)E_x(t) \rangle &= \dots = \frac{E_1E_2}{2} \cos(\delta) \end{aligned} \quad (2.7)$$

The whole $\langle E_y(t)E_x(t) \rangle$ integral resolution is omitted and can be solved by parts. The terms in Eq. 2.7, once substituted in Eq. 2.6 lead, after some easy mathematical manipulations (see Appendix A.2 for details), to Eq. 2.8.

$$(E_1^2 + E_2^2)^2 - (E_1^2 - E_2^2)^2 - (2E_1E_2 \cos(\delta))^2 = (2E_1E_2 \sin(\delta))^2 \quad (2.8)$$

Following Eq. 2.8, the Stokes parameters are defined as in Eq. 2.9

$$\begin{aligned} S_0 &= E_1^2 + E_2^2 \\ S_1 &= E_1^2 - E_2^2 \\ S_2 &= 2E_1E_2 \cos(\delta) \\ S_3 &= 2E_1E_2 \sin(\delta) \end{aligned} \quad (2.9)$$

under the condition in Eq. 2.10, which is just a rephrasing of Eq. 2.8.

$$S_0^2 = S_1^2 + S_2^2 + S_3^2 \quad (2.10)$$

In other words, the SOP can be geometrically represented as the evolution of a three-dimensional vector $\vec{S} = [S_1 \ S_2 \ S_3]^T$, called the Stokes vector¹, having its tip on the surface of a sphere, called Poincaré sphere, and modulus $\|\vec{S}\| = S_0$, which is also the sphere radius. S_0 , given the definition in Eq. 2.9, is also the light optical power. A representation of the Poincaré sphere is in Fig. 2.3, which also shows the geometrical relationship that the Stokes vector has with ellipticity χ and orientation ψ . In the remainder of this thesis and unless otherwise noted, the Stokes vector

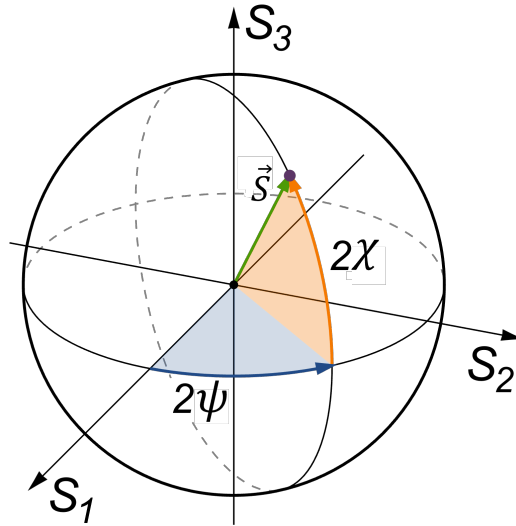


Fig. 2.3 Poincaré sphere space, showing generic Stokes vector $\vec{S}$, ellipticity χ and orientation ψ angles geometrical representation. Image taken from [52].

¹We will consider the Stokes parameters defined over an integration time T (see Eq. 2.7) that is much larger than the symbol duration, when applied to digital modulated signals (i.e., QPSK, QAM), and smaller than the time constants of any mechanical vibrations we'll discuss in the next chapters.

$\vec{S}$ will always be referred to as normalized with respect to S_0 , so that the SOP can always be represented as a point on the surface of the Poincaré sphere, of radius 1. To summarize, the final expression of (normalized) $\vec{S}$ is reported in Eq. 2.11.

$$\vec{S} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \frac{1}{S_0} \begin{bmatrix} E_1^2 - E_2^2 \\ 2E_1E_2 \cos(\delta) \\ 2E_1E_2 \sin(\delta) \end{bmatrix} = \frac{1}{S_0} \begin{bmatrix} \cos(2\chi) \cos(2\psi) \\ \cos(2\chi) \sin(2\psi) \\ \sin(2\psi) \end{bmatrix} \quad (2.11)$$

The relationship of each Stokes parameter to χ and ψ has been mathematically demonstrated in Appendix A.3.

2.1.2 Birefringence, Jones calculus and hints on coherent receivers polarization compensation

In the previous subsections, the fiber has been considered in perfectly ideal conditions, where the wavenumbers k_x and k_y are identical (i.e., the two LP modes are perfectly degenerate in polarization). This means, as stated above, that even if considering varying or not varying z , the input and output polarization states are the same. In more practical terms, this would only happen if the fiber is ideal (i.e., no core ellipticity, no strain/compressions of the fiber length, no material imperfections...), with the circular symmetry was preserved perfectly for its whole length. This condition is clearly impossible and far from what happens in reality: the symmetry usually breaks, lifting the degeneracy of the two modes (i.e., $k_x \neq k_y$) and making them propagate with two different velocities. This effect is called *birefringence*, defined in this thesis as β in Eq. 2.12.

$$\beta = k_0(n_y - n_x) = k_y - k_x \quad (2.12)$$

The Equation depicts $k_0 = \frac{2\pi}{\lambda_0}$ (λ_0 being the propagating light central wavelength) and n_x, n_y as the two degenerate modes refractive indexes, respectively for $LP_{0,1}^x$ and $LP_{0,1}^y$. In this case, Eq. 2.1 would break into Eq. 2.13,

$$\vec{E}(z, t) = \hat{x}E_1 \cos(2\pi ft - k_x z + \varphi_1) + \hat{y}E_2 \cos(2\pi ft - k_y z + \varphi_2) \quad (2.13)$$

where clearly making z vary would make the SOP change as the light propagates through the fiber, and is then not equivalent to fixing it to 0. This means that the change in polarization state is periodic, with a particular length over which it repeats,

called the beat length $L_b = 2\pi/\beta$, which depends on the fiber birefringence. Typical values of β , make L_b of the order of some meters [53]. Having introduced the concept of birefringence, the fact of having different but constant k_x and k_y through the fiber length has been accounted for. In reality, this condition is also quite far from being true, as the imperfections are not constant through the fiber, making the k_x and k_y values statistically change over its length. This means that the SOP also evolves randomly with light propagation, but results in a constant output SOP if the two propagation constants do not change over time. In order to mathematically describe the polarization evolution in optical fibers, a very useful and common notation is the Jones calculus. To make the reader understand the main concepts of this thesis, we report in the following some hints, described in [51]. Following Eq. 2.13, the electric field vector can be represented as a vector of complex numbers, as in Eq. 2.14, where, in E_x and E_y , we dropped the z and t dependencies for notational convenience.

$$\vec{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_1 e^{j(2\pi ft - k_x z + \varphi_1)} \\ E_2 e^{j(2\pi ft - k_y z + \varphi_2)} \end{bmatrix} \quad (2.14)$$

A generic polarizing element, a waveplate, would then have the following Jones matrix, in Eq. 2.15

$$J = \begin{bmatrix} A_x & 0 \\ 0 & A_y \end{bmatrix} \quad (2.15)$$

where A_x and A_y are short forms for what shown in Eq. 2.16.

$$\begin{aligned} A_x &= e^{-j(k_0 d)(n_x - j\alpha_x)}, \\ A_y &= e^{-j(k_0 d)(n_y - j\alpha_y)} \end{aligned} \quad (2.16)$$

The parameter d represents the thickness of the waveplate, while α_x and α_y are the absorption coefficients for the single polarization. The difference between the two absorption coefficients is called polarization dispersion loss (PDL). If the PDL can be neglected, both polarizations are affected by the same absorption coefficient α . In this case $\alpha_x \approx \alpha_y \approx \alpha$, so the exponential term containing the absorption coefficient can be gathered outside the matrix in 2.15, which can now be considered as unitary. Since the waveplate element needs to be aligned with the polarization axes of the received light, matrix J has to be rotated by an angle θ before being applied, and then rotated back. Any input electrical field $\vec{E}_{in}$ to any optical element with Jones matrix J , would generate an output field $\vec{E}_{out}$ equal to the one in Eq. 2.17, where $R(\cdot)$

represent a two dimensional rotation matrix.

$$\vec{E}_{out} = R(\theta)JR(-\theta)\vec{E}_{in} \quad (2.17)$$

The entire fiber can then be represented as a cascade of M waveplates, each with a proper Jones matrix, orientation angle, absorption coefficient, and x-y refractive indices, as a results of non-spatially-constant imperfections along the fiber length. The work in [51] also demonstrates that a cascade of M elements can be reduced to a single element, with the cumulative effect of all of them, representing the overall effect of the fiber on the input light polarization as it propagates through it. Figure

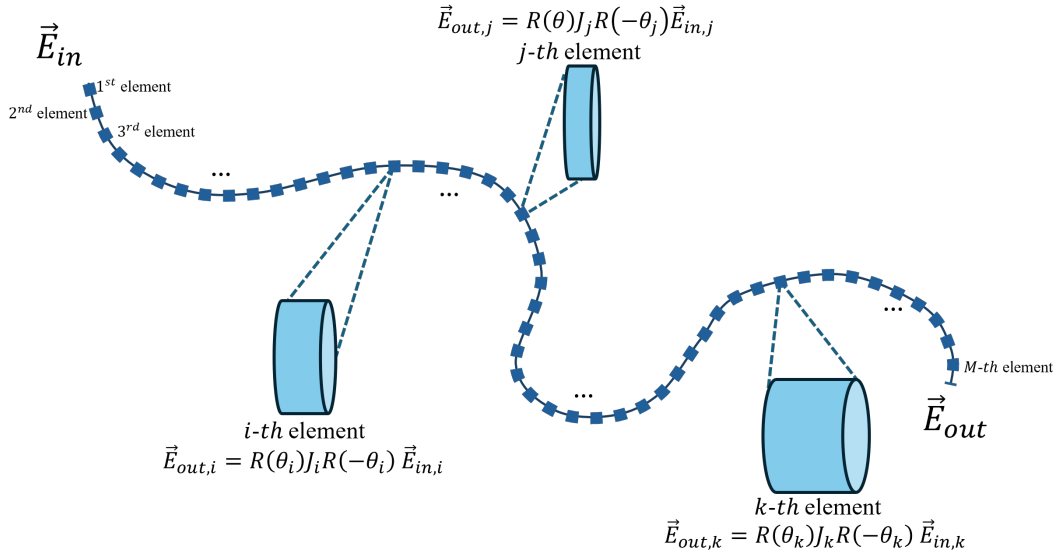


Fig. 2.4 Schematic representation of a fiber with highlighted the cascade of M waveplates, showing the effect on input $\vec{E}_{in}$ polarization.

2.4 shows a schematic representation of the cascade of different waveplates having different characteristics, and thus affecting polarization in different manners. What is important to notice from this discussion is that the electrical field at the output of the fiber, will have different polarization depending on the cumulative, *integrated* effect along the fiber: if we would be able to monitor the polarization at the i -th with respect to the j -th positions in Fig. 2.4, the SOP would be different. This also further explains why the SOP belongs to the LI sensing techniques (see Section 1.2.1). In general, and for the following discussion, the whole fiber Jones matrix J is considered as already involving the rotation matrices.

Up until this point, fiber imperfections due to the fabrication process have only

been considered as the main source of SOP change. Nevertheless, external factors can affect different portions of the fiber and alter the polarization at its output, cumulating over the entire link length. Different works theoretically demonstrated how strains coming from the surrounding environment can make the polarization change [24, 20, 22, 53, 54, 21]. These effects are called photoelastic [55], since they induce birefringence due to a mechanical interaction with the fiber. Also, temperature could make the SOP drift for the same reason. This would, in practice, correspond to having Jones matrices changing with time, not only along the fiber length, which in turn would deliver time-varying SOPs at the output of the fiber, whenever an external event affects the fiber. This is at the basis of the use of polarization, in the context of this research, for sensing purposes: each waveplate in Fig. 2.4 makes the SOP not only vary in space, but also in time, if some external event changes its matrix.

Despite having discussed here the evolution of the SOP using the Jones notation, it is important to specify that it has an equivalent representation with the Stokes notation. The equivalent Jones matrices describing the change on the input Jones vector are called Mueller matrices [49], which in turn would need to be applied to the Stokes vector described in Subsection 2.1.2. Using the Stokes representation for sensing is thus a perfectly equivalent and simple way to monitor the SOP and detect external agents acting on the fiber, such as mechanical stresses [56, 24, 22] and vibrations [23, 20, 54, 21]. From Eq. 2.11, Stokes parameters can be retrieved, considering the Jones vector in Eq. 2.14, as in Eq. 2.18.

$$\begin{aligned}
 S_0 &= |E_x|^2 + |E_y|^2 \\
 S_1 &= |E_x|^2 - |E_y|^2 \\
 S_2 &= 2 \cdot \text{Re}(E_x E_y) \\
 S_3 &= -2 \cdot \text{Im}(E_x E_y)
 \end{aligned} \tag{2.18}$$

The Jones representation is also the convention used by the DSP chain of coherent receivers when compensating for polarization impairments on the data [19, 18, 57]. The standard coherent receiver optical analog front-end returns four signals, undergoing optical-to-electrical conversions through photodiodes. The resulting electrical signals are input to the DSP chain, after analog-to-digital conversion. Coherent communications encode information not only on light's phase and intensity, but on polarization as well. This is why the resulting signals are four: one modulated complex number for polarization state. After the first DSP stages, which usually

involve data resampling and chromatic dispersion compensation, the 2x2 complex adaptive equalizer (also known as “butterfly equalizer”) block deals with polarization impairments [58, 35]. We have shown above how the overall SOP changes induced by the fiber channel can be compressed into a single Jones matrix, which also accounts for the rotation plane orientations θ . The operation done by the equalizer is to recover the inverse W of that Jones matrix J , and apply it back on the received data. In this way, the first-order polarization impairments on the signal SOP are eliminated, allowing the recovery of the actual data by the next stages of the processing chain. The equalizer also adapts (at the system baud rate, see [18] for details) to the changing conditions of the transmission medium, so that the (inverse of the) Jones matrix is always updated. The DSP of the coherent receiver then keeps track of any SOP change happening on the fiber, which usually is many orders of magnitude slower than the baud rate. Since in typical real systems the PDL is low, the resulting Jones matrix can be considered unitary. In this case, one column of W is physically a Jones vector, orthogonal to the other column, and can be used to retrieve the related Stokes vector [35]. More general analyses, including the PDL, are also available [16, 59]. Coherent receivers can then be used to record SOP: the only upgrade needed would concern the extraction of the equalizer taps and the following detection algorithms, which this thesis will discuss in the next chapters.

2.2 Distributed Acoustic Sensing Theory Background

Chapter 1 provides an overview of the state of the art of different sensing techniques used, both for the LI and LR cases. As mentioned, Brillouin and Raman-based systems will not be treated in this thesis, as not properly suitable to be integrated in an optical telecommunication system. Our focus will then be on DAS, for which, in this section, we will provide a theoretical introduction. Since this thesis is not focusing on the physical details of its working principle, we will only show the main points, allowing the reader to understand the chapters where the technology is involved.

The following subsections have been inspired by [45, 5, 60, 61].

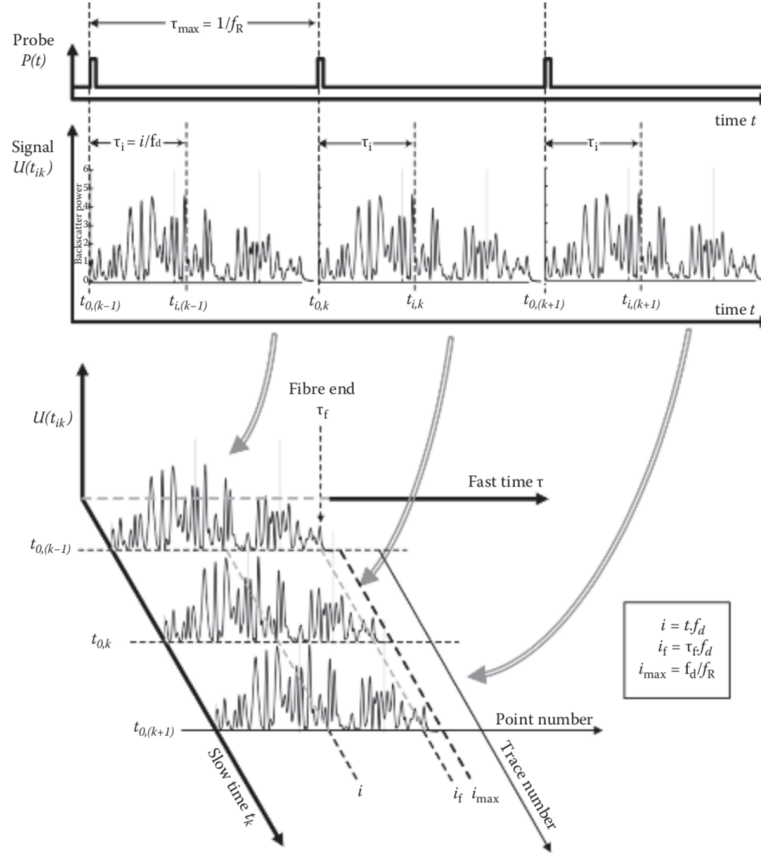


Fig. 2.5 Fast time and slow time visualization, versus pulse occurrences and backscattered traces amplitude. Picture taken from [5].

2.2.1 Optical time domain reflectometry and standard DAS

LR techniques, OTDR-based, exploit the light backscattering to retrieve information about the strain and temperature of the fiber. The known light flight time is used to localize the scattering locations (within a resolution cell) and characterize the physical phenomena happening along the link. The most common OTDR systems use a pulsed probe signal to propagate into the fiber. One pulse will deliver spatial information, changing in time, which is why a train of pulses is employed. This is well represented in Fig. 2.5 (taken from [5]), where the upper plot shows the probe $P(t)$ with pulse repetition period $\tau_{max} = 1/f_R$, making f_R the repetition rate. For a fiber of length L , the total single-pulse round-trip time is denoted by τ_f and scales linearly with L . In standard OTDRs, the condition $\tau_{max} > \tau_f$ must always be enforced to avoid overlapping of consecutive backscattered traces. The duration of

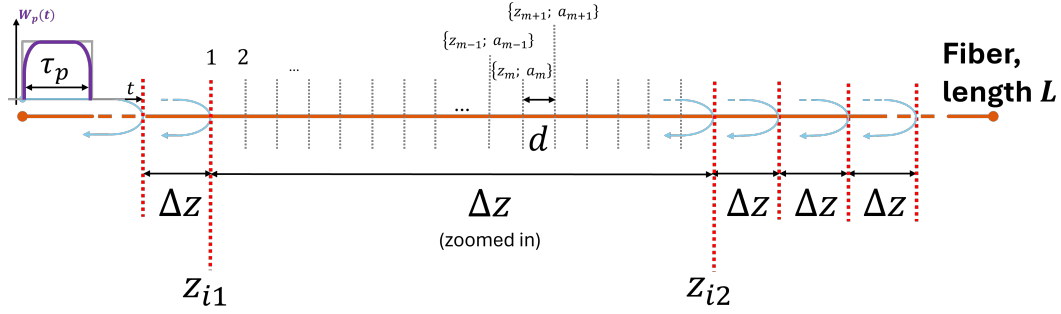


Fig. 2.6 Graphical representation of DAS pulse propagation in the fiber, highlighting the scattering area Δz and the m -th scatterers.

each pulse will be here called τ_p .

Fig. 2.5 depicts the probe $P(t)$ and backscattered signal $U(t)$. Consecutive pulses, correctly spaced, will deliver a continuous signal made of consecutive backscattered traces. Since OTDR systems track both spatial and time variations, two time axes are usually defined: in Fig. 2.5, τ is the *fast time*, while t_k is the *slow time*. The former refers to the single k -th pulse backscattered trace time variation. This signal is discretized at the receiver, with sampling frequency f_d . The i -th sample, acquired at f_d , refers then to time instant $\tau_i = i/f_d$ (see Fig. 2.5). Each i -th sample will be processed to deliver localization along the fiber, and the strain/temperature information. The latter is instead varying more slowly in time, as the pulse interrogates the fiber every $k\tau_{max}$ seconds. The set of backscattering signals can then be represented with $U(t_{i,k})$: by fixing k (the slow axis), the evolution of the backscattered trace related to the k -th pulse is obtained. Fixing i (the fast axis), the evolution of that same backscattering point (i.e., spatial point along the fiber) through time is obtained.

Any OTDR-based sensing system works as described above. The backscattered trace is then evaluated depending on the measurand that needs to be extracted from it (see Subsection 1.2.2 for Raman, Brillouin, and specifically Fig. 1.4). In the case of DAS, the Rayleigh scattering causes a small fraction of the traveling light to be re-radiated by inhomogeneities (or better, scatterers), randomly distributed along the medium. In particular, the propagating pulse will only occupy a section of the fiber, related to τ_p , containing a random, statistically relevant number of scatterers and called resolution cell. The overall reflected electric field is then a summation of all the scatterers' contributions having a stable, random phase relationship [5]. Any variation, due to axial strain or temperature, which changes the inherent phase relationship among the scatterers, will result in a backscattered signal variation.

Figure 2.6 shows a single pulse (on the left) propagating in a fiber. The resolution cell Δz depends on the pulse time duration as expressed in Eq. 2.19,

$$\Delta z = \frac{c\tau_p}{2n_g} \quad (2.19)$$

where n_g is the group refractive index and c is the light speed in vacuum. As previously mentioned, the pulse duration τ_p tweaks the spatial resolution of the sensor. In commercial DAS systems, a typical value of $\tau_p = 100$ ns corresponds to $\Delta z \sim 10$ meters. In Fig. 2.6, a zoomed-in view of one Δz cell shows the m -th scatterer, contributing to the backscattered light's phase and intensity. Specifically, the parameters $\{z_m; a_m\}$ define the position and amplitude of the scatterer inside Δz . In this regard, we need to make some assumptions, one expressed by Eq. 2.20,

$$\langle z_m - z_{m-1} \rangle = d \ll \Delta z = \frac{c\tau_p}{2n_g} \quad (2.20)$$

which relates to having a statistically representative number of scatterers inside the pulse duration, and is usually verified with the τ_p employed. In Eq. 2.20, d is the average distance between two consecutive scatterers. Notice that in Fig. 2.6, scatterers are equispaced: this is clearly not true in a real scenario, and was made only to ease the representation. The other condition that needs to be enforced, especially for systems based on direct detection of the backscattered trace, is that the source must be coherent for the whole Δz , i.e., at least over τ_p . This condition allows the Rayleigh scattered electric fields to sum up coherently and generate the backscattered signal. Consequently, these kinds of systems are often referred to as coherent-OTDRs, or even phase-OTDRs (ϕ OTDRs).

The parameter a_m in Fig. 2.6 refers instead to the amount of power backscattered by the m -th scatterer. For example, for typical SSMF fibers, in the C-band, losses are usually of $\alpha = 0.2$ dB/km, taking into account material absorption and light backscattering in all directions. This means that the power of the backscattered signal is very low compared to the forward propagating signal. This also strongly limits the sensing range. To compensate for it, typical ϕ OTDRs systems use quite high pulse-peak-powers, which can even reach 30 dBm, and receivers with very good sensitivity. Because of rising nonlinearities distorting the propagating pulse, typical commercial DAS powers reach 23-24 dBm [62, 46, 61].

Figure 2.6 also shows, in purple, in the left corner, the pulse envelope $w_P(t)$, which, in real systems, is usually a Supergaussian. As the Kerr-effect [63] (one of

the main causes of nonlinear self-distortion of the pulse) depends on the derivative of power, having more/less smooth transitions at the edge of the pulse can have different effects on nonlinearities for co-propagating signals, and on the pulse self-distortion [46].

The final expression for the backscattered electric field phasor $\dot{E}_i$ resulting from the coherent summation of the electric fields inside the resolution cell, sampled at the time instant τ_i (and thus referred to the spatial point z_i) and related to the k -th pulse, is shown in Eq. 2.21.

$$\dot{E}_i = \left[\sum_{z_{i1} < z_m < z_{i2}} a_m \cdot w_P(z_m - z_i) \cdot \exp \left(j \frac{4\pi}{\lambda} \int_{z_i}^{z_m} n(x) dx \right) \right] \cdot \exp(j\omega\tau_i/K_g) \quad (2.21)$$

Here, K_g is a constant connecting the refractive index n with the group refractive index n_g , such that $n_g = K_g n$. As shown in Fig. 2.6, z_{i1} and z_{i2} are the edges of the resolution cell Δz . The function $n(z)$ expresses the axial distribution of the refractive index along the fiber. The exponential term outside the square bracket is just accounting for the phase effect generated by the round-trip, with delay τ_i . Since it is not interesting for the following discussion, we do not show the equation derivation, which the interested reader can find, with much more details, in [5, 45]. Eq. 2.21 also further clarifies the effect of the pulse envelope on the backscattered signal, as each m -th scatterer is weighted by the m -th sample of its shape (i.e., the term $w_P(z_m - z_i)$). Any change of $n(z)$ will translate into a phase change of $\dot{E}_i$, which in turn means that the phase relationship between the scatterers has changed within a resolution cell. Recovering the electric field $\dot{E}_i$ will then deliver information concerning any change happening inside Δz . Distributed acoustic sensing systems (more generally called distributed vibration sensors, DVS) are based on the ϕ OTDR working principle here discussed. Several architectures, well described in [5], allow to recover the electrical field in Eq. 2.21. A quite common approach is based on intensity-only, direct-detection measurements of the backscattered field: despite neglecting the phase term of 2.21, this configuration does measure the amplitude-related changes within a resolution cell, due to the alteration of the phase relationships of the single scatterers, enabling strain and temperature sensing, but with no linear response of the trace with respect to the distortion. Phase recovering through coherent detection of the backscattered signal is also a viable way to sense external perturbation, allowing for enhanced performances, at the cost of a higher coherence of the laser employed, which also depends on the total length of the fiber under test [64].

2.2.2 Chirped-pulse DAS working principle

Rayleigh backscattering can also be exploited to enable quasi-static measurements: the work in [47], which is also included in [5], demonstrated measuring strain and temperature with very high resolution, but with a slightly different working principle than the one described above. The strain $\Delta\epsilon$ or temperature ΔT variation affecting a resolution cell can be compensated by a shift $\Delta\nu$ of the input probe pulsed laser, following the relationships in Eq. 2.22 [65],

$$\begin{aligned}\frac{\Delta\nu}{\nu_0} &\approx -0.78\Delta\epsilon, \text{ and} \\ \frac{\Delta\nu}{\nu_0} &\approx -(6.92 \cdot 10^{-6})\Delta T\end{aligned}\tag{2.22}$$

where ν_0 is the central laser frequency. As detailed in [47], perturbation sensing is enabled by doing consecutive OTDR measurements with shifting probe laser frequencies, so that the $\Delta\nu$ shift corresponding to the precise value of ΔT and $\Delta\epsilon$, following the relationships in Eq. 2.22, could be retrieved. The main point is thus to do a time-consuming frequency scan, keeping the OTDR working principle: despite delivering orders of magnitude more precise measurements than standard distributed sensing techniques, this method allows for quasi-static measurements only.

Since any temperature or strain event can be reduced to a (local) refractive index change Δn (see Eq. 2.21), assuming $\Delta n \ll n$, Eq. 2.23 holds [60, 61].

$$\frac{\Delta n}{n} = \frac{\Delta\nu}{\nu_0}\tag{2.23}$$

Given the relationships in Eq. 2.22 and 2.23, a more recent approach consists of employing a chirped pulse instead of one with a flat, non-modulated phase, which, in a single shot, would cover the required frequency scan proposed by [47]. The resulting input probe employed by the ϕ OTDR would then be a train of pulses $e_P(t)$ mathematically described as in Eq. 2.24.

$$e_P(t) = \text{rect}\left(\frac{t}{\tau_p}\right) \exp\left(-j2\pi \frac{\delta\nu_p}{2\tau_p} t^2\right)\tag{2.24}$$

The term $\delta\nu_p$ is the chirp spectral content. The overall phase of $e_P(t)$ is then quadratic, meaning that the frequency varies linearly in time. In this case, the pulse shape is rectangular ($\text{rect}(\cdot)$), but notice that the works [61, 46] discuss the

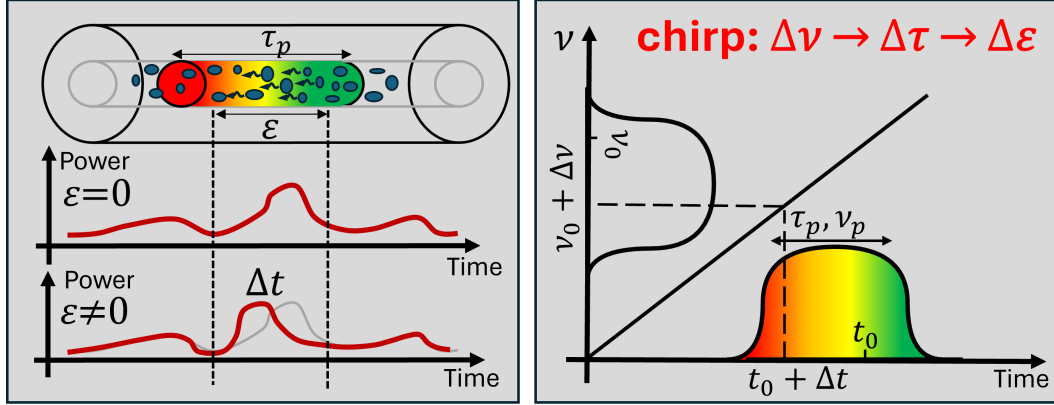


Fig. 2.7 Graphical explanation of CP- ϕ OTDR. The left part of the figure shows what happens to the backscattered trace time evolution when a strain is applied to the fiber. On the right side, the frequency-to-time conversion induced by the chirp shows the relationship with strain. Picture inspired from [61, 69]

consequences of employing different envelopes. The optical powers employed are of the same range as standard DAS. The frequency-shift $\Delta\nu$, because of the chirp-generated mapping with time, corresponds to a time-shift Δt as in Eq. 2.25,

$$\Delta t = -\frac{\tau_p}{\delta\nu_p} \Delta\nu \quad (2.25)$$

which can in turn be connected to Eq. 2.22 and 2.23, leading to a simple relationship, in Eq. 2.26 with strain and temperature.

$$-0.78\Delta\varepsilon \approx -(6.92 \cdot 10^{-6})\Delta T \approx \frac{\Delta n}{n} = \frac{\Delta\nu}{\nu_0} = -\frac{1}{\nu_0} \frac{\delta\nu_p}{\tau_p} \Delta t \quad (2.26)$$

The recovery of Δt would then correspond to a direct estimate of strain/temperature. This technology was first presented in 2016, in [60], commonly known as chirped-pulse- ϕ OTDR (CP- ϕ OTDR), and is becoming a widely used technique across a range of applications, mostly sensitive to slow strains and temperature variations [66–68]. Figure 2.7 graphically shows the working principle of using a chirped pulse to sense for external perturbations. Any strain induced inside the resolution cell, inherently generating a Δn , is compensated by the $\delta\nu_p$ content of the chirp, and translated into a local time shift acquired by consecutive pulses. As demonstrated by [61, 60, 69], direct-detection of the backscattered traces can be exploited (red curve in power versus time plots, left side of Fig. 2.7). Consequently, Δt containing

strain and temperature information can be retrieved by cross-correlation between local windows in consecutive shots.

Chapter 3

Polarization Sensing over Coherent Telecommunication Systems

Given the extensive optical network described in Chapter 1 and the relatively low complexity of extracting SOP samples from coherent receivers, polarization sensing is a viable option for self-monitoring fiber cables and detecting hazards in their surroundings. As mentioned above, by utilizing the adaptive equalizers in coherent receivers, polarization information can be obtained almost effortlessly [16, 70, 35], assuming that there is a transceiver input/output monitoring channel available to deliver SOP data, along with software capable of processing this data in real-time.

DAS is also an effective solution [71, 72], being an ad hoc sensing system, providing precise localization, detection, and measurement of any strain or temperature changes occurring in the fiber. Nevertheless, it comes with certain drawbacks when integrated with the telecommunication infrastructure. Firstly, the high-peak-power pulses employed by DAS systems may generate nonlinearities impairing the neighboring data channels. Moreover, its sensing distance is limited to about 100 km, and the presence of isolators, typically associated with EDFAs, completely blocks light backscattering. Secondly, the expensive narrow linewidth lasers [37, 47] required for efficient DAS operation are not typically included in standard commercial coherent transceivers. DAS systems also generate a vast amount of data; because they provide spatial and temporal resolution, the resulting data stream can be challenging to manage, potentially creating a bottleneck for real-time early warning systems for hazardous conditions, in non-sensing-dedicated systems, such as the telecommunication one. For these reasons, integrating DAS with existing optical network

infrastructure, even in a metropolitan environment, is complex and may not always be a cost-effective solution. This topic will be discussed in detail in Chapter 5.

State of polarization monitoring can be used as an alternative technique, also to forward optical phase monitoring (see Subsection 1.2.1), which is also recovered by the coherent receivers, in the DSP chain. Sensitivity to external agents has been demonstrated in various works in both the submarine [9, 73] and the terrestrial [14] environments. Nevertheless, the need for ultra-low-linewidth lasers could make the integration into the telecommunication system non-cost-effective as well.

In this chapter, we will explore, experimentally and through numerical simulations, the noise limits of SOP extracted from commercial coherent transceivers and analyze different approaches for polarization data processing. The detection algorithm exploiting SOP should be reliable against different kinds of events, while working in noise scenarios typical of metropolitan links. Moreover, some first experimental results concerning forward optical phase monitoring will also be presented and discussed, in comparison to SOP. Final discussions will also briefly address events' localization.

The matter presented in this chapter is partly based on the works reported in [15, 74–77].

3.1 Accuracy of State of Polarization Estimate from Coherent Receivers' DSP

This section experimentally examines the physical layer parameters that influence the accuracy of SOP estimation using standard coherent transceivers. The experiments detailed here utilize a commercial transceiver capable of providing the received light SOP estimate through its internal receiver DSP. In the following, we assess the accuracy of the SOP estimate over different system conditions:

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

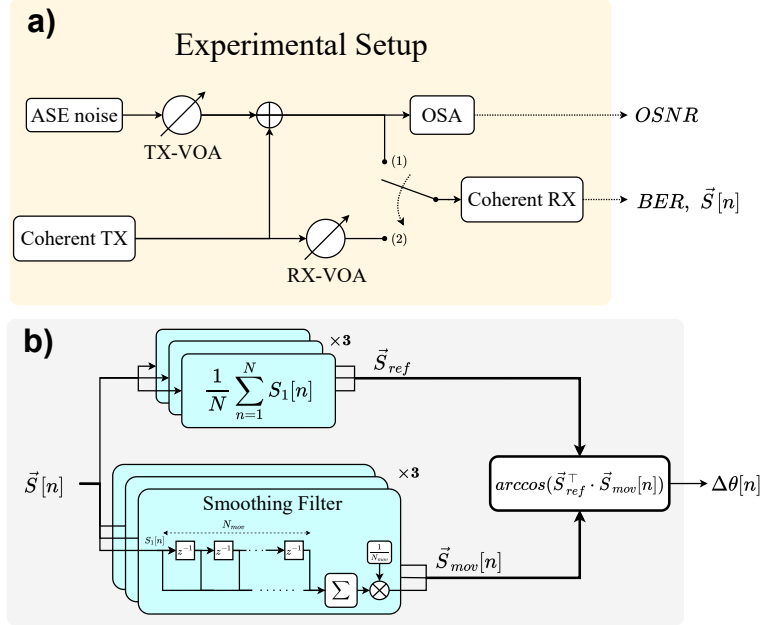


Fig. 3.1 a) experimental setup. When connection (1) is selected, the coherent RX considers ASE noise injected in the system. When instead connection (2) is selected, ASE noise is excluded. b) Post-processing scheme exploited to compute the angular deviation $\Delta\theta[n]$. A long-term average of N 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.

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

A scheme of the experimental transmission system is shown in Fig. 3.1a). To avoid stress-induced birefringence and geometrical deformations, all the fiber cords were fixed on a stable optical bench, ensuring a nominally constant received SOP. Conventionally, the variable optical attenuators (VOAs) have been named TX-VOA (transmitter side) and RX-VOA (receiver side). When performing experiments with ASE noise loading, the coherent receiver (RX) has been connected to the coherent transmitter (TX) through connection (1) in Fig. 3.1a). On the contrary, in the experiments without ASE noise, the coherent RX has been connected to the coherent TX, cascaded with the RX-VOA, through connection (2). The commercial transceiver can output SOP samples at about 20 S/s, and record the related bit error ratio (BER) during the acquisition.

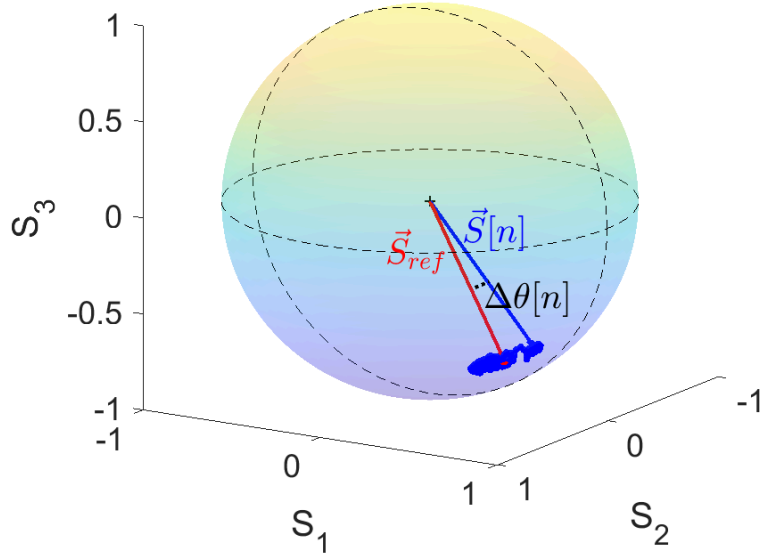


Fig. 3.2 Poincaré sphere showing the $\vec{S}_{ref}$ (in red) and $\vec{S}[n]$ (in blue) vectors and the angular deviation $\Delta\theta[n]$.

In parallel to the experiments, we also run time-domain simulations of the optical system, assuming a standard coherent RX [19, 18] operating at 2 Samples/symbol, using a least mean square (LMS)-based 2×2 adaptive equalizer, with $N_{\text{tap}} = 16$ taps. The input signal $x[n]$ and the output signal $y[n]$ at this stage are related by $y[n] = W[n] \cdot x[n]$, where n is the discrete time index and $W[n]$ the equalization matrix defined in Eq. 3.1 (see the end of Chapter 2 for more context):

$$W[n] = \begin{bmatrix} w_{11}^{(m)}[n] & w_{12}^{(m)}[n] \\ w_{21}^{(m)}[n] & w_{22}^{(m)}[n] \end{bmatrix}. \quad (3.1)$$

Here, m represents the tap index. Each element of the equalization matrix is an $N_{\text{tap}} \times 1$ vector, whose DC component is equal to $\bar{w}_{ij}[n] = \sum_{m=1}^{N_{\text{tap}}} w_{ij}^{(m)}[n]$ with $i, j = 1, 2$. Note that the DC component of either column of $W[n]$ is a Jones vector that can be used to compute the corresponding Stokes parameters, as in Eq. 3.2 (considering the first column of the matrix in Eq. 3.1), and following the definition in Eqs. 2.11

and 2.18.

$$\begin{aligned}
S_0[n] &= |\bar{w}_{11}[n]|^2 + |\bar{w}_{21}[n]|^2 \\
S_1[n] &= |\bar{w}_{11}[n]|^2 - |\bar{w}_{21}[n]|^2 \\
S_2[n] &= 2 \cdot \text{Re}(\bar{w}_{11}[n] \cdot \bar{w}_{21}^*[n]) \\
S_3[n] &= -2 \cdot \text{Im}(\bar{w}_{11}[n] \cdot \bar{w}_{21}^*[n]).
\end{aligned} \tag{3.2}$$

In Eq. 3.2, $(\cdot)^*$, $\text{Re}(\cdot)$, and $\text{Im}(\cdot)$ are the complex conjugation, real part, and imaginary part operators, respectively. In the following discussion, we will refer to the Stokes parameters using the normalized Stokes vector $\vec{S}[n] = [S_1[n], S_2[n], S_3[n]]$, where each element is normalized with respect to $S_0[n]$ (as mentioned in Chapter 2.1, this corresponds to always have the Stokes vector on the tip of the Poincaré sphere, with radius 1). We extracted the equalizer tap coefficients every 200 ns while processing a sequence of 20 million samples, leading to a SOP sampling frequency f_s of 5 MS/s. In all cases, both experiments and simulations, the transmission is operated back-to-back (i.e., with a short fiber patchcord between transmitter and receiver) at 34 GBaud (DP-QPSK line rate is 100 Gbit/s, DP-16QAM line rate is 200 Gbit/s), shaped with a square-root raised-cosine filter with roll-off $\rho = 0.2$.

To measure the SOP estimate accuracy, we evaluated the angular deviation of each Stokes vector with respect to a reference one. Figure 3.2 shows as blue dots the vector $\vec{S}[n]$ time evolution, extracted from the commercial coherent receiver, or numerical simulation equalizer. The red $\vec{S}_{ref}$ vector is the reference to compute the angular deviation, denoted as $\Delta\theta$. The post-processing algorithm is shown in Figure 3.1b). Each parameter $S_1[n]$, $S_2[n]$, $S_3[n]$ is passed through a moving average filter (smoothing filter in Fig. 3.1b)), with filtering window length N_{win} ($N_{win} = 1$ sample is equivalent to no-filtering). The output of this block is a smoothed version of the input Stokes vector time evolution, denoted as $\vec{S}_{mov}[n]$. Each Stokes parameter of the whole $\vec{S}[n]$ acquisition is also averaged over a total number of N samples inside the acquisition (long-term average in Fig. 3.1b)), with N of the order of a few hundred samples. The output of this block is $\vec{S}_{ref}$, in red in Fig. 3.2. This represents a “ground-truth” vector, placed at the center of the noise cloud over the Poincaré sphere surface. We remind that in this specific experiment, fiber birefringence was intentionally constant over time, thus the SOP variations are only due to the estimation noise generated inside the coherent receiver. The angular deviation $\Delta\theta[n] = \arccos(\vec{S}_{ref}^T \cdot \vec{S}_{mov}[n])$ (right-most block in Fig. 3.1b)), $(\cdot)^T$ being the transposition operator, gives an insight into the noise condition, representing the spread of the SOP noise cloud [78].

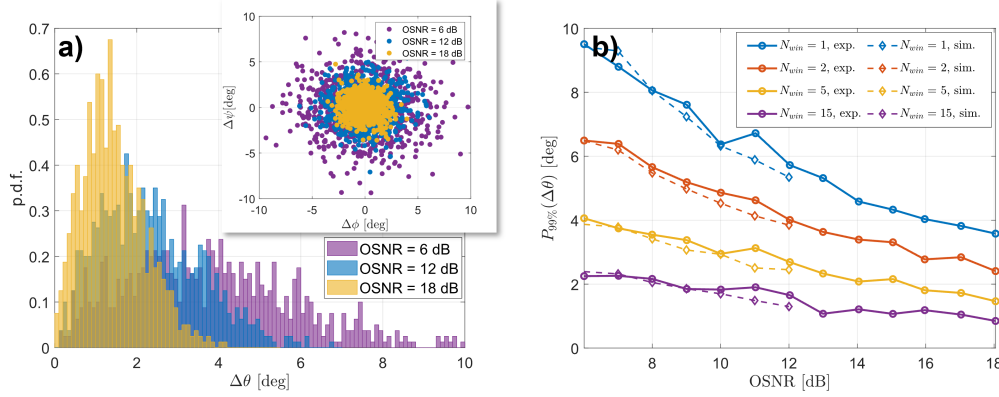


Fig. 3.3 a) $\Delta\theta$ histograms at three different OSNR levels. The inset reports the cloud distribution of the SOP points over the Poincaré sphere surface, in angular coordinates. b) $P_{99\%}(\Delta\theta)$ vs. OSNRs for different moving average windows N_{win} (experiments and numerical simulation).

3.1.1 Performance in ASE noise

In this scenario, the coherent RX goes through connection (1) in the experimental setup (see Fig. 3.1a)), allowing for the TX-VOA to control the injection of ASE noise. The OSNR values, ranging between 6 dB and 18 dB, have been measured with the optical spectrum analyzer (OSA), while SOP samples were returned from a commercial coherent transceiver as Stokes vector time evolution.

Fig. 3.3a) shows the probability density functions (pdf) of $\Delta\theta$ for three different values of OSNRs (6 dB, 12 dB, and 18 dB) for DP-QPSK modulation format and $N_{win} = 1$. The figure's inset also shows the SOP cloud spread in angular coordinates (i.e., mapped over two orthogonal rotation axes). As expected, these histograms show that, for higher OSNR values, the statistical spread on the $\Delta\theta$ pdf is smaller and, in a practical sensing system, mechanical stresses generating higher deviations would be easier to detect, since less blurred by noise. To quantitatively assess this consideration, we introduce the 99th percentiles of the angular deviation, i.e., the angle $P_{99\%}(\Delta\theta)$ at which the probability of $\Delta\theta$ exceeding it, is 1%. Since the angular deviation is always positive and the pdf are not symmetrical, this evaluation metric is more suitable in assessing the distribution spread than either the mean value and/or the standard deviation. Fig. 3.3b) shows $P_{99\%}(\Delta\theta)$ vs. OSNR for different values of N_{win} . Circle-marked lines represent the experimental results, while the diamond-marked dashed lines represent the time-domain simulations, demonstrating an almost complete match between the “ideal” condition used in simulations and

experiments. The presented results thus seem independent from the actual RX DSP implementation details. The diamond-marked dashed lines are limited to 12 dB, the highest OSNR value at which we could obtain reliable BER values ($\sim 10^{-4}$) through time-domain simulations, with a reasonable expense of numerical effort and running time. We observe that for increasing N_{win} , $P_{99\%}(\Delta\theta)$ decreases, going for instance below 2° for $N_{\text{win}} = 15$, for all the measured OSNR values. The moving average introduced to evaluate $\vec{S}_{\text{mov}}[n]$ can be implemented with very limited additional DSP complexity and can thus be used to reduce the impact of SOP noise significantly. The only trade-off to be considered is that when increasing N_{win} , the effective sample rate in SOP estimation is reduced. Consider also that the mechanical events to be detected have quite low-frequency content (few Hz to few tens of Hz) [16, 31, 79, 40, 41]. This eases the need for extremely fast and high-cost processing hardware and also for complex SOP data storage solutions.

3.1.2 Performance limited by low ROP (without ASE noise)

In this scenario, referring to the scheme in Fig. 3.1a), connection (2) has been selected, thus excluding the ASE noise loading, the TX-VOA, and the OSA. The ROP, in the following referred to with P_{rx} , has been varied using the RX-VOA. Experiments have been repeated for DP-QPSK and DP-16QAM, with BER and SOP estimates always recorded at the coherent RX in each situation. The experimental results are shown in Fig. 3.4a) and 3.4b) in terms of $P_{99\%}(\Delta\theta)$ vs. P_{rx} , and show a similar trend to Fig. 3.3b), so that the same system comments can be derived also for this ROP-limited situation and for the two different modulation formats considered here. Once again, averaging controlled by the N_{win} parameter confirms its strong impact on the accuracy, since it allows for lowering the percentiles up to around 1° in the best cases.

Fig. 3.4c) shows $P_{99\%}(\Delta\theta)$ as a function of the BER measured for the different considered ROP values at the output of the coherent receiver, when no smoothing is applied ($N_{\text{win}} = 1$). This represents a practical way to assess the SOP angular accuracy in commercial systems, since given a BER threshold set by the chosen forward error correction (FEC)¹, it indicates the corresponding typical values of

¹We briefly define forward error correction (FEC) for non-telecommunication readers. FEC adds overhead bits to the data stream, which the receiver uses to detect and correct errors generated by channel impairments. While standard systems allocate around 15% of the payload to FEC overhead, modern receivers can reach 27%: a higher overhead improves error correction but reduces the net

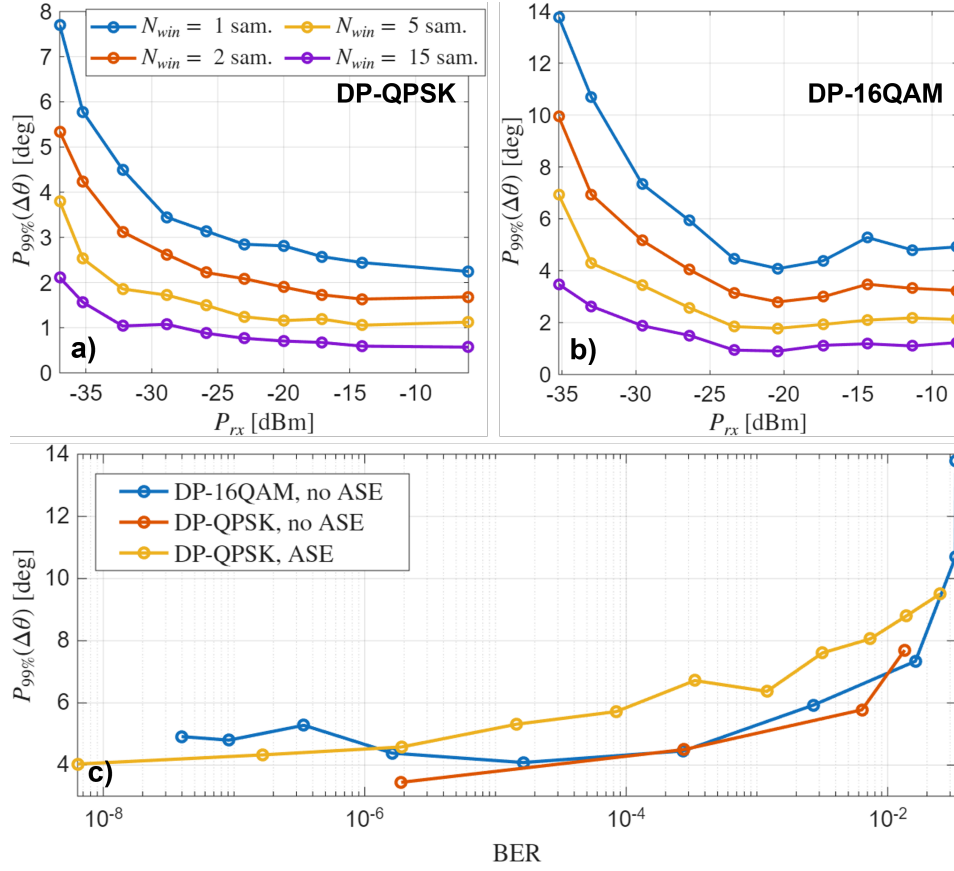


Fig. 3.4 $P_{99\%}(\Delta\theta)$ vs. ROP for a) DP-QPSK and b) DP-16QAM, using different averaging windows. Legend in a) applies also in b). c) $P_{99\%}(\Delta\theta)$ vs. BER levels in all the considered situations, with $N_{win} = 1$.

$P_{99\%}(\Delta\theta)$. Moreover, in Fig. 3.4c), the blue and red curves show a high degree of overlap, suggesting that, in the absence of ASE noise, the relationship between $P_{99\%}(\Delta\theta)$ and BER is quite insensitive to the modulation format. Finally, it can be observed that the yellow $P_{99\%}$ curve in Fig. 3.4c), corresponding to the situation depicted in the above paragraph (see Fig. 3.3), is shifted above the others of around 1° , clearly indicating a significant impact of the ASE noise in the system.

data rate. The error rate before correction is the “pre-FEC” BER, which is the one we are considering, without specifying, in this chapter. The FEC algorithm can achieve a “post-FEC” BER of 0, provided that the pre-FEC BER remains below a specific threshold (typically $\sim 10^{-2}$). Above this limit, the coherent receiver’s DSP loses tracking due to excessive distortion. However, under harsh conditions such as the ones discussed in Chapter 5, uncorrectable FEC errors can occur even below this threshold. It is therefore important to relate SOP noise to this FEC threshold, which represents the ultimate operational limit for both data and polarization recovery.

3.1.3 Discussions and conclusions

We characterized the accuracy of the SOP data provided by a commercial coherent transceiver (able to output the SOP samples at around 20 S/s), evaluating the estimation noise cloud spread over the Poincaré sphere surface. The results obtained in both an ASE noise-limited scenario and ROP-limited one underline the possibility of enhancing the accuracy, which was originally quite low. $P_{99\%}(\Delta\theta)$ values can reach 8° to 14° in the worst cases. Using a simple low-pass filter improves accuracy even by a factor of four, using a window length of $N_{\text{win}} = 15$ samples (see Figures 3.3 and 3.4). The matching between experimental and numerical simulation results also suggests independence from the actual RX DSP implementation details. The SOP data stream, sampled at sampling frequencies of the order of the symbol rate, could be low-passed and then decimated, keeping the SOP estimate accuracy fixed. Due to the low-frequency components generated by mechanical vibrations, a sampling frequency of around a few tens of Hz could also be suitable to reduce processing and data storage complexity. When limited by ROP, averaging benefits the SOP noise reduction as well. In this case, changing the data format, with comparable BER values, does not seem to affect the SOP angular noise. The latter is instead higher in the case of ASE noise loading, considering the same data format and BER values, suggesting an impact of it.

3.2 Anomaly Detection Algorithms over a Metropolitan Fiber Link

The previous section dealt with the noise generated by a commercial coherent receiver, showing a good match with numerical simulations. In the context of exploiting SOP samples coming right out of the adaptive equalizer, this noise source is fundamental to be considered, and also depends, as demonstrated, on different telecommunication parameters (e.g., OSNR, ROP) which affect the system performances. We discuss here other noise impairments, mainly related to the deployment environment of the fiber link, which may affect the detection performances of SOP-based algorithms. Typical events generating polarization fluctuation, possibly related to hazards, are also characterized. In this context, we also discuss and propose two processing algorithms, based on completely different working principles, that may

be able to trigger an alarm whenever an anomalous condition is detected.

Different from Section 3.1, where a commercial coherent receiver was employed, all the following experiments were conducted using a commercial polarimeter. As the SOP sampling frequency of the available coherent receiver is fixed to 20 S/s by the internal telemetry system, it is not suitable to correctly characterize the dynamic metropolitan environment and detect malicious mechanical events producing vibrations at frequencies higher than about 10 Hz. Moreover, the polarimeter allows for an arbitrary adjustment of the sampling frequency up to the MS/s range and thus enables a more complete analysis of the proposed algorithms.

3.2.1 SOP environmental noise in metropolitan fibers

When implemented on a metropolitan optical fiber cable, a polarization-based sensing system is inevitably influenced by the urban environment, which causes random SOP fluctuations (referred to in this subsection as *SOP environmental noise*). External factors such as temperature changes, traffic, and construction works can change the fiber birefringence, resulting in SOP variations. We show here how some of these factors can affect the SOP.

Figure 3.5 illustrates the experimental setup, which utilizes fiber cables deployed in the Turin metropolitan area, with their endpoints located in our laboratory. Specifically, we primarily used a 35-km fiber (green line in Fig. 3.5), while some experiments in Subsection 3.2.4 will also involve the 10-km fiber (red line in Fig. 3.5). The setup comprises an external cavity laser operating in continuous wave mode, with 0 dBm launch power and 100 kHz linewidth, and a Novoptel PM1000 polarization analyzer to acquire the SOP at the other endpoint. The sampling frequency is set to 95.4 S/s, one of the f_s values made available by the device, which is suitable for our purposes given the low-frequency ranges typically excited by the urban environment (i.e., less than a few tens of Hz, [14, 16]). The SOP data are provided as the time evolution of normalized Stokes vectors.

To characterize the SOP environmental noise, we acquired the SOP evolution over the 35 km long metropolitan fiber in quiet conditions, without generating any external event. Figure 3.6a) shows the evolution of the Stokes vector acquired over two days, starting from March 4th, 2023. At first glance, the statistics of the Stokes parameters exhibit gradual hourly changes. These slow SOP variations generally exhibit a daily pattern: as shown in Figure 3.6a), during both March 4th and 5th, the

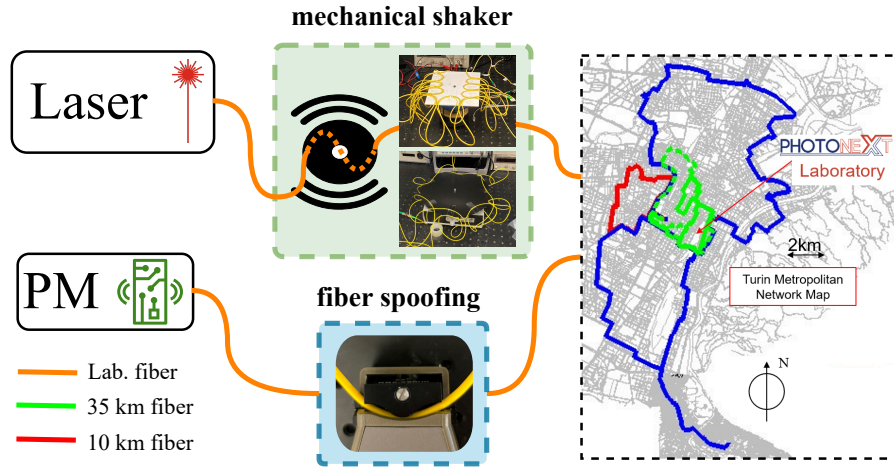


Fig. 3.5 Experimental set-up used for the experiments. The laboratory fiber is represented by the orange line. A mechanical shaker is applied to it (green-dashed block) before it enters the metropolitan ring, while spoofing attempts (blue-dashed block) are generated just before the polarimeter (PM, in the scheme). The pictures of the two mechanical shakers are shown, of different geometrical shapes, materials, and fiber wrappings layouts. Green and red lines depict the metropolitan fibers used for the experiments, running around Turin (Italy), measuring 35 km and 10 km, respectively. The blue line depicts a fiber that was not used for the experiments.

SOP remains relatively stable around midnight, starting to deviate only a few hours before noon, likely due to increased human activities in the urban environment, and temperature variations. When examining a shorter time window of a few tens of seconds (insets in Figure 3.6a)), the SOP environmental noise becomes evident: the Stokes parameters display random fluctuations around their hourly-varying average values. On average, the recorded $P_{99\%}(\Delta\theta)$ value is 0.23° , which is lower than the ones obtained using a coherent receiver and discussed in Section 3.1.

The SOP fluctuation can be analyzed through the evaluation of the power spectral density (PSD) of S_1 , S_2 , and S_3 . Figure 3.6b-d) shows the evolution of the PSDs (i.e., the spectrogram) of the three Stokes parameters². The three PSDs exhibit several common features: a high-magnitude zero-frequency component (red lines

²It's worth noting that, as mentioned above, the Stokes parameters are normalized with respect to S_0 and are therefore dimensionless. Consequently, the dB/Hz unit is mathematically rigorous and referenced to a unit spectral density (1 Hz^{-1}). This is physically consistent since the normalized parameters provide a geometric representation of the SOP on the Poincaré sphere, rather than tracking absolute power fluctuations.

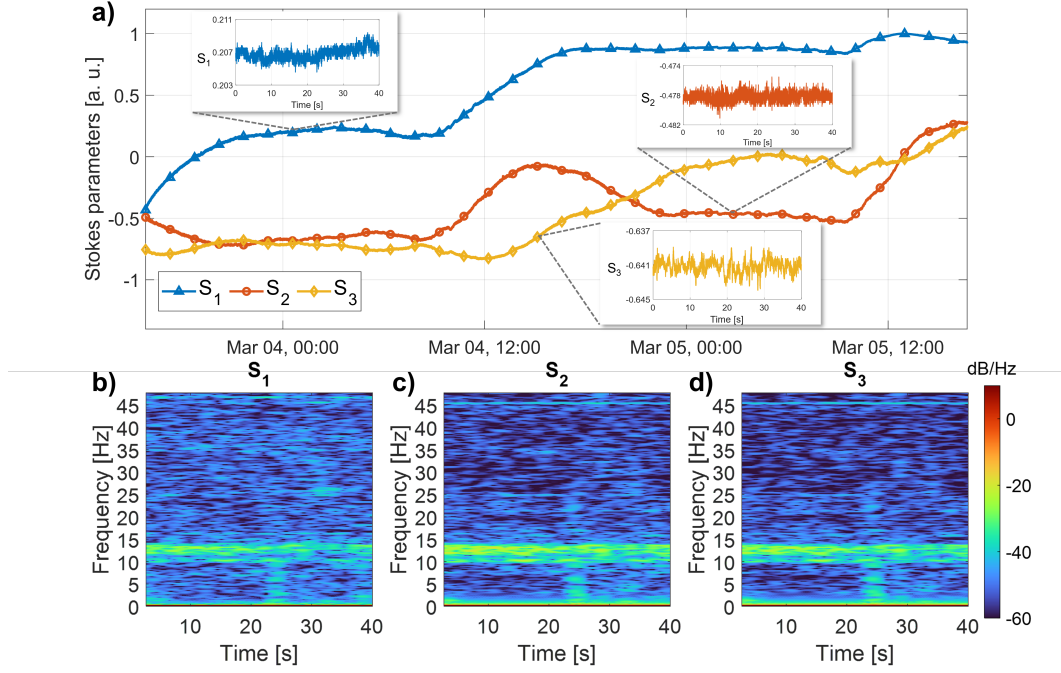


Fig. 3.6 a) Stokes parameters time evolution over a two-days-long acquisition considering the 35 km long metropolitan fiber, started on March 4th 2023. Insets provide a 40 seconds zoom on one Stokes parameter, in different portions of the acquisition. b-d) 40 seconds long spectrogram of the single Stokes parameters.

at $f = 0$), consistently high magnitudes in the frequency range between 5 and 15 Hz, and an intense pure frequency component at 46 Hz. To comprehensively observe all the frequency components in the SOP noise, Figure 3.7 illustrates the spectrogram corresponding to the sum of the three PSDs over the same time window as in Figure 3.6a). It can be clearly observed that this representation effectively captures the characteristics of the SOP noise, giving equal weight to each Stokes parameter and incorporating all the frequency components present in their relative spectra in Figure 3.6b-d). Environmental agents indeed affect the Stokes parameters arbitrarily, depending on the current SOP. However, their contribution to the SOP spectrum remains consistent at specific frequencies, regardless of the direction the Stokes vector takes on the Poincaré sphere. This characteristic is exploited in the SOP-PSDG algorithm [74], which we will illustrate in Subsections 3.1.3 and 3.2.4. Additionally, as shown in Figure 3.7, certain low-frequency components (below 5 Hz) tend to be more intense around noon, corresponding with the daytime Stokes fluctuations observed in Figure 3.6a). Conversely, the frequency range becomes less intense when reaching the nighttime hours.

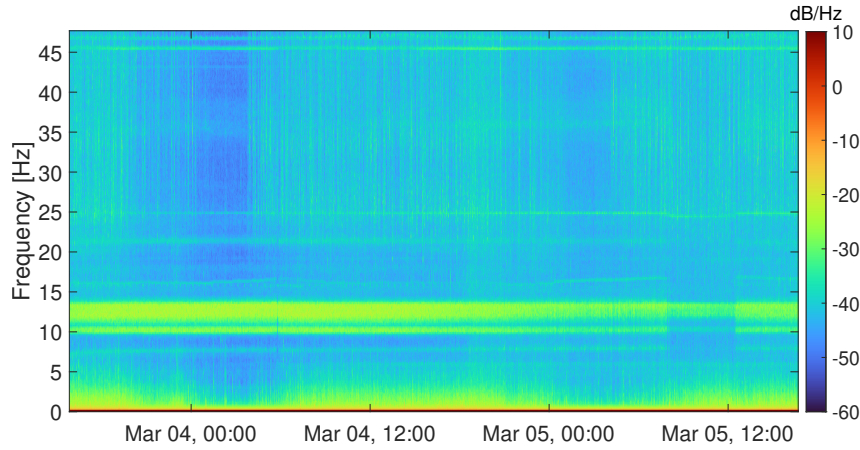


Fig. 3.7 Spectrogram of a 2-days acquisition over the 35 km long metropolitan fiber, obtained as the sum of the PSDs of the three Stokes parameters.

Regarding the frequency components with significant magnitudes between 5 and 15 Hz, as well as other higher-frequency tones that are less intense but almost perfectly constant, these do not appear to be caused by the urban environment. These frequency components are also observed when the metropolitan fiber is not part of the setup (i.e. when acquiring the SOP using only the optical fiber within the laboratory). The likely cause of this effect in the SOP spectrum is the presence of cooling fans near the optical fiber path, such as those in our laboratory. This condition is common in practical scenarios, such as central offices and data centers.

3.2.2 Anomalous conditions characterization

On top of the SOP environmental noise, characterized in the previous subsection, anomalous events, which may be connected to hazards jeopardizing the optical fiber health status, can generate SOP variations that can be analyzed both through angular deviation and SOP spectral analysis. These conditions will be discussed in the following paragraphs. A telemetry architecture will also be proposed to process and detect events of different natures.

Mechanical vibrations

In the metropolitan scenario, fiber cuts and physical network infrastructure damages represent the most typical hazards. Maintenance or construction works, which

usually employ excavators and jackhammers, can jeopardize the health of the underground fiber cables, with consequent re-installation costs and inconveniences for the vendors controlling the network services. Since the SOP is sensitive to mechanical stresses and geometrical deformations, the vibrations induced on the fiber before the occurrence of the actual damages could be used as an immediate early warning for potentially hazardous conditions.

In this analysis, we use a mechanical shaker to generate vibrations (green-dashed block in Fig. 3.5) over a portion of the laboratory fiber (in orange in Fig. 3.5), assuming that no abnormal condition occurs on the 35-km metropolitan fiber during our tests. For the experiments discussed below, we considered the white rectangular shaker in the upper picture, among the two. The laboratory fiber cable is a simplex standard single mode G.652 fiber patchcord with low smoke zero halogen (LSZH) coating and 2 mm diameter, while the rest of the metropolitan fiber uses standard telecom fiber cables, for which we do not have detailed information. Since fiber displacements, geometrical deformations, and stresses are generated during the experiments, they can be used to assess the effects that different vibrations of different intensities would have on the SOP. It should be pointed out that we will not accurately reproduce the effects that real-life maintenance works, jackhammers, or excavators [35, 14] would have on the fiber before generating damages or cuts. The precise modeling of how they would couple on the fiber cable after ground propagation is out of the scope of this thesis. The mechanical shaker is driven by sinusoid signals generated by an analog waveform generator (AWG) and consists of a vibrating rectangular plastic plate, where one meter of fiber has been glued, oscillating in the vertical direction and generating a maximum displacement of 4 mm. The oscillation frequency f_{osc} can be changed from the AWG, as well as its amplitude, expressed in peak-to-peak voltages, to which we will refer as V_{pp} units.

We first characterize the vibrations by computing the angular deviation $\Delta\theta$ (consistently with what has been done in Section 3.1, but no smoothing has been applied in this case) of the SOP captured from the polarimeter, when the vibration is turned on. The map in Fig. 3.8a) shows the values of $P_{99\%}(\Delta\theta)$ versus f_{osc} and V_{pp} . As previously mentioned in Subsection 3.2.1, the average value of $P_{99\%}(\Delta\theta)$ in quiet conditions is around 0.23° , thus shaker-induced angular deviations with similar values correspond to SOP variations comparable with environmental noise. In general, vibrations having amplitude higher than $6 V_{pp}$ and f_{osc} from around 12 Hz to 32 Hz seem to have non-negligible consequences on the SOP. The one generating the

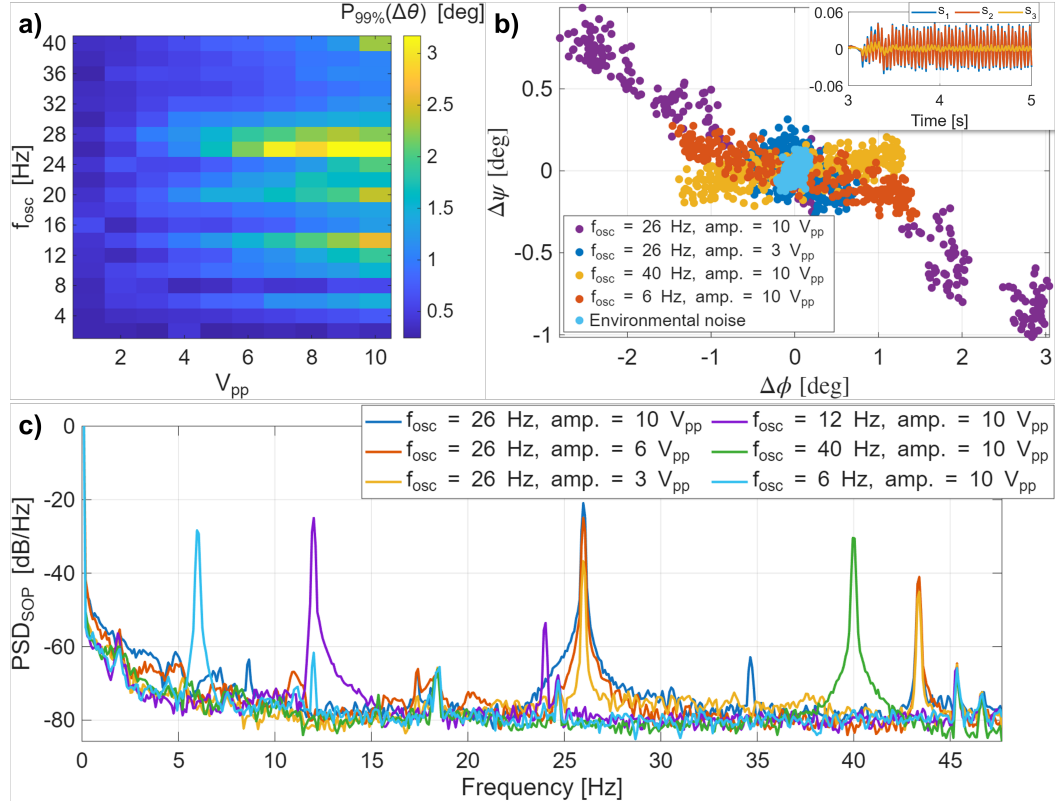


Fig. 3.8 a) $P_{99\%}(\Delta\theta)$ values for different vibrations induced on the fiber, changing f_{osc} and V_{pp} . b) angular coordinates plot showing the SOP cloud on the Poincaré sphere surface for different vibrations (purple, blue, yellow, orange dots), and for the environmental noise only (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.

largest SOP variation occurs for f_{osc} values around 26 Hz with an amplitude of 10 V_{pp} . However, it should be noted that the intensity of mechanical vibrations on the attached fiber depends not only on the oscillation frequency and amplitude but also on the geometry and material properties of the plate. To better observe the effects of the vibration on the SOP, Fig. 3.8b) shows a scatter plot of the Stokes vector angular coordinates for different vibrations. The light-blue cloud at the center of the graph represents SOP environmental noise only. When a vibration with $f_{osc} = 26$ Hz and 10 V_{pp} is applied, it generates the largest spread (purple points in Fig. 3.8b)), with a deviation of around 3° from the initial noise cloud, consistent with Fig. 3.8a). Testing different f_{osc} and V_{pp} pairs results in reduced vibration-induced cloud spread (blue, yellow, orange).

Comparing these results to the ones illustrated in Section 3.1, it should be noted

that mechanical oscillations yielding $P_{99\%}(\Delta\theta)$ values of 3° , i.e. the most intense generated in this case, would be difficult to be detected in that scenario. As observed in Figures 3.3 and 3.4, the $P_{99\%}(\Delta\theta)$ can reach as high as 8° to 14° when using commercial transceivers, although being strongly reduced to around 2° when filtering is applied. As a result, the mechanical vibrations considered in this study would be obscured by noise in most cases (at different ROPs, OSNRs and N_{win}). The inset of Fig. 3.8b) shows the time evolution of the Stokes vector when a vibration with $f_{\text{osc}} = 26$ and amplitude $10 V_{pp}$ is considered, with applied an high-pass filter (HPF). The HPF with a 3 Hz cut-off frequency is used to enhance visualization, eliminating the DC component and preserving the mechanical ones. Depending on the specific fiber displacement over the vibrating plate surface, geometrical deformations, and induced stresses, S_3 oscillates more weakly compared to the other Stokes parameters. Consequently, relying on a single Stokes parameter for event detection could be misleading, potentially resulting in a misinterpretation of the overall picture.

Regarding the SOP frequency response, Fig. 3.8c) shows the PSDs for various induced vibrations on the fiber. Similarly to the spectrograms in Figures 3.6b-d) and 3.7, these spectra have been obtained by direct summation of the single PSDs' amplitudes of the three Stokes parameters. This eliminates the recorded SOP vibration intensity dependency on the Stokes vector fluctuation direction. The 26 Hz event generates the strongest component, which attenuates as the vibration amplitude is reduced from $10 V_{pp}$ (blue curve) to $6 V_{pp}$ (orange curve) and $3 V_{pp}$ (yellow curve). The other two vibrations, at 6 Hz and 40 Hz (green and light blue curves), generate components of comparable intensity. Resonance harmonics are evident in the plot, underlying the (reasonable) nonlinear behavior of the vibrating plate. This picture provides valuable insights for the detection algorithms that will be discussed later, demonstrating that frequency content can be extremely useful for event detection.

Fiber spoofing

A malicious person, a hacker, could act on the telecommunication system's physical layer to eavesdrop on sensitive data and cause damage to the vendors. Among the different fiber-tampering techniques that have been identified [80], the most common one is called fiber spoofing, which consists in macro-bending the fiber cable at a low curvature radius so that the total internal reflection condition allowing for light propagation is compromised and, in the bending point, light leaks from the fiber

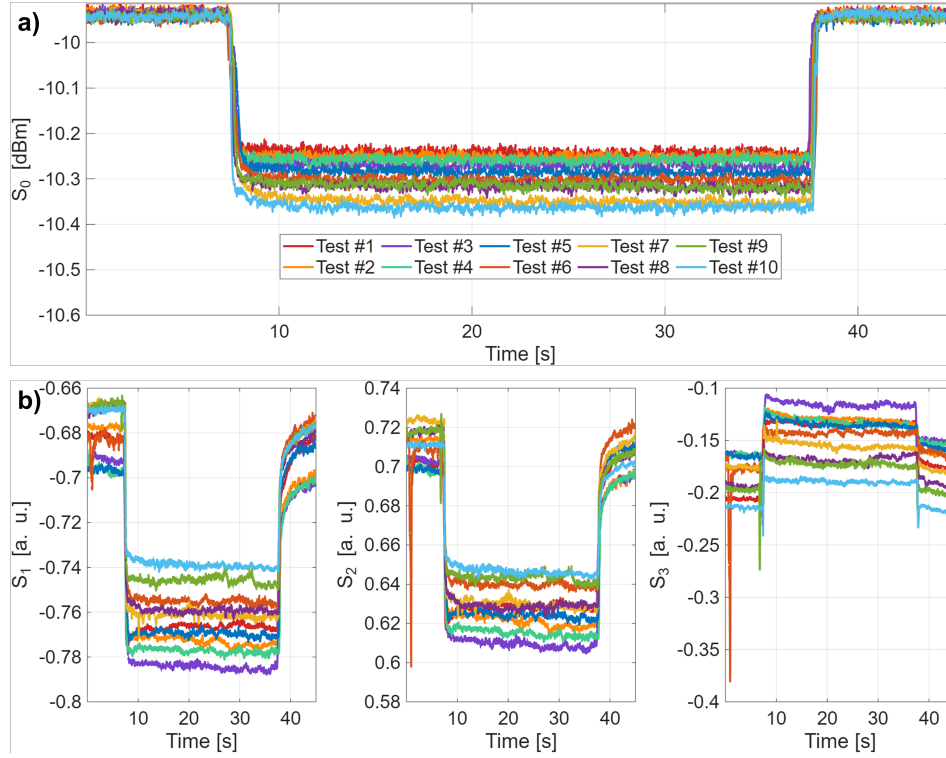


Fig. 3.9 Effect of fiber clamping on a) the instantaneous power S_0 , and b) the SOP as Stokes parameters S_1 , S_2 , S_3 . Legend in a) applies also to all the plots reported in this figure.

and can thus be captured by an eavesdropping device. One of the consequences for the communication system is a small received power drop [81, 82], in parallel with a bending-induced SOP variation [83], both of which can be detected by a SOP-sensing system.

In order to emulate this kind of event, we employed a commercial optical fiber identifier (OFI) tool which, as shown in Fig. 3.5 in the dashed-blue block, clamps the laboratory fiber (in orange in Fig. 3.5), connected to the 35 km metropolitan ring (in green in Fig. 3.5), and heavily bends it [84]. The clamping is controlled by a handgrip, which is tightened to bend the fiber inside the instrument. When the device detects light leakage, a fiber spoofing event is generated.

To characterize the signature that the macro-bends have on the SOP, initial experiments were carried out with OFI firmly secured to the optical bench, isolating it from external agents. The fiber was gently clamped for ~ 30 seconds and then released. The polarimeter outputs the complete Stokes vector, with the S_0 component recording instantaneous power (see Chapter 2). The results of ten tests are shown in Fig. 3.9a). The closing/opening of the clamp (around 7 and 37 seconds, respectively) causes

the instantaneous power to transition gradually between levels over approximately one second (depending on the person who is actually handling the clamp). When the clamp is completely closed and pressing on the fiber, S_0 remains constant. To gain a more comprehensive understanding of S_0 's response, the fiber spoofing tests were repeated about 120 times, revealing an average power drop of around 0.3 dB. No fatigue (i.e., an increasing power drop with the experiment repetitions) has been recorded.

Fig. 3.9b) reports the behavior of the three Stokes parameters for the same ten tests, showing a strong impact of the macro-bends on the SOP. To quantify the impact of macro-bends on the polarization state [20], we computed the angular deviation as described in Fig. 3.1b). Here, the reference Stokes vector $\vec{S}_{ref}$ is the average Stokes vector measured a few seconds before the fiber spoofing, while $\vec{S}[n]$ represents the time evolution of the Stokes vector when the clamp is closed. For the 120 measured events, the average angular deviation $\Delta\theta$ was found to be 9° , which is three times greater than the deviation caused by the most intense vibration discussed in the previous subsection (see Fig. 3.8a-b)).

In a real-life scenario, a malicious individual would likely manipulate the fiber before inserting it into the device, rather than keeping it completely firm over a surface. Additionally, the device would probably remain closed on the cable for several hours to intercept as much data as possible, rather than just for a few seconds. This more realistic hacking situation is depicted in Fig. 3.10. In this case, beyond the SOP angular deviation caused by clamping, the manipulation of the fiber before bending is also considered. The Stokes parameters in Fig. 3.10a) show abrupt changes just before the S_0 parameter drops, in Fig. 3.10b), starting from second 235, when the fiber is handled to be inserted in the OFI. The power drop itself occurs at the 241st second, when the macro-bend is introduced. It is noteworthy that S_0 remains completely unaffected by any manipulation before clamping, as no power leakage is generated. The same applies to the induced mechanical vibrations discussed in the previous paragraph. A possible detection algorithm could then jointly monitor the Stokes vector and instantaneous power, triggering alerts only when both metrics exhibit significant changes. This approach would help differentiate malicious activities from generic power fluctuations or SOP variations caused by accidental, non-hazardous touches to the fiber.

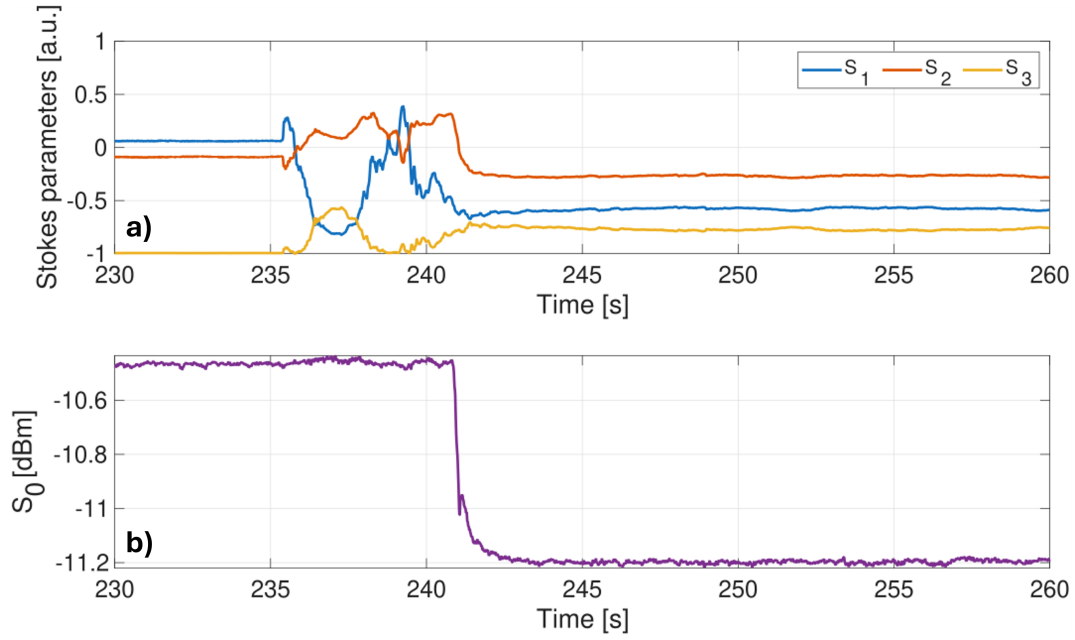


Fig. 3.10 Effect of hacker-like fiber spoofing on a) the Stokes parameters and on b) the instantaneous power S_0

Lightning strikes

Lightning strikes occurring near underground fiber cables or hitting aerial fibers can induce extremely rapid (krad/s to Mrad/s) polarization rotations due to the Faraday effect [85]. This can cause a loss of polarization tracking and potentially disrupt communications [70], as this kind of event, differently from the slow, mechanical fiber impairments discussed up to now, has time constants comparable to the coherent receiver DSP. Although lightning strikes significantly impact the SOP, their duration is very brief, ranging from about 20 to 60 μ s [13]. To provide some hints concerning the detection of this kind of event, we added a polarization scrambler (Novoptel EPS1000) right after the mechanical shaker in Fig. 3.5 [77]. This device is largely used to emulate very fast SOP rotations, especially reproducing lightning strikes [86]. To this purpose, the sampling speed of the polarimeter has been increased to 1.6 MS/s, which is enough to detect the Mrad/s variation induced on the polarization through the scrambler. Fig. 3.11 shows the related fluctuations in the Stokes parameters. Given their characteristics, they are impossible to study and, most importantly, detect at the sampling rate discussed so far: for this reason, they will not be discussed further in this thesis. The detection scenario needs in this case quite a different approach with respect to the ones presented here [87].

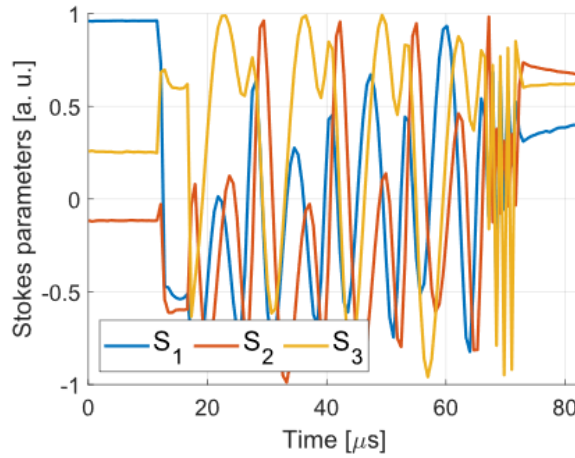


Fig. 3.11 Scrambler-generated lightning strikes effect on the three normalized Stokes parameters time-evolution.

3.2.3 SOP-based algorithms for automatic detection of anomalous events

The noise scenario and the events discussed in the previous subsections have highlighted various types of perturbations affecting the state of polarization. This suggests that by analyzing the polarization time evolution, it may be possible to detect harmful and anomalous events occurring along the deployed optical fiber path, and distinguish them from noise-related SOP variations.

We describe here two DSP algorithms that we proposed in [74, 75, 88, 89]. The first method evaluates the SOP angular speed (SOPAS, see below) using a simple, non-adaptive, time-domain solution. The second method (SOP-PSDG, see below explanation and acronym definition) employs a more advanced, frequency-based scheme capable of adaptively tracking the non-stationarity of the SOP fluctuations that typically occur in the deployed optical fiber scenario. Both methods detect anomalous events by raising an alarm when a processed signal, derived from the SOP evolution, exceeds a given threshold.

Time-based solution: the SOPAS algorithm

A straightforward method for detecting anomalies using a threshold-based approach involves monitoring the rate at which the SOP varies over time. This can be achieved by evaluating its angular speed, i.e. measuring the variation over time of the angle

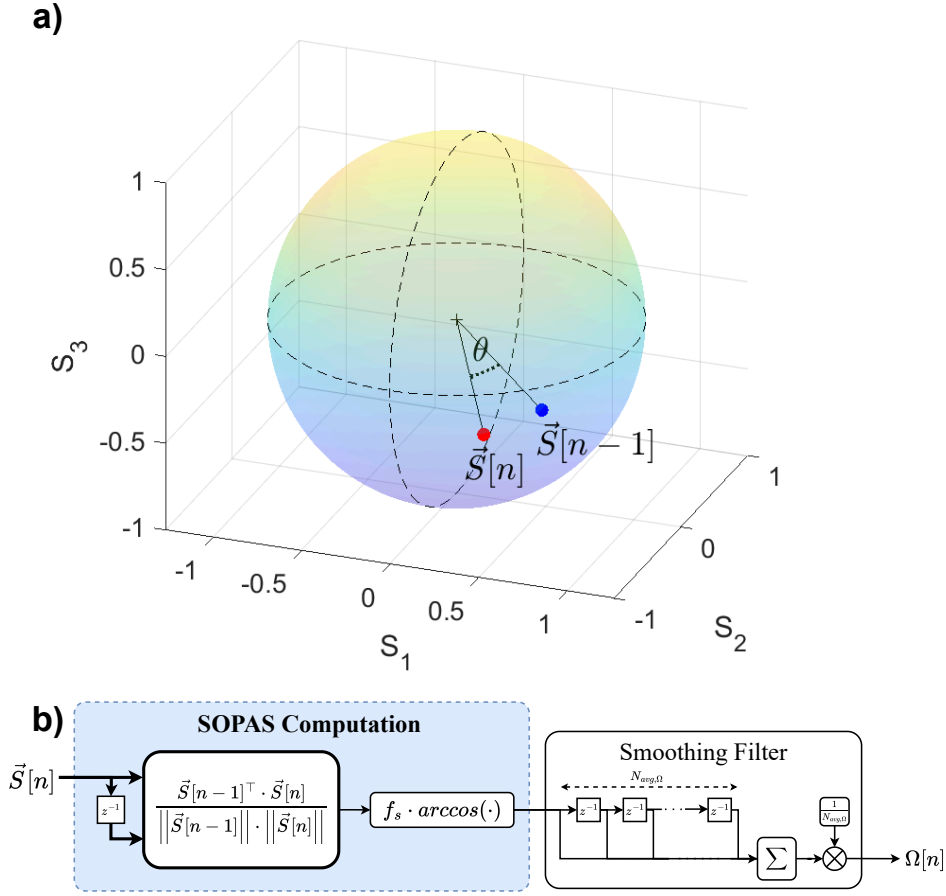


Fig. 3.12 a) Poincaré sphere where an example of two consecutive Stokes vectors (blue dot $\vec{S}[n-1]$, red dot $\vec{S}[n]$), and the angle θ in between them has been reported, to make the scheme in b) clearer. b) DSP scheme for the SOPAS anomaly detection algorithm, where $\Omega[n]$ is the SOPAS post-smoothing filter. $\vec{S}[n]$ is the input Stokes vector time series.

between two consecutive Stokes vectors over the Poincaré sphere (illustrated as θ in Figure 3.12a)). The SOPAS signal $\Omega[n]$ can be computed from the Stokes vector $\vec{S}[n]$, according to Eq. 3.3.

$$\Omega[n] = f_s \cdot \arccos \left(\frac{\vec{S}[n-1]^\top \cdot \vec{S}[n]}{\|\vec{S}[n-1]\| \cdot \|\vec{S}[n]\|} \right) \quad (3.3)$$

Figure 3.12b) illustrates the DSP scheme used to compute the SOPAS. The scheme also includes a smoothing filter, implemented as a moving average of length $N_{avg,\Omega}$ samples, to attenuate the SOPAS fluctuations caused by the SOP environmental noise, discussed previously. Despite the definition in Eq. 3.3, $\Omega[n]$ refers to the

already smoothed version of SOPAS, to ease notations.

This metric requires only the current and previous SOP samples, making it extremely simple to compute, even in real-time scenarios. However, it is not adaptive to slow daily urban changes of the SOP, as they require more consecutive SOP samples in order to be effectively monitored. This characteristic makes it suitable for scenarios where anomalous conditions are well-defined and cause polarization rotations significantly faster than those generated by the surrounding environment. For example, the fluctuations generated by the lightning strikes (see Fig. 3.11 and related paragraph) would be easily detected, with a simple threshold, by a SOPAS-based algorithm.

Additionally, the SOPAS has an upper limit bounded by the employed sampling frequency f_s , since the arc length drawn over the Poincaré sphere surface cannot exceed π without resulting in undersampling, as stated in [13]. This means that the maximum measurable SOPAS is given by the relationship $\Omega_{max} = \pi \cdot f_s$ [rad/s], which is anyway usually sufficient if considering mechanical vibrations and stresses.

Adaptive and spectrally-resolved solution: the SOP-PSDG algorithm

When environmental agents surrounding the fiber induce polarization rotations at speeds comparable to those caused by anomalous events, the SOPAS algorithm may become ineffective. However, as observed in the SOP spectrograms in Section 3.2.1, SOP environmental noise contributes to the spectrum at specific (though not static) frequencies, which can significantly differ from the frequencies excited during an anomalous event. Consequently, an alternative approach to process the SOP evolution for anomaly detection can be to compute a metric based on the analysis of the evolution of Stokes parameters in the frequency domain, i.e. studying how the SOP PSD changes over time.

The method we propose, simple yet effective, involves comparing historical values of the SOP PSD (i.e., the time-domain average of the SOP PSD spectrogram) with current SOP PSD values computed in real-time from the Stokes vector time series. The main idea is that anomalies are likely to occur when the current SOP PSD deviates significantly from its historical average. This concept is illustrated in the spectrogram in Figure 3.13, where a mechanical vibration is induced by a shaker on the experimental setup (with an oscillation frequency of $f_{osc} = 40$ Hz). By examining the spectrogram, the anomalous event can be easily identified by simply

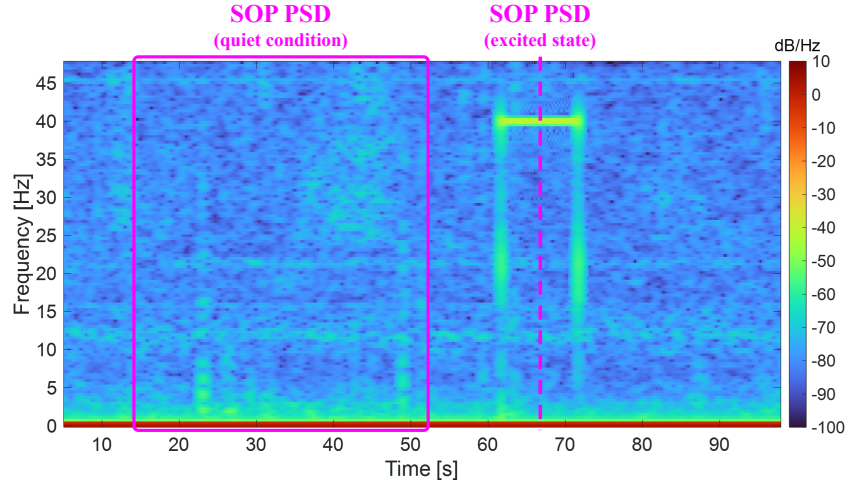


Fig. 3.13 SOP spectrogram, computed as the sum of the three Stokes parameters PSDs, acquired over the 35 km metropolitan fiber when inducing a mechanical vibration ($f_{osc} = 40$ Hz) for 10 seconds. The area within the solid violet rectangle is the SOP PSD in a quiescent condition, while the dashed violet line is the SOP PSD when the anomaly affects the fiber.

comparing the time-domain average PSD of the SOP in a quiescent condition (e.g., the area within the solid violet rectangle in Figure 3.13) against the PSD computed when the anomaly affects the SOP (dashed violet line in Figure 3.13). By quantifying this discrepancy, unexpected PSD patterns can be identified as anomalies, leading us to the design of the SOP-Power Spectral Density Gap (SOP-PSDG) algorithm.

The DSP scheme for SOP-PSDG-based anomaly detection is illustrated in Figure 3.14. The real-time SOP-PSDG is calculated as follows. First, each of the three $\vec{S}[n]$ components (where n represents the discrete-time index), $S_1[n]$, $S_2[n]$ and $S_3[n]$, is stored into a tapped delay line of N_{FFT} consecutive samples, from which, at each sampling time a one-sided PSD is evaluated: its computation is implemented by means of real-valued fast Fourier transform (FFT) [90], followed by the computation of the square magnitude of the FFT points. The evolution of the PSDs of the three Stokes parameters is represented by the signal vectors $\vec{P}^{S_1}[n]$, $\vec{P}^{S_2}[n]$ and $\vec{P}^{S_3}[n]$, defined as in Eq. 3.4,

$$\vec{P}^{S_i}[n] = \left[P_1^{S_i}[n], P_2^{S_i}[n], \dots, P_{\frac{N_{FFT}}{2}}^{S_i}[n] \right], \quad i = 1, 2, 3 \quad (3.4)$$

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 Stokes parameter. For practical reasons, in the computed PSDs, we discard the FFT point relative to the lowest frequency bin ($f = 0$), as shown in Fig.3.14.

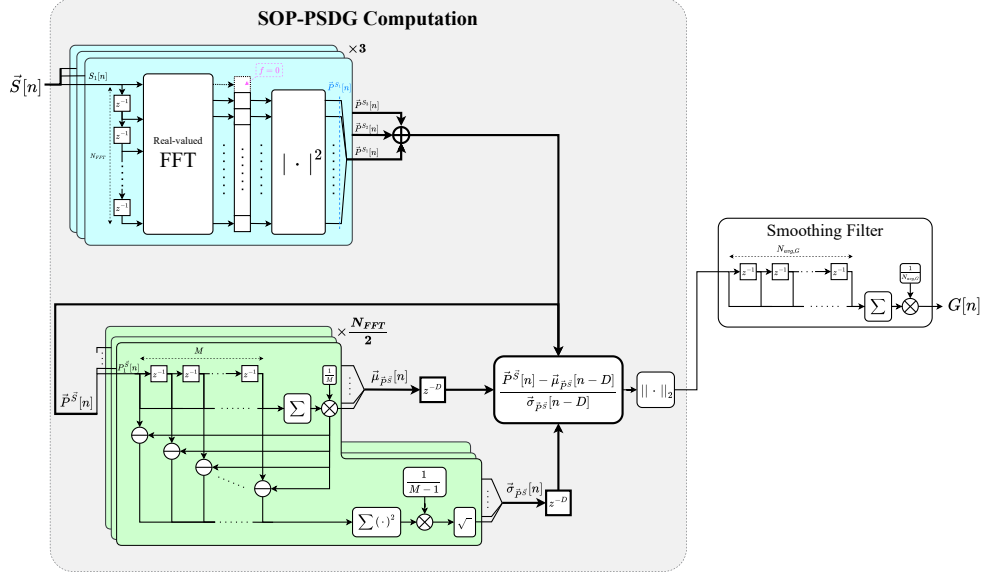


Fig. 3.14 DSP scheme for the SOP-PSDG anomaly detection algorithm. Light-blue DSP blocks indicate operations on individual Stokes vector parameters, while light-green DSP blocks denote operations on individual SOP PSD frequency components. Thick lines represent element-wise operations on vector signals.

This removal helps exclude discrepancies relative to the “stationary” SOP (i.e., the average value of the Stokes parameters, which could also be seen as the DC component) from the metric computation, as they are not relevant for anomaly detection purposes. The stationary SOP can indeed slowly vary over time, encompassing the entire Poincaré sphere even in the absence of anomalies.

The three computed PSDs are then summed together element-wise, to form the vector $\vec{P}^{\vec{S}}[n] = \vec{P}^{S_1}[n] + \vec{P}^{S_2}[n] + \vec{P}^{S_3}[n]$ (as done in Subsection 3.2.2 when analyzing the SOP spectra). This single SOP PSD constitutes an “isotropic” representation of the SOP power spectral content: indeed, $\vec{P}^{\vec{S}}[n]$ provides information on the fluctuations of the SOP over the Poincaré sphere regardless of the direction of these variations.

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

delay), as in Eq 3.5.

$$G[n] = \sqrt{\sum_{k=1}^{\frac{N_{FFT}}{2}} \frac{1}{\sigma_{P_k^{\vec{s}}[n-D]}^2} \left(P_k^{\vec{s}}[n] - \mu_{\vec{P}^{\vec{s}}}[n-D] \right)^2}, \quad (3.5)$$

Here, $\vec{\sigma}_{\vec{P}^{\vec{s}}}[n] = [\sigma_{P_1^{\vec{s}}}[n], \sigma_{P_2^{\vec{s}}}[n], \dots]$ represent the moving standard deviation of the elements in $\vec{P}^{\vec{s}}[n]$. As done for the SOPAS, the SOP-PSDG scheme also incorporates a smoothing filter, of length $N_{avg,G}$ samples, applied to attenuate the $G[n]$ fluctuations. In Eq. 3.5, the normalization of both the current and average SOP-PSD values with respect to their standard deviation allows the algorithm to account for variability in the intensity of the frequency components in the SOP spectrum. In this way, frequency components with more unstable or variable intensities are appropriately weighted, preventing random increases in $G[n]$ values under normal conditions (and thereby enhancing anomaly detection performance).

As shown in Figure 3.14, the moving averages and standard deviations of the spectral elements of the SOP PSD are continuously computed over $N_{FFT}/2$ separated tapped delay lines, each with a *memory* of M consecutive samples. This approach provides a DSP scheme with adaptive capability, able to memorize and track the pattern and variability of the SOP PSD in real-time. Consequently, the algorithm can adapt to the non-stationary behavior of the SOP PSD, which varies on an hourly basis (as observed in Section 3.2.1).

Moreover, as illustrated in Figure 3.14 and Eq. 3.5, both $\vec{\mu}_{\vec{P}^{\vec{s}}}$ and $\vec{\sigma}_{\vec{P}^{\vec{s}}}$ are delayed by D samples with respect to the current SOP PSD $\vec{P}^{\vec{s}}[n]$: this ensures that anomalies are not memorized by the DSP-scheme immediately upon their occurrence, which would degrade the detection capability of the algorithm. In fact, a margin delay $D > N_{FFT}$ is sufficient to prevent this issue, since in this way $D - N_{FFT}$ samples are required to be processed before the SOP-PSDG scheme starts to adapt its statistics to the anomaly.

Compared to SOPAS, this metric is clearly more complex, requiring the storage of more SOP samples and the accumulation of statistics on the SOP spectrum. Nevertheless, its ability to adapt to slow variations in the SOP provides a significant advantage in detecting anomalous events.

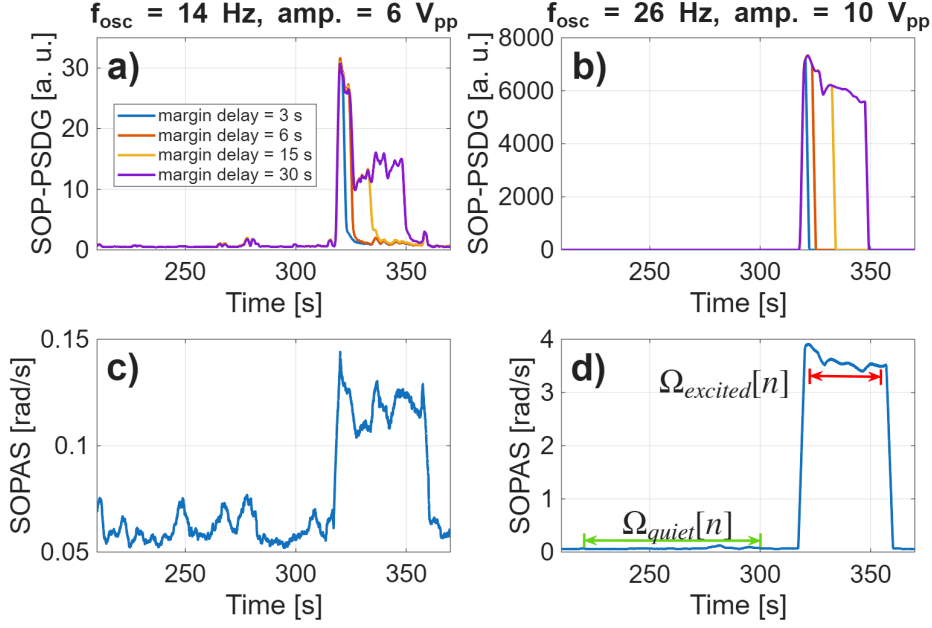


Fig. 3.15 a-b) SOP-PSDG signal when $f_{osc} = 14$ Hz, amp. = $6 V_{pp}$ and $f_{osc} = 26$ Hz, amp. = $10 V_{pp}$, for different values of margin delay. Legend in a) applies also to b). c-d) SOPAS signal when $f_{osc} = 14$ Hz, amp. = $6 V_{pp}$ and $f_{osc} = 26$ Hz, amp. = $10 V_{pp}$.

3.2.4 Experimental results using SOP-based algorithms.

The two DSP schemes illustrated in the previous subsection will now be evaluated based on their responses to the anomalous events described in Subsection 3.2.2. To ensure a fair comparison of the two methods in terms of detection delay induced by the DSP scheme, the smoothing filter length employed to compute the SOPAS has been set to $N_{avg,\Omega} = 287$ samples (corresponding to 3 seconds with $f_s = 95.4$ Hz) [74]. For the SOP-PSDG, the smoothing filter length is adjusted to $N_{avg,G} = N_{avg,\Omega} - N_{FFT}$ samples, to account for the delay induced by FFT input tapped delay line (see Figures 3.12 and 3.14). Unless stated otherwise, all subsequent results will use these parameters with $N_{FFT} = 128$ points.

Mechanical vibrations detection using SOPAS and SOP-PSDG

Figure 3.15 illustrates the evolutions of the SOP-PSDG and SOPAS under two different vibration scenarios induced by a mechanical shaker in the experimental setup described in Fig. 3.5 (as mentioned, in this case, the white rectangular one),

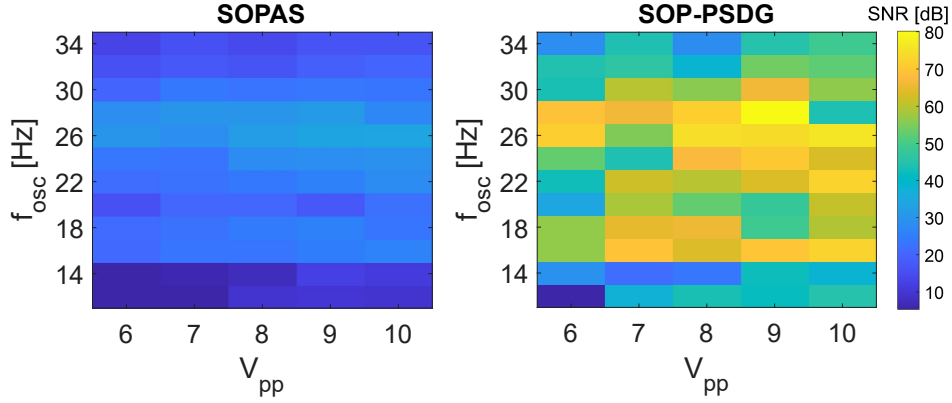


Fig. 3.16 SNRs computed for SOPAS and SOP-PSDG at different f_{osc} and V_{pp} .

considering the 35 km long fiber. In the first scenario, the setup was configured to produce an angular deviation of approximately 1° (see Figure 3.8a)), with an oscillation frequency of 14 Hz and a peak-to-peak voltage of $6 V_{pp}$ (Figures 3.15a) and c)). The second scenario, characterized by a more intense vibration, induced an angular deviation of approximately 3° , with an oscillation frequency of 26 Hz and a peak-to-peak voltage of $10 V_{pp}$ (Figures 3.15b) and d)). For this analysis, the memory duration was set to 180 seconds (i.e. M around $17 \cdot 10^3$ samples), while various margin delays were tested, ranging from 3 to 30 seconds.

In Figure 3.15, both the SOPAS and SOP-PSDG methods detect anomalies at approximately 320 seconds for the induced vibrations. However, the SOP-PSDG signal demonstrates a key advantage: after the specified margin delay has been surpassed, it quickly returns to its pre-detection levels. This indicates that the SOP-PSDG can rapidly adapt to changing conditions once the margin delay has been exceeded. Furthermore, comparing Figures 3.15a) and c) reveals that, during detection, the SOP-PSDG signal shows a significantly larger relative increase compared to the SOPAS. This difference highlights the superior sensitivity of the frequency-based SOP-PSDG algorithm.

In order to quantitatively compare the sensitivity of the two algorithms, we define a detection signal-to-noise ratio (SNR) as the ratio between the average squared values of the detection signal in excited and quiet conditions. For instance, the SNR of the SOPAS signal is defined as in Eq. 3.6.

$$SNR_{SOPAS} = \frac{\mathbb{E} \left[(\Omega_{excited}[n])^2 \right]}{\mathbb{E} \left[(\Omega_{quiet}[n])^2 \right]}. \quad (3.6)$$

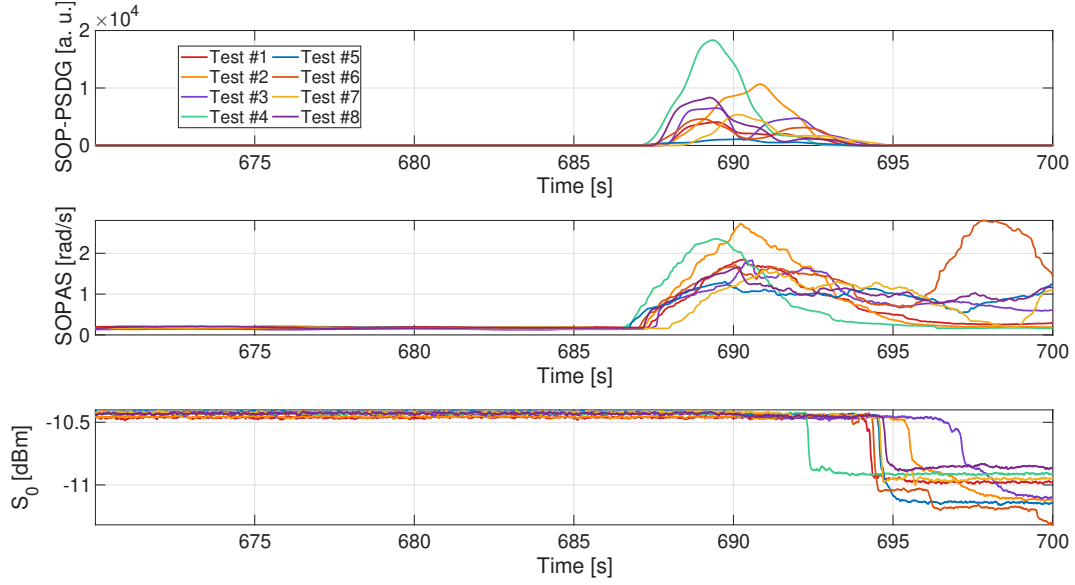


Fig. 3.17 Hacker-like spoofing effect on SOP-PSDG, SOPAS and S_0 .

As shown in Fig. 3.15c), $\Omega_{quiet}[n]$ refers to a few tens of seconds before the vibration is activated. $\Omega_{excited}[n]$ refers instead to the samples related to the event acting on the fiber, neglecting the transients due to the smoothing filter. The same windowing of Fig. 3.15c) and Eq. 3.6 has been applied on the SOP-PSDG, considering $G_{quiet}[n]$ and $G_{excited}[n]$. The latter refers to the SOP-PSDG samples when the vibration is activated, up to the margin delay value, neglecting the transients due to the smoothing filter and FFT. Figure 3.16 displays the evolution of the detection SNR over a subset of the cases considered in Subsection 3.2.2 (refer to Fig. 3.8a)). For this analysis, the SOP-PSDG margin delay was set to 10 seconds. For all the combinations of f_{osc} and V_{pp} , the SOP-PSDG exhibits a consistently higher SNR (50 dB - 70 dB) than the SOPAS (20 dB - 40 dB).

Fiber-spoofing detection using SOPAS and SOP-PSDG

As outlined in Subsection 3.2.2, fiber spoofing events have been simulated through an OFI over the 35 km long fiber. Each spoofing event was replicated 120 times, with each occurrence lasting 30 seconds and separated by 60 seconds. The relevant part of each event was the closing of the fiber insertion clamp, rather than its release. This means that spoofing detection needs to occur promptly after the clamp starts closing.

Figure 3.17 illustrates the responses of the SOP-PSDG and SOPAS to several fiber spoofing events. For the SOP-PSDG algorithm, the memory M has been set to 30 seconds (i.e., M around $2.8 \cdot 10^3$ samples), while the margin delay has been fixed at 5 seconds. The insertion of the fiber into the clamp causes a noticeable increase in both SOPAS and SOP-PSDG signals, occurring about 7-8 seconds before the S_0 drop. This early rise highlights the superior responsiveness of the SOP-based DSP schemes, which is crucial for minimizing the data leakage during a fiber spoofing attack. Notably, the SOP-PSDG signal drops after 5 seconds, coherently with the imposed margin delay, while the SOPAS signal remains in its excited state until the fiber stabilizes within the OFI device.

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

As a final discussion, we present preliminary results using both methods on SOP data collected from the commercial coherent transceiver described in Section 3.1, which replaces the laser and polarimeter depicted in Fig. 3.5. For this experiment, to further change the scenario and demonstrate how the two algorithms work and compare in a completely different condition, we exploited the 10 km long metropolitan fiber (indicated red line in Fig. 3.5). Given the significant SOP estimation noise in this scenario, as detailed in Section 3.1 (see Fig. 3.4), we introduced strong mechanical vibrations using a mechanical shaker. For this purpose, the vibrating plate has been substituted with the circular metallic one (see Fig. 3.5), which is most intense on the fiber for an oscillation frequency of 20 Hz and a peak-to-peak voltage of $10 V_{pp}$. The $P_{99\%}(\Delta\theta)$ is around 2° in the absence of vibration and increases to 4° when vibrations are applied. 130 vibrational events lasting 5 seconds each have been periodically induced in the experimental setup. Fig. 3.18 shows the corresponding SOP-PSDG and SOPAS evolutions for each event. The SOPAS scheme used a smoothing filter with $N_{avg,\Omega} = 76$ samples (corresponding to approximately 4 seconds) and sampled at $f_s = 20$ S/s. To achieve a similar detection delay with the SOP-PSDG, N_{FFT} was set to 64 points and $N_{avg,G}$ to 12. The SOP-PSDG memory was set to 180 seconds, with a margin delay of 3 seconds. As shown in Fig. 3.18, the SOP-PSDG seems to effectively react to the induced anomaly events: during detection, the PSDG values increase by around one order of magnitude compared to pre-detection levels. In contrast, due to the smoothing filter, the SOPAS signal stays high and nearly constant before detection, with peak intensities only doubling when an event occurs.

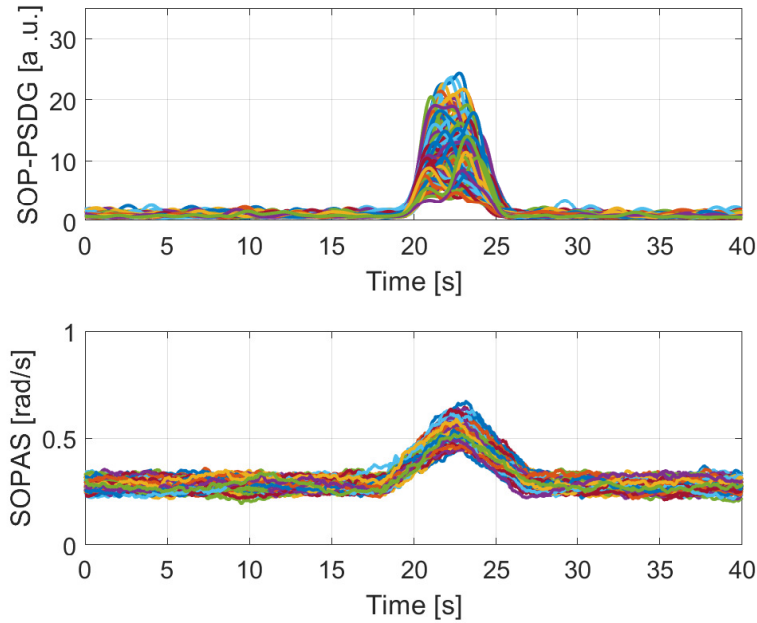


Fig. 3.18 Several occurrences of SOP-PSDG and SOPAS signals considering SOP data extracted from the commercial transceiver, when a vibration having $f_{osc} = 20$ Hz and amplitude $10 V_{pp}$ is induced on the fiber.

In summary, preliminary results indicate that SOP-PSDG outperforms SOPAS for threshold-based detection even when using commercial coherent receivers.

3.2.5 Discussions and conclusions

We analyzed polarization sensing in an urban environment, employing metropolitan fibers running around Turin, in Italy. A characterization of the SOP fluctuations generated by the urban scenario, which we called SOP environmental noise, has been provided, showing different agents that could impinge on the cable and enhance the noise. Experiments have been carried out exploiting a polarimeter so that the sampling frequency could be tweaked for our purposes, and set to 95.4 S/s. Specifically, time-varying external conditions to which the fiber is subject generate SOP fluctuations, making it non-stationary. This represents an issue for any anomaly detection algorithms. On top of this scenario, we have shown the effect of different mechanical vibrations on the SOP, characterizing the effect that they have on the cloud of points on the surface of the Poincaré sphere, as Stokes vector time evolution and frequency

content. This analysis showed that different vibrations have particularly strong or weak effects on the fiber cable, which translates to SOP angular deviation. Fiber spoofing has also been characterized, showing a strong effect on the SOP variation and instantaneous power drop.

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

The latest research on anomaly detection of hazardous conditions within the optical network's physical layer broadly employs machine learning techniques [91–93], particularly for fiber spoofing events, earthquakes [94, 43], but also for traffic monitoring [95]. Nevertheless, a DSP algorithm that can output a signal indicating an anomalous condition without requiring prior training could be extremely useful. When used in conjunction with neural networks, this approach could enable much more reliable detection of potentially hazardous events. Key features such as event duration and signature over the Poincaré sphere surface could be used as further detection parameters. This would enhance the resilience of optical networks to fiber cuts in metropolitan environments, robustness against eavesdropping, and potentially offer early warnings for a wide range of anomalous conditions not only limited to the urban scenario.

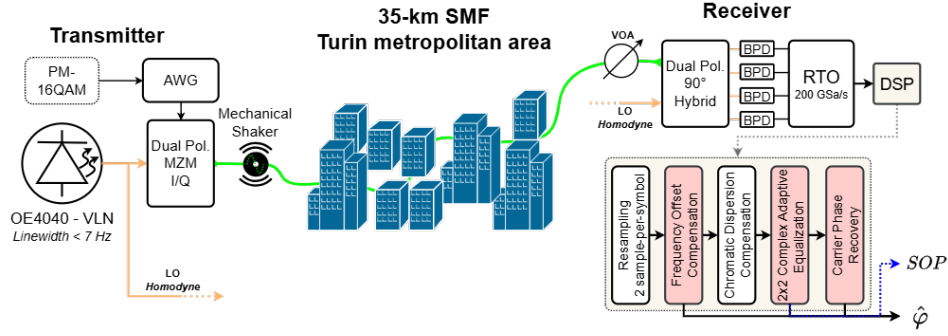


Fig. 3.19 Experimental setup. AWG: arbitrary waveform generator, MZM: Mach-Zehnder modulator, LO: local oscillator, SMF: single-mode fiber, BPD: balanced photodetector, RTO: real-time oscilloscope, DSP: digital signal processing, VOA: variable optical attenuator.

3.3 Comparison Between Phase and Polarization Sensing Using Coherent Transceivers Over Deployed Metropolitan Fibers

In Chapter 1, we mentioned that external agents acting on the fiber cable can also be sensed by the forward optical phase. Despite being less efficient in terms of costs, several works demonstrated reliable events detection exploiting this technique. As for polarization, the coherent receiver's internal DSP tracks the signal phases as well, as it also encodes information. That information, provided that a low-linewidth laser is employed, could be used for sensing.

In this section, we then propose a (preliminary) experimental comparison of phase- and SOP-based sensing capabilities, similarly to [35].

3.3.1 Experimental setup and results

The experimental setup is outlined in Fig. 3.19. At the transmitter side, an ultra-low phase noise OE4040-VLN laser, centered at 1545.17 nm and with a spectral linewidth < 7 Hz, modulates a 32 GBaud DP-16QAM signal having square-root raised-cosine spectral shape with roll-off 0.2. The experiments have been carried out on the same 35 km long underground fiber link deployed in the Turin metropolitan area (see the map in Fig. 3.5) that has been used in Section 3.2. Since no EDFAs were present in the metropolitan link, both BER and SOP/phase estimation accu-

racy are solely determined by the coherent receiver internal noise, as in a typical unamplified link. At the receiver, we performed offline post-processing of real-time oscilloscope (RTO, sampling at 200 GS/s) signal acquisitions by using a typical DSP chain for standard coherent receivers. In particular, the RTO acquires signal bursts of 200 ns every 1 ms: this allows for extending the acquisition time to the range of tens of seconds, comparable to the typical time constants of mechanical vibrations. As shown in Fig. 3.19, each burst undergoes DSP front-end corrections, 2-sample-per-symbol resampling, frequency offset compensation (FOC), chromatic dispersion compensation (CDC), data-aided adaptive equalization, and carrier phase recovery (CPR). Equalization is performed using an LMS-based 2×2 complex-valued equalizer with 16 taps (same as Section 3.1). Note that the DSP elements manage to converge within the burst duration, yielding a mean SNR higher than 17 dB for both configurations. The corresponding measured BER over 1000 data bursts is reported in Fig. 3.20. With the presented post-processing procedure, it is then possible to retrieve SOP and phase information from each processed burst at a sample rate of $f_s = 1000$ S/s. The signal optical phase is computed according to the algorithm proposed in [35], and reported in Eq. 3.7.

$$\hat{\phi}[n] = -2\pi\Delta\Omega n + \arg \left\{ \sum_{ij} \bar{w}_{ij}[n] e^{-j\Delta\psi_i[n]} \right\}, \quad i, j = 1, 2 \quad (3.7)$$

where n is the burst index, $\Delta\Omega$ is the digital frequency offset from FOC, $\bar{w}_{ij}[n]$ is the mean value of the $w_{ij}^{(m)}[n]$ element, being m the tap index, in the equalization matrix $W[n]$, and $\Delta\psi_i[n]$ is the i -th element of the phase rotation vector $\Delta\Psi[n]$ from CPR. SOP is instead extracted from the DC components of either column of $W^{(n)}$ (exactly as discussed in Sec. 3.1). To assess the achievable sensing capabilities of these quantities, we induced controlled vibrations on the metropolitan fiber link by means of a mechanical shaker placed right after the transmitter (see Fig.3.19). A low-frequency (i.e., a few Hz) signal generator drives the shaker to induce a sinusoidal stress at a tunable frequency over the fiber. This is very similar to what was discussed in Section 3.2, specifically concerning the mechanical vibration paragraph. Nevertheless, the vibrating plate employed for this study differs from the one used previously.

The effect of the vibrations induced on the fiber is studied by means of spectrograms, computed for both optical phase and SOP using the same procedure. At first, the DC component of the signals is removed with a high-pass filter, implemented by

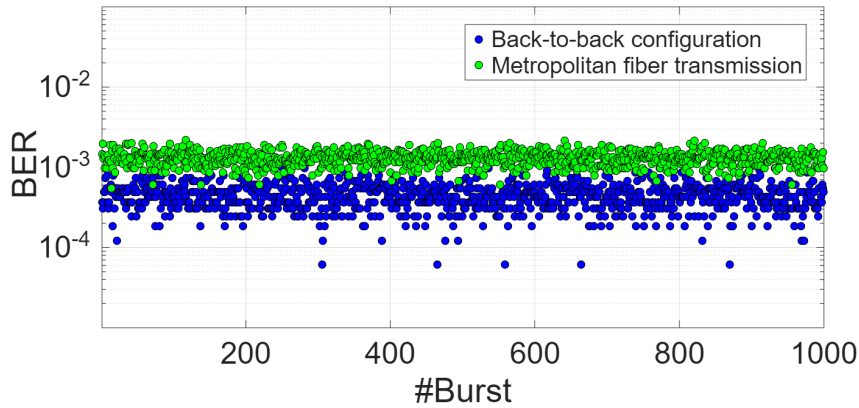


Fig. 3.20 Measured BER for the first 1000 data bursts in back-to-back and after metropolitan transmission.

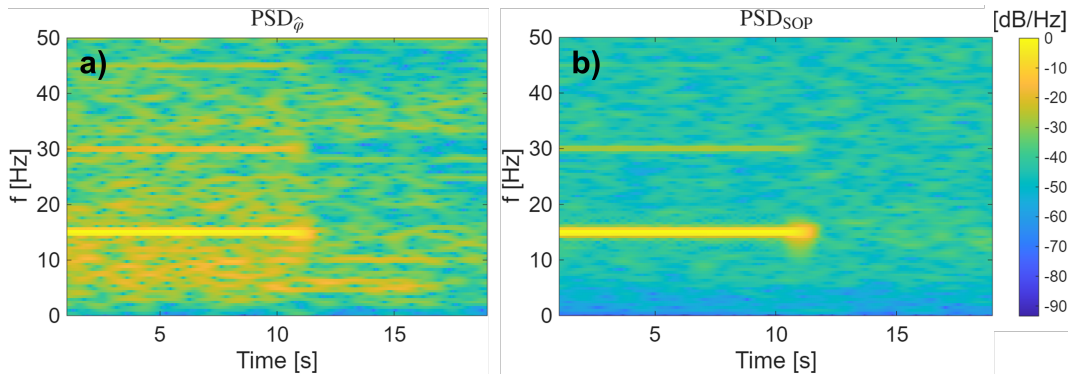


Fig. 3.21 PSD in back-to-back configuration for the a) optical phase and b) SOP with a 15 Hz shaking.

subtracting from the original signal a moving-averaged version of it, with a sliding window of 100 ms. Subsequently, the PSD is computed and smoothed through a moving average operation with a window of the same length. Spectra are normalized to enhance the visualization of the relative power levels between the points where the vibration is present and the noise floor. In the case of SOP, the PSDs of the three individual Stokes parameters are summed up before averaging, as we did for the spectrograms in Sec. 3.2. The results obtained for an acquisition of 20 seconds in the back-to-back configuration are reported in Fig. 3.21. In particular, the signal generator controlling the mechanical shaker has been configured to generate a sinusoidal signal with a frequency $f_{osc} = 15$ Hz during the first ~ 10 seconds of the acquisition and then turned off. The vibration (and its nonlinear harmonics) is clearly detectable in the PSDs of both the optical phase and SOP, though with different sensitivity: the spectral component at $f = 15$ Hz is indeed the strongest one over the whole time

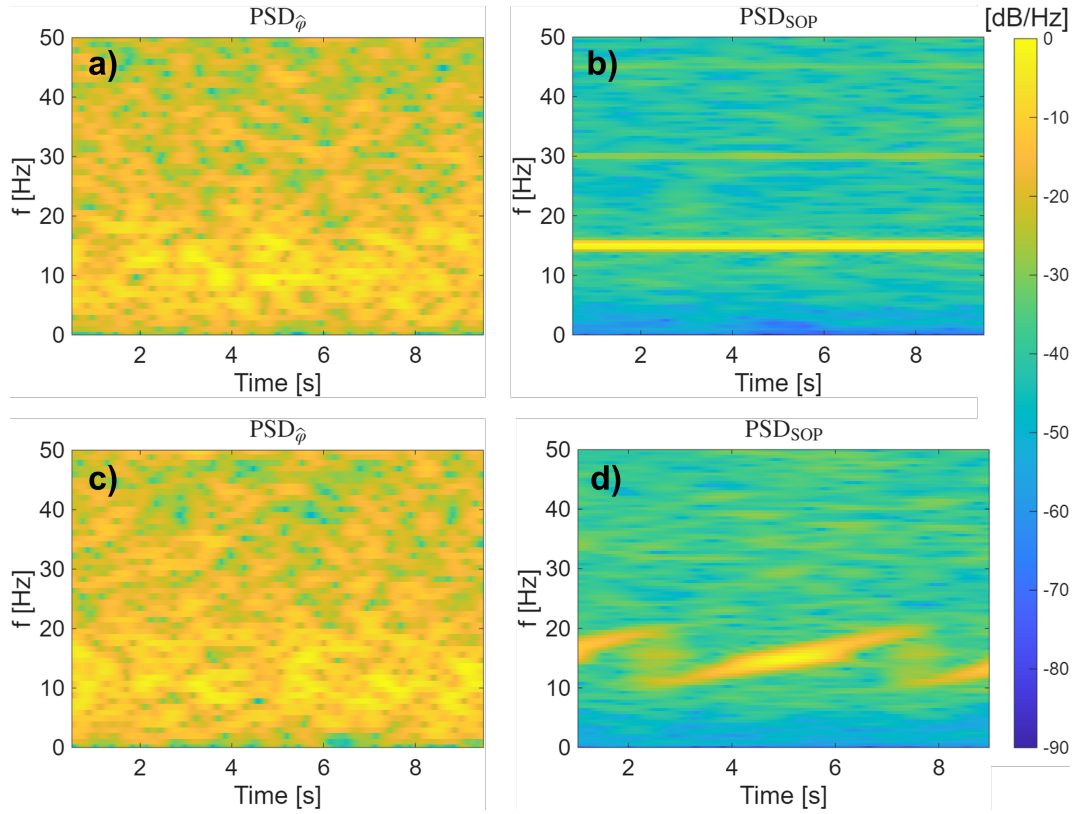


Fig. 3.22 Power spectral density after metropolitan transmission of a) optical phase and b) SOP for 15 Hz shaking, c) optical phase and d) SOP for a shaking frequency swept from 10 Hz up to 20 Hz every 5 seconds.

interval in which the mechanical shaker is on. However, it is around 20 dB above the noise floor for the optical phase, whereas it achieves a separation of around 40 dB for the SOP. Hence, the optical phase appears to be more sensitive to external perturbations, i.e., characterized by a noisier PSD, also considering the fact that in a back-to-back configuration, no strong disturbances are present. These considerations are confirmed by the results obtained in the 35-km metropolitan fiber configuration for an acquisition of 10 seconds, as reported in Fig. 3.22a-b). In this case, the mechanical shaker was active for the whole duration of the acquisition. At the output of the metro fiber, no information on the induced mechanical vibration can be retrieved from the PSD of the optical phase. In this scenario, the spectral component relative to the induced vibration is completely immersed in a “background” noise, likely generated by the micro-vibrations caused by the metropolitan environment on the deployed fiber. On the contrary, the SOP proves to be more robust to external perturbations, since the vibration is once again the dominant spectral component

with a separation around 30 dB from the background noise floor. The same applies for a shaking driven by a chirped sinusoidal signal whose frequency varies from 10 Hz up to 20 Hz with a periodicity of 5 seconds, as shown in Fig. 3.22c-d).

While these results might seem contradictory to those outlined in [35], it is important to point out the different scenarios in which they were obtained. In particular, two aspects need to be highlighted, namely the transmission environment and the type of excitation applied to the optical fiber. Data transmission was conducted across a metropolitan optical fiber network situated in the downtown area of Turin, which represents a noisier environment with respect to a suburban area. Moreover, the excitation induced by means of a mechanical shaker driven by a sinusoidal signal is intentionally quite weak in amplitude, in order to test the ultimate sensing capabilities in the two cases.

3.3.2 Discussions and conclusions

We have presented in this section a comparison between the sensing capabilities of coherent receivers, designed to extract the received optical signal phase and SOP from the internal DSP. In this scenario, SOP appears more robust than phase when compared to the background noise. Nevertheless, it should be pointed out that noise is strongly dependent on the fiber cable installation environment: we do not exclude that, for quieter installations with respect to the metropolitan one considered in this work, phase, viceversa, outperforms SOP. It is, anyway, essential to highlight that, while SOP extraction is a relatively straightforward process, requiring only a minor modification to the receiver DSP, the use of phase information would require a total re-engineering of the coherent transceiver, requiring a very narrow-linewidth laser (i.e., with low phase noise), significantly increasing the overall costs.

3.4 Chapter Conclusions and Hints on Localization

This chapter demonstrates how threat detection based on SOP monitoring is a reasonable solution that can be adopted in the ISAC context, especially in metropolitan networks. For coherent transceivers, SOP samples can be easily extracted from the equalizer taps, resulting in an almost ready-to-work polarization analyzer running on top of the telecommunication hardware. This comes at the cost of different noise con-

ditions related to the working point of the coherent system employed, meaning OSNR and ROP, which may hinder SOP fluctuations and affect any processing algorithm. Events generate clear polarization fluctuations that can be detected as long as data are made available by the receivers, and a proper processing algorithm is employed. We demonstrated how important it is for the latter to be well-suited to the context where the sensing system works: any non-adaptive detection-algorithm-derived metric would suffer from changing conditions of the surrounding environment, related to the most common temperature drifts, to the more trivial control rooms' fans switch on/off, to human activity. By proposing an adaptive algorithm (the SOP-PSDG), we also showed how fundamental it is to exploit the frequency information of the recovered SOP. Given the huge quantity of data and the need to adapt to any non-threatening changing condition, any algorithm would surely benefit from the use of any machine-learning approach, which would make the detection more robust to false alarms.

Forward optical phase has also been investigated for sensing purposes, provided that an ultra-low linewidth laser is employed: the phase information is also extracted by the coherent transceivers DSP for data demodulation. We investigated any relevant advantage in substituting SOP with phase as the sensing measurand, which should also justify the increased cost of adding a laboratory-grade laser at the transmitter side. Our work demonstrated no reasonable benefit: in the metropolitan environment, it showed significantly higher noise, which masked all the induced events on the fiber, unlike the SOP. The change of scenario to a more silent one, such as the submarine or rural terrestrial areas, could demonstrate a more convenient use of this measurand.

The added value of using SOP was then demonstrated in several contexts, but limitations should also be mentioned. Despite the current telecommunication optical networks moving in the direction of making available the SOP samples from coherent receivers as a standard, demonstrating also the economic interest in the subject, the use of this technique is not to be considered as the only available one: it depends on the application context. There is still research to do concerning a blind processing algorithm able to tell apart noise fluctuations with respect to an actual event. For example, several studies demonstrated sensitivities to earthquakes, but never blindly detected one. The work in [12] is the perfect example: SOP sensitivity to physical phenomena (surface gravity waves, in this case) is demonstrated only through correlation with other sensors, making the sensing system far from being completely blind. A large number of papers also demonstrated the benefits that

this system would have if employing machine learning [93, 96], particularly in a metropolitan scenario. A much more detailed discussion and comparison will be delivered in the last chapter of this thesis, once the coexistence of telecommunication and DAS systems is addressed.

Additionally, events' positioning would take the technique a step further. Despite having been treated only partially during this PhD, we did develop some knowledge concerning the topic. The nature of SOP sensing, as any other LR technique, to which this same discussion could be applied, does not allow for an almost "ready-to-go" system when it comes to events' localization, as would be the case for DAS. An approach that has been investigated exploits the spatial diversity of the fiber links in terrestrial/metropolitan environments. Given a vibration epicenter, mostly connected to earthquakes, the acoustic wave propagation delay would hit different fibers at different times, depending on their distance from the event. Exploiting the knowledge of the delays (which could be recovered by cross-correlation) and the (known) cables displacement, the epicenter could be recovered through triangulation [97, 98]. Assuming a centralized and synchronized SOP-data sharing among the different fiber links (which are non-negligible assumptions), the localization error would nevertheless strongly depend on each fiber link's layout, and on the direction towards which the acoustic wave hits the cable, leading to biases in the epicenter position estimate. On the other side, on submarine systems, per-span localization has been demonstrated, even if not fully exploiting all the telecommunication hardware already available. In [73], a large-scale earthquake has been localized through tens-of-km-spaced spans, typical of amplified systems.

Concerning small-scale events, which usually involve a single point of the fiber, two main approaches have been proposed, reaching localization accuracies even below 1 km. On one side, works such as [70, 99] proposed to exploit the walk-off between two different wavelengths to localize an event. Depending on where along the fiber the SOP fluctuation happens, the time delay between the two SOP traces will change, at the receiver. Through cross-correlation of the received polarization traces, the time delay can be recovered and translated into the position estimate. This approach demonstrated reasonable and consistent localization outcomes, but, to our knowledge, it has only been tested to position extremely fast events, generated by polarization scramblers and mostly emulating lightning strikes. On the other side, the most well-known and investigated approach concerns a bidirectional fiber link, where two transceivers transmit light in opposite directions. The ideal model, for

completeness and the reader's interest, is reported in Appendix B. The main idea is always based on computing the cross-correlation between the traces recorded at the two fiber ends, to recover the propagation delay difference and, in turn, obtain the positioning information. The idea was first proposed in [26] and then further explored in works such as [35] or, more recently, [34], even if with phase as measurand. These works all managed to localize mechanical vibrations happening along a fiber link, with coexisting communications. The same approach has also been used for fast SOP fluctuations [100, 101]. Despite having delivered interesting results, even with very localized mechanical events, there is still no work that demonstrated this approach to work in general cases, with generic fluctuations, for SOP. Moreover, localization of slow events is quite critical for this approach. Cross-correlation techniques, either exploiting wavelengths' walk-offs or counter-propagating signals, require a very high sampling speed (that could be relaxed in the case of detection-only of events), perfect synchronization (or, at least, almost perfect), and polarization data exchange between transceivers, which could not be straightforward to obtain. Similar to the triangulation techniques, information about the layout of fiber displacements needs to be known to avoid large positioning errors.

At this stage, given the above brief hints on localization, we envision the SOP to be used mainly as a detector in metropolitan areas, to detect if some anomalous condition is happening in the surroundings of a specific fiber link. In submarine scenarios, given the size of the events coupling to the fiber cables (e.g., earthquakes or tsunamis), SOP monitoring could also be a viable solution. Given the speed at which research is progressing in this topic, we do not exclude, anyway, that any of the mentioned positioning approaches will deliver, in the near future, more applicable outcomes.

Chapter 4

Polarization Sensing in Mountain Areas

The mountain environment is increasingly affected by destructive events, including rockfalls, landslides, avalanches, and debris flows. When these phenomena occur near inhabited areas, monitoring systems with response times of a few seconds, for fast detection and warning/alarm generation, can mitigate their consequences and reduce the risks for the local communities, minimizing damages to public or private properties and disruptions to local services such as transportation and utilities. In this scenario, geotechnical engineering solutions have been developed and are now widely adopted. These techniques focus primarily on identifying initiation mechanisms, the earliest indicators that a hazardous event may be imminent, so that potential events can be timely detected. In addition, monitoring debris flow dynamics remains essential. This includes measuring vibrations generated by the moving mass, sensing flow depth, evaluating basal stress, and recording surface-flow velocity. The related sensors are usually based on different technologies [102–104] such as geophones or seismometers [105]. More recently, systems based on radars, lidars, or infrared cameras [106–109] have also been proposed and installed. In the search for a technology that can address the shortcomings of commercial solutions, optical fiber SOP-sensing may be the ideal candidate. In general, the primary limitations of legacy mountain engineering techniques are outlined below.

- **Reliability.** The monitoring system should be located in positions where the acquired data are reliable for correct interpretation. Unreliable data evaluations

Table 4.1 Comparison of mountain engineering monitoring systems with optical fiber sensing.

Technique	Reliability	Coverage	Power supply	Cost	Visual impact
Legacy Mountain Engineering techn.	Depends on the sensor and installation place	Very limited	Often needed in situ	Depends on the technology and installation	Often non-negligible
SOP-based sensing	Demonstrated in other contexts, to be addressed in the mountain	Tens of km	Not necessarily in situ	To be investigated	To be investigated, but mostly absent

would increase false and missed alarm occurrences when detecting dangerous events. As an example, a camera with limited visibility into a gully subject to hazards can hinder the system's detection capabilities. Optical fiber sensing requires a more detailed investigation in mountain scenarios. Despite current limitations, the previous chapter demonstrated the SOP reliability in urban environments.

- **Coverage.** In the case of mountain engineering sensors, monitoring is usually active over areas of limited extent, which could cause the system to miss dangerous events occurring in out-of-reach areas. Optical fibers can cover tens of km, and be sensitive all over their length.
- **Power supply and maintenance.** Sensors that need to be powered directly on site, in this context, are to be avoided as they are often installed in difficult-to-reach positions, making maintenance complex. Given the extent of coverage provided by optical fibers, there is no need for this to happen. Geophones or visual sensors could sometimes suffer this condition.
- **Cost.** For the specific target of our investigation, it is important for the in situ sensing devices to be inexpensive, since they might be damaged by catastrophic events. This point will be better addressed in the following chapters.
- **Visual impact.** In areas often subject to environmental restrictions, such as national parks or natural reserves, these sensors should not be visually impacting, but better smartly hidden. Optical fibers are often buried, which could mitigate the problem.

Table 4.1 summarizes the main differences between the legacy sensing systems and the optical fiber SOP-based.

Although we discussed several LI and LR techniques which could fit the mountain scenario, we analyze in this chapter the use of SOP as a measurand to build a detection system which could deliver early warning whenever a hazardous condition is detected. The system would be, in principle, standalone and not connected to anything related to telecommunication. The driving reasons for choosing this technology include potential cost savings compared to traditional fiber sensing methods (e.g., ϕ OTDR or Brillouin-based fiber sensing systems), as it does not need sophisticated optoelectronic equipment and has reduced complexity.

The following sections are organized as follows: Section 4.1 studies a laboratory in-scale reproduction of a mountain gully, where optical fibers have been displaced, buried in soil, and some events emulating some real hazards are generated. Section 4.2 will discuss how the monitoring system scales in a real-life scenario. We specifically monitored for a few days a mountain gully in Cogne, Valle d'Aosta (Italy). The same site will be studied in Section 4.3, where an actual, working monitoring system based on the analysis in the previous section has been developed.

The matter presented in this chapter is partly based on the works reported in [88, 110, 89, 111]. While treating a quite transversal topic, which strongly overlaps with geosciences, it is important to acknowledge the fundamental contribution that the Dipartimento di Ingegneria Strutturale, Edile e Geotecnica (DISEG) and the company Geosolving srl have provided to this work.

4.1 Algorithm Optimization for Rockfalls Alarm System Based on Fiber Polarization Sensing

This section aims to provide a preliminary characterization of the LI optical fiber SOP-based detection system for a mountain scenario. As a starting point, we monitored a reduced-scale mountain gully where optical fibers have been buried, and generated small-scale events. The system we have in mind would deliver an immediate alarm, with delay times in the order of one second. In this way, a traffic light could turn red on a mountain road immediately after a rockfall or an avalanche, before it tramples the road, jeopardizing people's safety. Clearly, speed of detection is a key element. We thus tried to develop and optimize a detection algorithm which we tested on the experimental small-scale physical model. In the following subsections, we will

present a possible implementation and the related post-processing for the fiber-based alarm system relying on detecting anomalous polarization variations.

4.1.1 Small-scale experimental setup of the SOP-based detection system

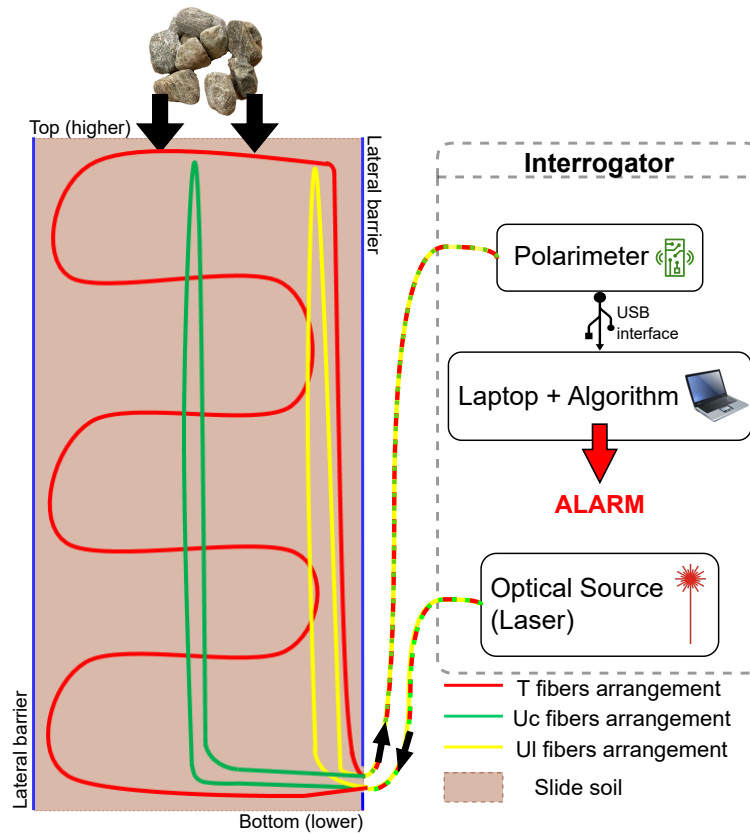


Fig. 4.1 Scheme of the monitoring system showing the T (red line), Uc (green line), and UI (yellow line) fibers configuration. The same layouts exist at different depths.

The experimental setup shown in Fig. 4.1 depicts both the tested ramp and the hardware. The monitoring site recreated in our laboratory is a scale model of the slope of a mountain [112]. Essentially, it is a ramp made of wood inclined by 30° , 0.7 meters wide and about 3 meters long. It has been filled with a mixture of sand and soil for a total thickness of about 10 cm. A CW laser (Fabry-Perot, centered

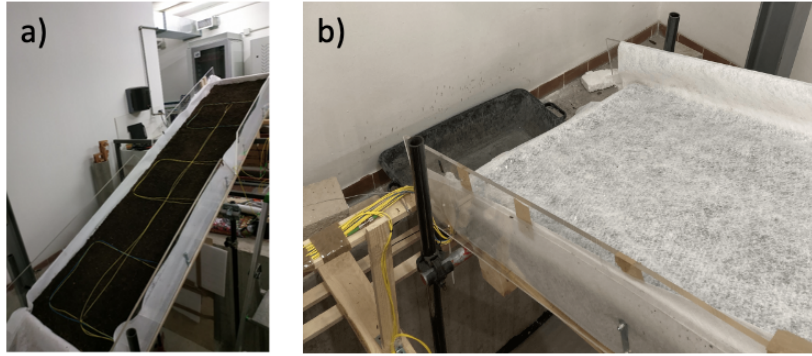


Fig. 4.2 a) Experimental model with no geotextile showing the most superficial (and not yet buried) fiber configuration, b) slide covered in geotextile.

at 1550 nm) emits a signal with 0 dBm optical power to the in-situ buried SSMF (red, green, or yellow line in Fig. 4.1). The output end of the fiber is connected to a polarimeter, the same commercial device we extensively used in Chapter 3, that allows for measuring the Stokes vector with a sampling frequency f_s . A USB cable connects this device to a computer, where the hardware parameters, such as the sampling frequency or the total acquisition time t_{tot} , can be set. A software running on a laptop then extracts the SOP samples from the polarimeter for further processing. Per fiber configuration, a total of three fibers have been deployed within the soil at 1 cm, 5 cm, and 9 cm from the surface. The T fibers configuration, in red in Fig. 4.1, is installed in a serpentine layout, with six transversal crossings of the slope longitudinal segment. We also conducted several experiments on other configurations installed longitudinally along the model: Uc fibers, in green in Fig. 4.1, and Ul fibers, in yellow in Fig. 4.1, are U-shaped and longitudinal along the slide, on the center and right lateral part of it, respectively. For each configuration (i.e., color), one should imagine the three fibers stacked at the three different depths. We underline that the fibers are all installed concurrently in the ramp soil, but only one layout at a time is “active”, i.e., connected to the interrogator in Fig. 4.1. This work will mainly focus on the T fibers only, but some final results will be shown for the others as well. Fig. 4.2a) depicts the most superficial T, Uc, and Ul displacement, without the 1 cm soil layer. A layer of geotextile material (see Fig. 4.2b)) encloses the soil and sand mixture to prevent the erosion caused by the repeated rockfall tests. To distinguish fibers of the same configuration buried at different depths, a convention has been adopted. The number “1” indicates the deepest at 9 cm from the surface, number “2” refers to the middle one at 5 cm, and number “3” is for the most superficial, at 1 cm

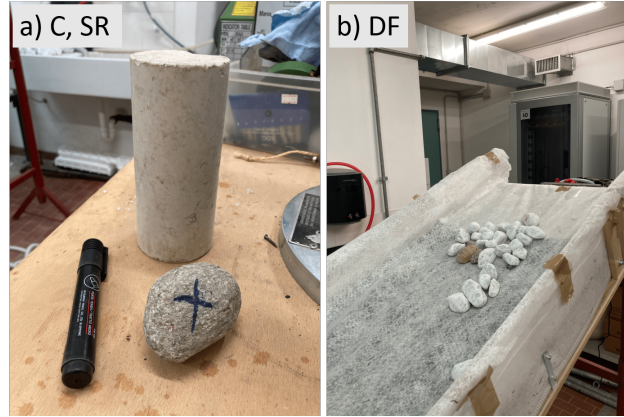


Fig. 4.3 a) Picture of the cylinder and the single rock used to generate C and SR events. b) Example of rockfalls event occurring on the slide.

depth. For instance, T1 is used to name the fiber installed at the larger depth (9 cm) with a T configuration. Three different types of events have been generated over the slope to emulate real, possibly dangerous, rockfall events.

- Single rock (SR): rolling of a 270 grams single rock as in Fig. 4.3a).
- Cylinder (C): rolling of a 890 grams test cylinder made of ceramic material, 15 cm long and with a diameter of 5 cm (see Fig. 4.3a)).
- Rockfall (RF): rolling of 25 rocks about 5 cm wide, each weighting 280 grams on average, as shown in Fig. 4.3b).

We also measured the background noise on SOP time evolution to study the occurrences of false alarms, as we will discuss in the following.

4.1.2 SOPAS algorithm for anomalous vibrations detection

The detection algorithm that we will discuss in this section (and also in the whole chapter) employs the state of polarization angular speed (namely, SOPAS) that we have introduced and discussed in detail in the previous chapter, Subsection 3.2.3. The specific SOPAS equation is in Eq. 3.3, a graphical explanation in Fig. 3.12a), and the block diagram in Fig. 3.12b). Specifically, in this case, the output $\Omega[n]$ of the smoothing filter is compared to the threshold ω_{th} to determine:

- **Alarm condition**, if $\Omega[n] \geq \omega_{th}$;

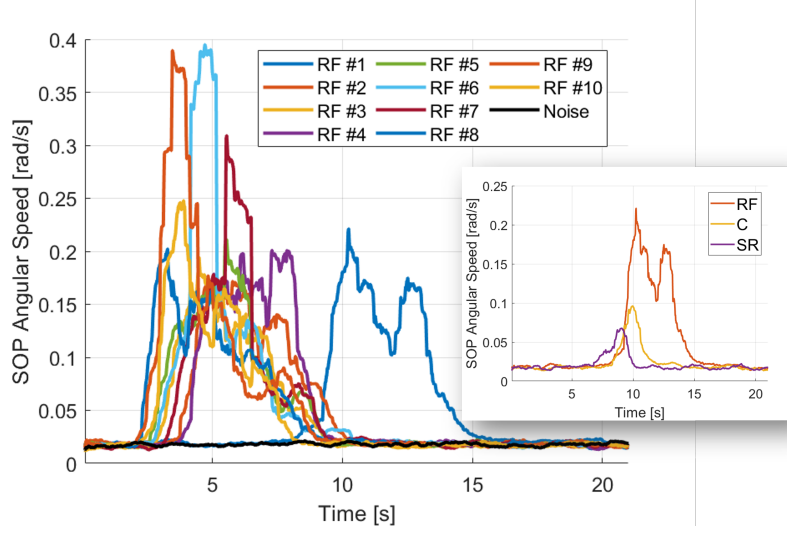


Fig. 4.4 Ten different runs of RF and one of background noise on fiber T3, represented with different colors. The inset shows an example of SOPAS traces for the three tested events. T_{mov} used is 1 second.

- **No-alarm condition**, if $\Omega[n] < \omega_{th}$.

The SOPAS traces have been smoothed through a moving average filter of length T_{mov} . Notice that in the previous chapter, the latter was expressed in samples $N_{avg,\Omega}$ (see Fig. 3.12): we preferred here to call it T_{mov} and express it in seconds. Both the ω_{th} and T_{mov} are key parameters of the detection algorithm, and will need careful discussion. The polarimeter is the source of the Stokes vector samples $\vec{S}[n]$ taken at discrete time instants n , for a recording time of t_{tot} seconds. The whole acquired trace has then been post-processed to compute the SOPAS time evolution. Fig. 4.4 shows the SOPAS time evolutions, when T_{mov} is set to one second, when no event is generated (in black), and for 10 RF event occurrences, measured through fiber T3 (the blue SOPAS trace has a ~ 5 seconds delay due to an erroneous starting of the RF roll during the experiments). The inset in Fig. 4.4 shows how the SOPAS evolves during events with different intensities, related to the size and weight of the items. The relationship between vibrations and SOP variation is, first of all, nonlinear, but it also depends on how the vibrations generated by the falling rocks couple to the underground fibers. This is thus hard to properly define, even though it is evident that a higher angular speed is produced by usually heavier events. In our specific experimental setup, RF is the most intense as it is composed of several rocks, SR is the weakest as it is generated only by a small rock, and C is in between as it is

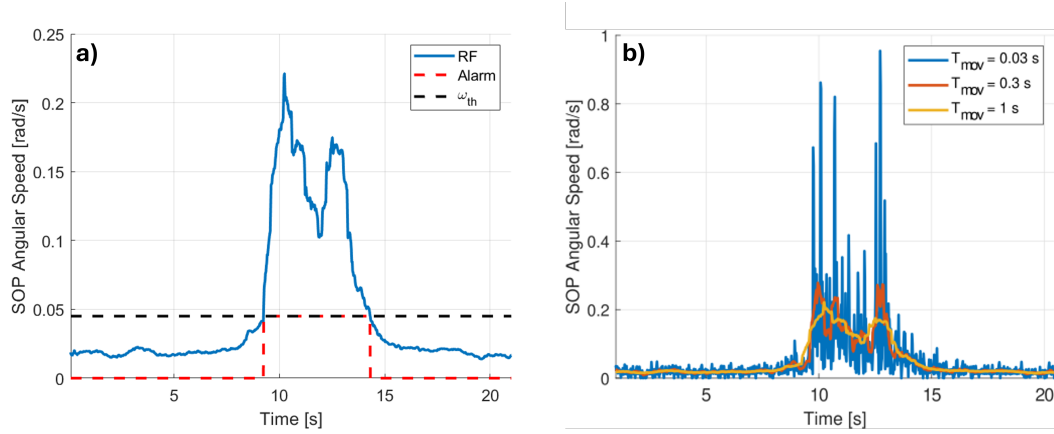


Fig. 4.5 a) Rockfalls SOPAS on fiber T3, ω_{th} and alarm signal using $T_{mov} = 1$ second. b) SOPAS time evolution of an RF event generated on T3 for different T_{mov} values.

generated by a cylinder bigger in size and weight than the single rock. As concerns the sampling speed, in our first experiments, we chose $f_s = 48.8$ kS/s and a total acquisition time $t_{tot} = 21.5$ seconds. Fig. 4.5a) shows one SOPAS trace for a single RF event measured on fiber T3, compared to a threshold $\omega_{th} = 0.045$ rad/s. The two-state alarm signal is also represented in red, and, in a real-world scenario, it could correspond to a traffic light turning red and/or send a message to a remote emergency control room. As any “binary” alarm system, its performance depends on the probability of the following three situations:

- **Missed detection (MD):** an anomalous event is not detected (threshold ω_{th} is thus too high).
- **False alarm (FA):** no event takes place, but the system generates an alarm (threshold is too low).
- **Correct detection (CD):** events are accurately detected in the SOPAS time evolution, with no FAs or MDs.

Ideally, our system should always be in the CD condition. The probability for the other two conditions to occur is minimized by appropriately choosing T_{mov} and ω_{th} : for increasing values of the averaging window, the oscillations in the original SOPAS evolution reduce, making the algorithm more robust. Peaks are also lower, requiring a lower threshold to be selected. If the threshold value is set too high without accounting for this effect, MD cases are likely to happen. On the other hand,

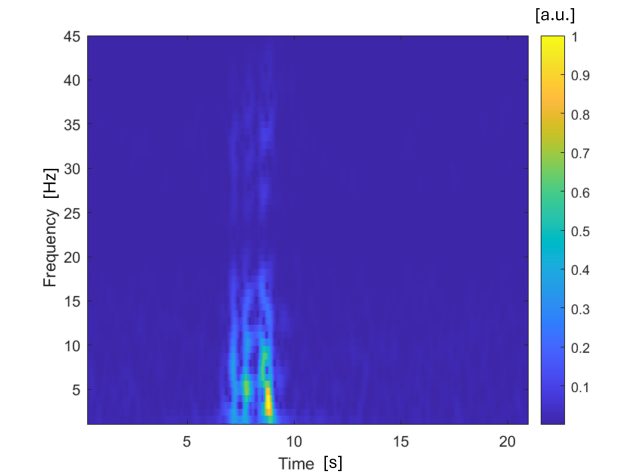


Fig. 4.6 SOPAS spectrogram of an RF event in linear, normalized to the maximum value.

a very low value of T_{mov} could enhance the noise oscillations and, if the threshold is set too small, trigger the alarm generating FAs. In Fig. 4.5b), the same SOPAS evolution of a) is reported for three different T_{mov} values, underlining the importance of a correct parameter choice. A reasonable choice of T_{mov} is also paramount since it determines the speed of reaction of our system. To a first approximation, the system latency is directly proportional to T_{mov} (plus the polarimeter and DSP internal delay in data transfer).

4.1.3 Experimental results and assessment of system performance

We focus here on the optimal parameter choice for the detection algorithm. For each fiber, we have generated 10 RF, 10 C, 10 SR events, and also acquired 3 steady state traces, for a total of 99 acquisitions per one fiber configuration (e.g., 33 for T1, 33 for T2, 33 for T3). Despite initially setting the sampling frequency to several tens of kS/s, the actual f_s needed is much lower for mechanical, especially natural, events. This has been shown in Chapter 3, even if mainly for other scenarios. The typical frequency content of a SOPAS trace during one of the generated anomalous events is given in Fig. 4.6 as a time-frequency spectrogram, normalized with respect to its maximum value. Most of the spectral content is below 10 Hz, as it is typical for these kinds of mechanical vibration events on the terrain. A more detailed analysis, which further confirms this point, is in [113].

For the following parts of this section, we then reduced the sampling frequency

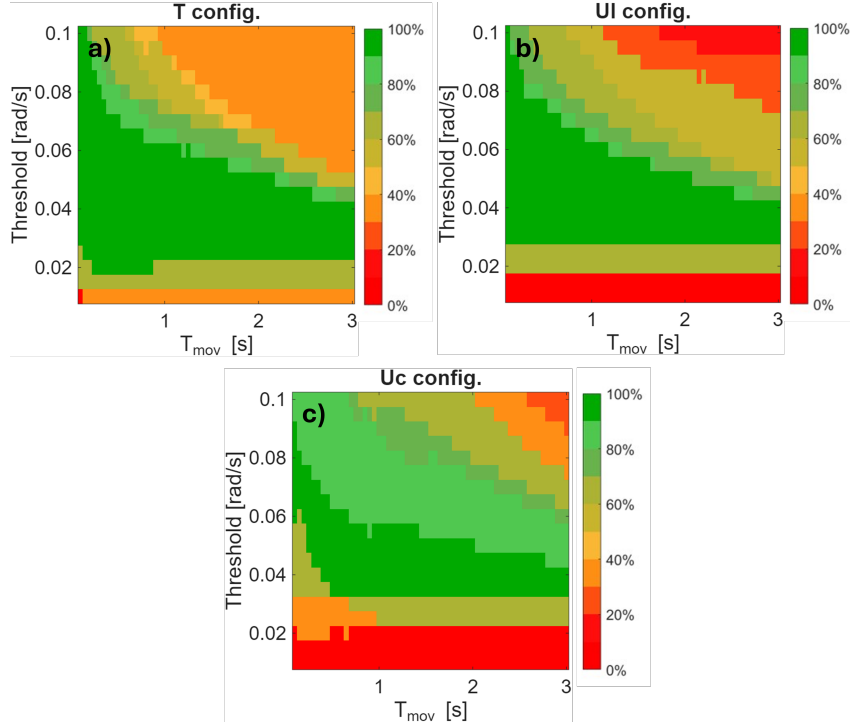


Fig. 4.7 Detection maps for a) T configuration, b) Uc configuration, c) UI configuration.

down to $f_s = 95.4$ S/s, which happens to be the lowest one enabled by the polarimeter: this is very important, since it goes in the direction of reducing the computational effort. For instance, $f_s = 95.4$ S/s would allow the use of extremely low-cost analog-to-digital converters (ADC) and DSP processing boards. Regarding the polarimeter, although the one used for this work is quite expensive (about 12k€), potentially allowing extremely high sampling frequency, lower cost instruments (<5k€) with sampling rates in the 100 S/s range are also available on the market.

The output of the post-processing analysis is a two-dimensional color map showing, for each parameter pair $[T_{mov}, \text{threshold } \omega_{th}]$, whether the algorithm works in CD mode. We call these “detection maps”, and they are shown in Fig. 4.7. The T_{mov} range has been kept smaller than 3 seconds to avoid a larger detection delay. We remind that, for each hazard, we generated 10 repetitions, per fiber depth, for each configuration. The resulting smoothed SOPAS traces are then compared against different thresholds ω_{th} , and classified as follows:

- if, for a single event occurrence, the SOPAS has at least one sample above threshold and all the samples of the noise are always below threshold, we are in a CD condition.

- if at least one sample of the noise is above threshold, we are in a FA condition.
- if all the samples of the SOPAS evolution for one event occurrence are below the threshold, we are in the MD condition.

Fig. 4.7 shows the overall detection maps for all the fiber configurations, considering also the three different depths (e.g., the title “T config.” considers the cumulated T1, T2, T3). In a real-life installation, it is basically impossible to ensure a constant depth of the fibers for the whole gully length, due to the terrain not being homogeneous, which is why we considered all of them. The colorbar indicates in this case the percentage of events in CD over the total number of generated events. The maps in Fig. 4.7 demonstrate reduced sensitivity to the events for the Uc and Ul configurations, in Figs. 4.7b) and c), with respect to the T configuration in Fig. 4.7a). The detection map obtained for the latter has a larger green (i.e., 100% CD occurrences) area with respect to the former. This is probably because Uc and Ul configurations are dependent on where the event develops when falling from the top (see Fig. 4.1), while, instead, this is less important for the T configuration, which crosses the whole ramp in both left/right directions. Nevertheless, for all three configurations, there is always a green area where the system always delivers correct detection in the experimental scenario.

4.1.4 Localization using spatially separated fibers

The above subsection demonstrated that by properly setting the two main parameters of the algorithm, our system can be optimized to detect hazardous events in the small-scale setup. However, the proposed single-fiber system may be prone to false alarms if occasional non-dangerous events (e.g., animals walking in the area or a tree falling) occur in the vicinity of the fiber, and it cannot localize events along the slope. We then sought to improve the setup by deploying two fibers at different positions within the gully, buried at 5 cm depth. As shown in Fig. 4.8, they are separated by ~ 2 meters, one at the top of the ramp, the other at the bottom. The interrogator is the same as the one in Fig. 4.1, with some additions. The optical signal was split at the laser output. At the polarimeter input, an optical switch was used to alternately select each of the two fiber outputs, with a switching period of 5 ms and rise/fall times of ~ 0.5 ms. The polarimeter was set to sample around 6 kS/s, to obtain a few tens of Stokes vector samples inside each switching period, per

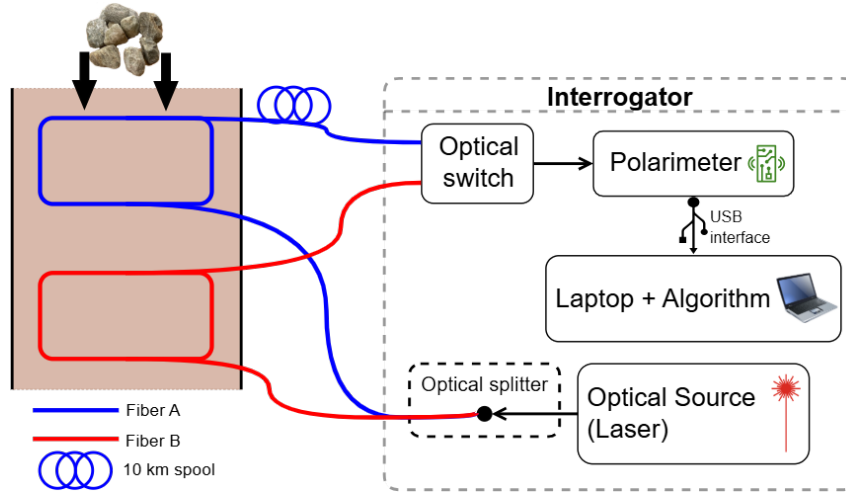


Fig. 4.8 Experimental setup of the two-fibers system. The blue line represents Fiber A (with highlighted 10 km spool), while the red line represents fiber B.

fiber. We then averaged them: in this way, we measured the SOP on each fiber with nearly the same f_s of the previous single-fiber system configuration, i.e., $f_s \sim 100$ S/s per fiber, simultaneously. This approach has been adopted to test the working principle of the idea, allowing us to neglect any synchronization issues, also due to the non-negligible rise/fall times, which could be relevant when using a lower sampling speed (e.g., potentially the minimum one would correspond to the inverse of half the switching period, ~ 200 S/s). To test the performance of the system on even longer fibers (e.g., possibly over wider monitored areas, or a remotely located interrogator), we also inserted a 10 km spool of SMF on one of the two optical signal paths. The inset of Fig. 4.9 shows the SOPAS evolution on the two fibers when an SR event was generated. It can be noticed that the SOPAS traces have a relative delay of around 1.5 seconds, which is approximately the time that the rock takes to roll down between the two fibers. Fig. 4.9 shows the normalized SOPAS cross-correlation for five different SR events, and their centroids around the peak (red dots): the τ -axis coordinate of these points corresponds to the delay estimate between the two SOPAS traces. All of them produce a cross-correlation centroid at about 1.5 seconds delay, consistent with the SOPAS evolution. The centroid of the cross-correlation curve in the five cases is reported in the table in Fig. 4.9b), confirming an average estimated delay of 1.48 seconds between the two fibers and slight variations due to the different shapes of the used rocks and, consequently, their falling speed. The use of two (or possibly more) geographically separated fibers

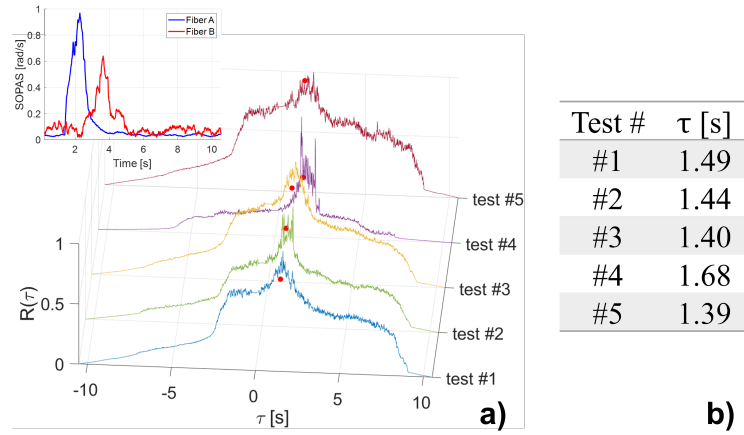


Fig. 4.9 a) Cross-correlation curves and centroids (red dots) between SOPAS on fiber A and B for five SR events. The inset shows the SOPAS curves for one of the five SR events. b) Table of delays τ of the five cross-correlation curves.

could greatly reduce false alarms by allowing activation of the alert only when an above-threshold SOPAS is detected on both fibers. Moreover, the system would be able to estimate the dynamics of the events by providing a rough estimate of the rockfall time and speed. Rough localization can also be provided.

4.1.5 Discussions and conclusions

We discussed above the detection performances of a SOP-based mountain monitoring system, which should be able to deliver alarms when a hazardous event (debris flow, rockfall, or any flowing mass in general) occurs. Compared to a real installation (e.g., on a mountain gully), the SOPAS traces obtained on the small-scale model are less noisy, but the anomalous events that we were able to generate are also weaker than in a real mountain environment. We envision that f_s around 100 S/s and T_{mov} of a few seconds, could approximately remain the same also in a real environment. The chosen f_s allows for the detection of anomalies whose spectral content is limited to a few tens of Hz, as for the events of interest in our case. Moreover, we experimentally verified that the tested averaging window values work for a whole range of weak and intense events.

Our experiments also verified that the T fiber configuration is the most efficient layout since it provides the best detection performance. The serpentine shape probably makes the system independent of the evolution of the event, which could

sometimes be localized only in a specific side of the ramp (e.g., SR or C mainly rolling on the left/right side) and explains the worse sensitivity of Uc and Ul fibers.

The setting of ω_{th} is the most crucial, since it depends on many factors. The most important are listed below.

- Depth at which the fibers are deployed underground. In this section, we didn't discuss this point further, as in a real application, fiber depth will most certainly change along the gully. Further analysis is needed to better investigate this point, mostly related to a real-life scenario.
- Position of the fibers (for instance, in the center of a gully or slightly on its side). Even if we demonstrated that the T configuration is the most sensitive, the specific morphology of a real-life gully could prevent us from employing it.
- Strength of the anomalous events/noise level. This should be tested in a real environment.

Moreover, landslides, rockfalls, and debris flows are often erosive phenomena. Erosion, entrainment, and deposition processes result in crucial changes of local material compositions, properties, and flow dynamics, including the flow depth, speed, and mobility [114]. In these complex yet realistic situations, the performance of the proposed system should also be evaluated.

In a real installation, the probability of false alarms can be high since spurious events (animals or people crossing the fibers, for example) would commonly occur, and a threshold-based algorithm, although made adaptive, would likely sense them. As we have shown, this can be mitigated by monitoring in parallel more than one fiber by means, for example, of an optical switch, and activating the alarm only if ω_{th} is exceeded by all of them. Anomalous events are usually spatially diffused and would surely be detected by more than one fiber, whereas spurious events are usually localized and would be sensed by only one of them. The double-fibers configuration also demonstrated the ability to provide for a reliable estimate of the speed of the events tested in the laboratory, which could be connected to the hazard level of the event. Multiple fibers could also be used to monitor different portions of the gully, allowing rough localization capabilities, which the system wouldn't have otherwise. Machine learning algorithms [115–117] can also be used to distinguish between

steady state and hazardous conditions, and can also enable event type classification: a much larger in-situ data collection is needed for this purpose.

4.2 Polarization-Based Fiber Optic System for Debris Flow Early Warning: On-Field Demonstration

We extend here the analysis of the monitoring system proposed above, with on-field experiments performed over a mountain gully, to test in a real environment the detection algorithm which we previously studied only on a reduced-scale laboratory model. We displaced several fibers along a mountain gully and connected them to a SOP interrogator. We then emulated the downhill fall of some heavy material and showed that by properly setting the algorithm's main parameters, the normal/threatening conditions can be properly identified, thus demonstrating a promising, realistic application of our sensing method. We focus on the validation of our approach in normal conditions when vehicles, passers-by, and animal wildlife could produce false alarms and thus reduce the reliability of the threat detection system.

4.2.1 On-field setup

The test site selected for this work is a mountain gully in Cogne, Valle d'Aosta, Italy, depicted in Fig. 4.10. One cable containing a bundle of 24 SMF has been installed along a roadway approximately half a meter underground, in the same housing used for the common power line (underground fiber cable in Fig. 4.10a)). Access to the cable is granted by two manholes, #1 and #2 in Fig. 4.10. The interrogator hardware remains unchanged compared to the laboratory version shown in Fig. 4.1. The only difference is that the fibers are now utilized for sensing events along a real gully: the green fiber in Fig. 4.10a) is the one subject to dangerous events and, through the underground fiber cable, connects to the interrogator, which processes the SOP delivering, if necessary, alarms. We should mention that this is an active gully, where debris flows happen more or less once per year. As shown in Fig. 4.10a) and Fig. 4.10b), the roadway is in a particularly dangerous location at the bottom of the gully, at about 30 m from the depicted red line. This is a fundamental aspect of this work, since a flowing mass event would hit the road and be potentially extremely

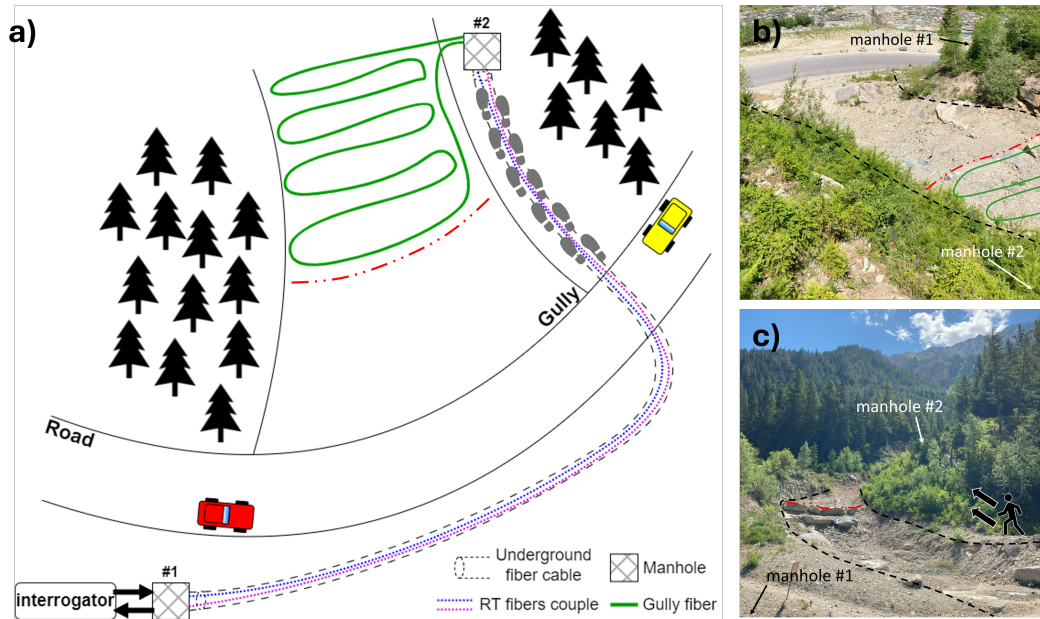


Fig. 4.10 a) Schematic representation of the monitored site with fiber layout. b) View of the gully from manhole #2 and c) from manhole #1. The dashed blue and violet lines are the fibers selected for the round-trip, contained inside the black dashed cylinder representing the underground cable. The green line shows the fiber configuration on the surface. Footsteps indicate a semi-exposed portion of the cable in a passageway in the woods. The red line shows the bottom limit of the fiber installation. The black dotted lines in b) and c) show the lateral edges of the gully.

dangerous for cars and people in the area. A signaling system (e.g., a traffic light, as mentioned in the previous section) should then restrict access to the dangerous area after detecting the threat. On the other hand, at specific times of the year, this area is very populated: bikers, hikers, or cars could generate spurious events in proximity to the fibers, possibly causing false alarms. As shown in Fig. 4.10b) and Fig. 4.10c), the underground fiber cable path crosses the road and reaches manhole #2 through a walkway (footsteps), where it runs inside a corrugated hose that is only partially buried and is thus semi-exposed.

As mentioned above, the gully fiber, in green in Fig. 4.10a) and Fig. 4.10b), is the actual sensing-dedicated portion of the whole fiber path, as it is laid out over the area where real hazards can occur. Unlike Section 4.1, we did not bury it underground, in order to analyze the worst noise conditions, as the sensor is completely exposed to any surrounding environmental agent. We define noise as the small SOP variations that occur when the fiber is completely at rest, i.e., in normal conditions, and environment-induced noise as the SOP variations due to

environmental effects such as road traffic, weather conditions (e.g. wind, rain), people, and animals walking in the vicinity of the fiber, and all other effects that can occur during a normal day but are not related to dangerous events and should not trigger an alarm. The gully fiber is connected to two of the 24 fibers inside the cable at the manhole #2. The fiber pair connects the interrogator in Fig. 4.10a) with the fiber in the gully in a round-trip configuration, and will thus be referred to as round-trip (RT) fiber pair. The selected RT fibers are highlighted in Fig. 4.10a) as blue and violet dashed lines.

The gully fiber is arranged in an S-shaped configuration (i.e., laid in a serpentine pattern) as already tested in Section 4.1. Notice that this fiber layout has been chosen as a consequence of the T fiber studied above, which delivered the highest sensitivity (see Fig. 4.7). Experiments considering gully fiber lengths of 40 m and 80 m have been carried out and will be presented in the following subsections. The underground cable is about 200 m long, for a total RT fiber length of 400 m. The whole fiber length is then approximately 440 m and 480 m when the gully fiber is connected, respectively. This configuration has been chosen to emulate a situation where the interrogator is placed in a secure location, such as a street cabinet, that can be far from the monitoring site.

The interrogator is connected to the RT fibers at manhole #1 location. The optical source is a low-cost (a few hundred €) CW Fabry-Perot laser emitting light at 1550 nm into one of the RT fibers, identical to the one employed in the previous section. In a loopback kind of configuration, the optical signal travels to manhole #2, through the gully fiber (when connected), and then back to the interrogator through the second RT fiber, where it is collected by the same polarimeter (Novoptel PM1000) used in section 4.1 (see Fig. 4.1). A low sampling frequency $f_s = 95.4$ S/s proved to be sufficient for our purposes, due to the low frequency content associated with real-life natural mechanical events [113].

4.2.2 Environment-induced noise analysis

The effects that the natural environment has on the fiber and, therefore, on the detection capabilities of the proposed system need to be well characterized to fully understand its level of reliability in an on-field scenario on a real mountain slope. Results shown in this and the following subsections are obtained by analyzing the SOPAS, as discussed in the section above, when setting a $T_{mov} = 1$ second.

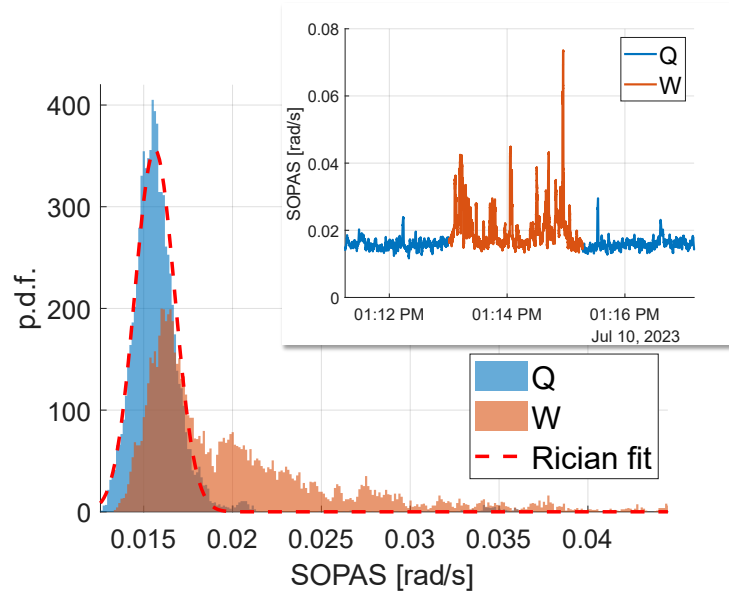


Fig. 4.11 Distribution of SOPAS samples for the walking (W) and quiet (Q) case, normalized to show probability density functions. The red-dashed line shows the theoretical Rician pdf fit on the Q distribution. The inset shows the corresponding SOPAS evolution in time.

To characterize in detail the effect of environmental noise on the system, different configurations are considered. First, we focus on the characterization of the noise level, considering only the RT fiber couple inside the cable. In this first analysis, the gully fiber is not connected, and the loop is closed at the manhole #2 location through a patch cord connecting the two RT fibers. In this configuration, we also tested our algorithm in a somewhat critical situation where anomalous vibrations can be generated by animals, hikers, or bikers stepping over the semi-exposed fiber segment installed on the side of the gully up to manhole #2, in an area where the hazard would not be sensed, and no other events should generate a false alarm (walking steps in Fig. 4.10a)). The results are shown in Fig. 4.11 as a comparison between the condition where we introduced SOP perturbations by walking on the fiber (W) and the quiet state (Q) without walking. The two histograms display the distribution of SOPAS samples acquired over 2 minutes (corresponding to the time spent walking over the fiber) and are normalized to obtain a probability density function. For the Q distribution, a fit with the theoretical Rician probability density function is provided, showing good correspondence. Since the SOPAS intensity is higher when the effect of walking on the fiber is present, the corresponding distribution is slightly more spread on the x -axis. Nevertheless, the two pdfs overlap

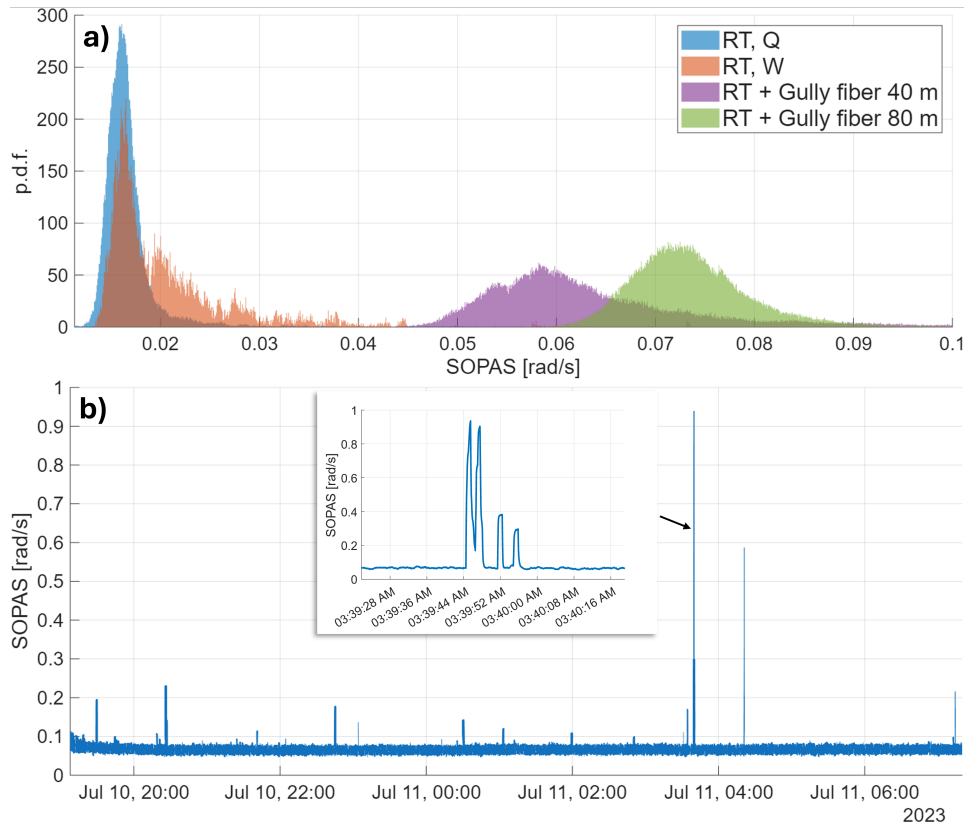


Fig. 4.12 a) Distribution of SOPAS samples in the walking (orange) and quiet (blue) case with RT fibers only, in the quiet state with 40 m gully fiber (purple), and in the quiet state with 80 m gully fiber (green). b) SOPAS time evolution over 12 hours in the configuration with 80 m gully fiber.

for the most part, showing that the generated perturbations are relatively small. Moreover, as it will become clear in the next subsection, the intensity shown in Fig. 4.11 is much smaller than that of mass transport phenomena and can be easily disregarded by setting a proper alarm threshold on the SOPAS.

The configuration with only the RT fiber is discussed as a baseline since it is not significant in the aim to detect anomalous conditions occurring over the gully. We now introduce the more relevant cases where a segment of SSMF is added to the underground portion and deployed on the surface of the gully. This is the actual portion dedicated to the sensing of potentially dangerous rockfall events. We deployed a 40 m and then an 80 m long piece of fiber in the gully. Fig. 4.12a) shows the distributions of the SOPAS samples acquired in the configurations with the added gully fibers, and compares them to the distributions shown in Fig. 4.11 for the RT fiber only. Please note that all the distributions refer to SOPAS acquisitions over 20

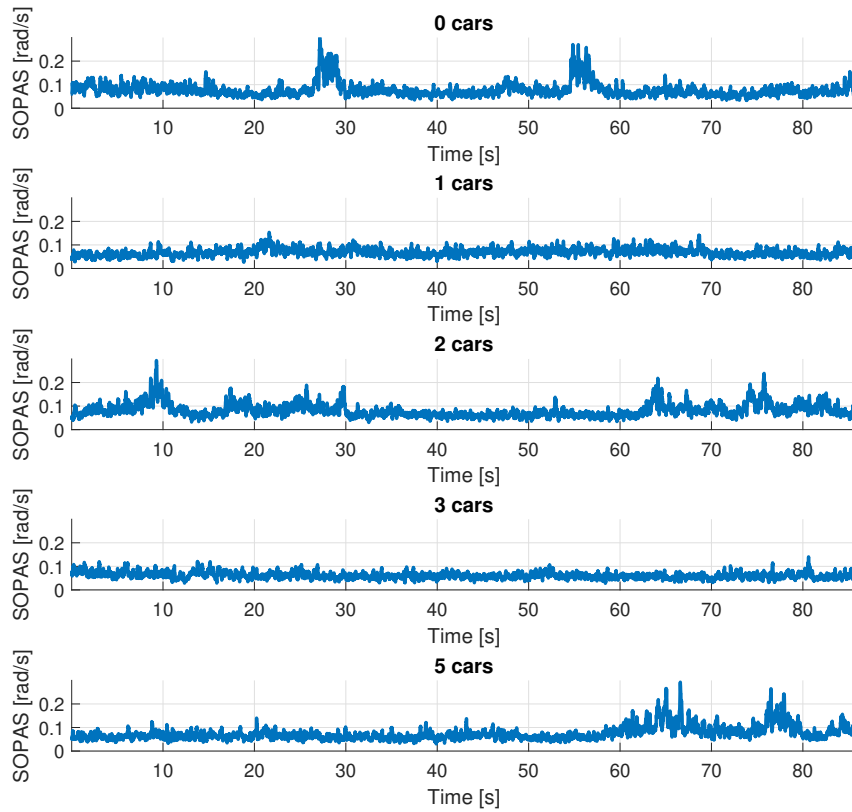


Fig. 4.13 SOPAS traces acquired during the crossing of RT fibers of 0, 1, 2, 3, 5 vehicles. The fiber configuration considers the 40 m gully fiber.

minutes except that for the walking case (orange histogram), which lasted 2 minutes only. The RT fibers are buried, thus well isolated from external agents that may affect the SOP. This explains why the blue (RT, Q) distribution is well separated from the purple (RT + Gully fiber 40 m) and green (RT + Gully fiber 80 m) ones, which instead refer to the addition of gully fibers, completely exposed to the mountain environment. The mean value of the SOPAS increases with the fiber length, showing that the amount of noise rises slightly when a longer fiber is deployed, as a longer portion is exposed to external events. In our on-field test, this effect is partly due to the fact that the sensing fiber is laid onto the gully surface without being secured, and, therefore, additional effects due to the weather (e.g., wind) or ground topology can contribute to the overall noise floor. Nevertheless, we have examined the behavior of the system with the longer fiber in the gully over several hours, thus characterizing the inherent noise level of the configuration with 80 m SSMF. Fig. 4.12b) shows the 12 hour overnight evolution of the SOPAS, highlighting a consistent average value of around 0.07 rad/s. It shows also some spurious peaks with a duration of 1-2 seconds

and intensity comparable, for the majority of them, to the walking case shown in the inset of Fig. 4.11.

Another possible source of false alarms could be related to vehicles driving across the RT fibers installed underground, perpendicular to the traffic direction. Works such as [41, 40] have shown the effect of low-frequency vibrations, mainly in the range from 3 to 20 Hz, induced on underground metropolitan fibers by moving vehicles, to which DAS systems are particularly sensitive. We characterized the effect of traffic on the SOPAS in the configuration with 40 m gully fiber added to the RT fibers. Fig. 4.13 shows the acquired SOPAS traces processed with a moving average window, only for this case, of 0.1 s duration for different numbers of vehicles driving by on the road. In all five cases, there is no significant evidence of SOP variation due to traffic, confirming that the installation is robust and the system would not respond with wrong detection alarms to everyday conditions.

4.2.3 Anomalous events detection analysis

We move here from the characterization of the normal operating conditions of our installed monitoring system to the on-field measurements of anomalous events. As we are not able to generate realistic mass transport events, we emulated the stresses associated with solid material hitting the fiber by releasing several types of balls from the top and letting them roll on the 40 m gully fiber. Specifically, we launched 6 small spheres (750 grams, about 7 cm in diameter) and a larger one (a 3 kg medical ball, 19 cm in diameter). Please note that this methodology was not intended to mimic real catastrophic rockfall episodes, but rather to emulate out-of-the-ordinary situations, and was selected to calibrate the system and demonstrate that, given the great difference between normal conditions and exceptional circumstances, through proper setting of the algorithm parameters, false alarms can be reasonably prevented. The situations that will be discussed are pessimistic in terms of intensity if compared to a real flowing mass event occurring over the gully, which would be much more intense and also longer in time. In the following two paragraphs, we will discuss the system detection capabilities when monitoring one fiber only or two fibers simultaneously.

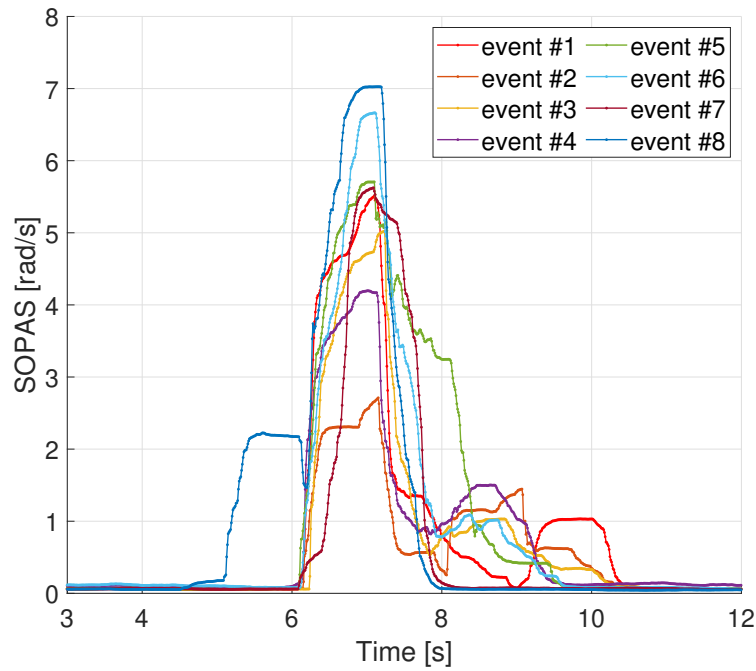


Fig. 4.14 Eight different SOPAS traces associated with out-of-the-ordinary events generated over the 40 m long gully fiber.

Single fiber configuration

The aforementioned events were generated on the configuration with the 40 m gully fiber. The SOPAS traces of eight events are reported in Fig. 4.14. On average, the SOPAS peak values are between 3 rad/s and 7 rad/s, two orders of magnitude higher than the mean values shown in Fig. 4.12a) for the 40 m (0.047 rad/s) and 80 m (0.071 rad/s) gully fiber added to the RT pair. Realistically, we can assume that actual debris flows generate even higher SOPAS; thus, these results suggest that the proposed system can be operated to produce only correct detection without any false alarm or missed detection.

In a scenario where actual flowing masses strike the fibers displaced on the gully surface, it's reasonable to assume that not only is their intensity higher than that shown in Fig. 4.14, but also their duration is much longer than the 2-3 seconds of the events that we were able to generate. Thus, by also monitoring the event duration, whenever an above-threshold condition is detected, it would be possible to further distinguish between real flowing masses and non-dangerous events generated spuriously. An example is represented by the two highest SOPAS spikes in Fig. 4.12b). The peak angular speed in these two cases, although much lower than

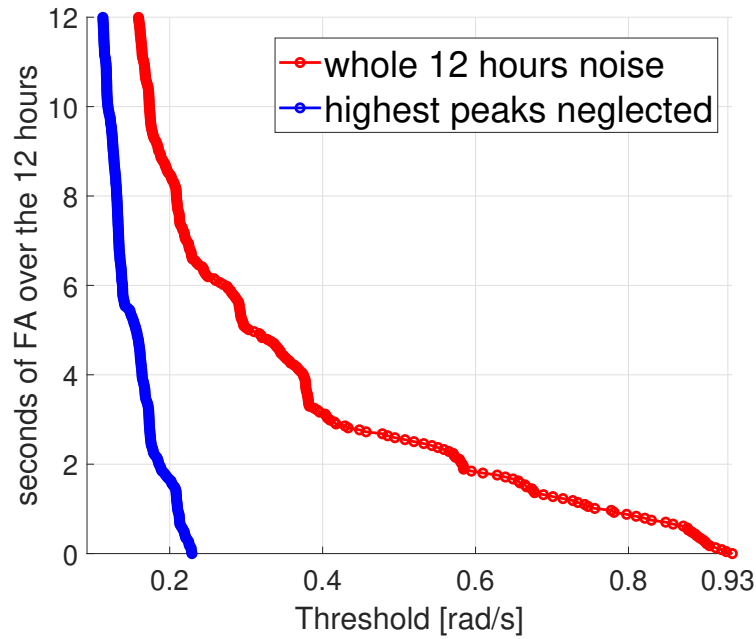


Fig. 4.15 Seconds of FA over the 12 hours SOPAS acquisition as a function of the threshold value. The red curve has been obtained considering the whole 80 m fiber overnight acquisition, the blue one has been obtained neglecting the two highest spurious spikes.

what we expect in realistic hazardous phenomena, is comparable to some of the peak values in Fig. 4.14. Nevertheless, these spurious noise spikes have a limited duration, about 2 seconds each, a completely different time scale if compared to true debris flow events, whose duration is in the order of tens of seconds [118]. In this context, considering the 12-hour acquisition in Fig. 4.12b), the red curve in Fig. 4.15 shows the total duration of FA alarms, i.e., the total time that SOPAS samples have been above the threshold, versus selected threshold. The upper x -axis limit is set to 0.93 rad/s, which is the highest value of SOPAS during the night acquisition. The red curve depicts an interesting scenario for the detection system, since even for thresholds one order of magnitude smaller (0.4 to 0.6 rad/s) than the SOPAS peak values associated with the events in Fig. 4.14, the system would deliver about 2 to 3 seconds of FA in 12 hours, meaning that spurious noise peaks can be easily disregarded by fixing a time-duration threshold around 2 seconds. Moreover, the two noise spikes measured overnight, might not be related to actual events but to the specific limitations of our experimental setup (e.g., gully fiber not properly deployed), which would be minimized in a real installation. By neglecting the two peaks, the blue curve in Fig. 4.15 is obtained. In this case, all the threshold values above 0.23 rad/s will not produce any FA, allowing for a more robust detection.

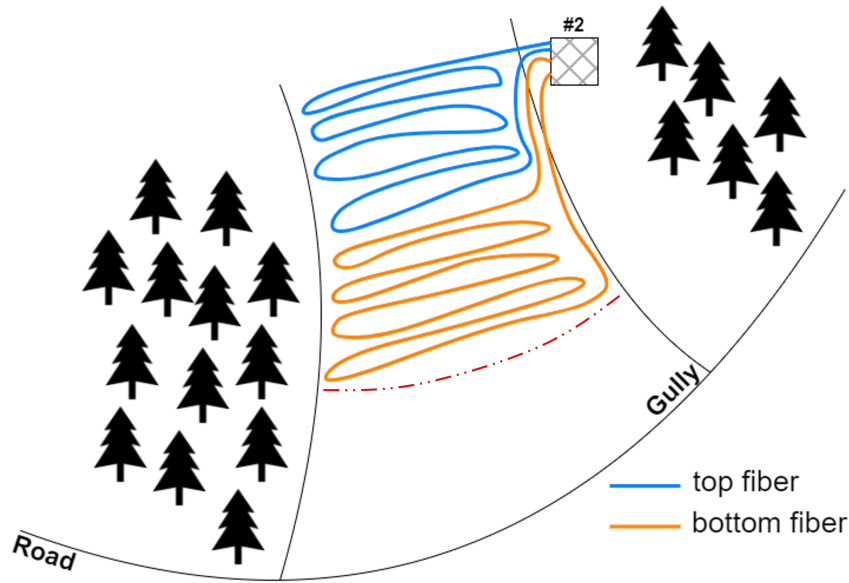


Fig. 4.16 Two-fiber detection system setup showing the top (blue) and the bottom (orange) fiber.

Generally speaking, employing a time-duration threshold increases the detection time by a delay equal to the threshold value. If an alarm generated for monitoring gullies is delayed by about 2 seconds, it would not be critically harmful. Gullies can be several hundred meters long, and the gully fibers can be moved further uphill to compensate for it, if needed.

A potential approach for establishing operating thresholds would first involve acquiring the SOP data over an extended timeframe (weeks, months) to ensure greater statistical relevance, and subsequently repeating the analysis discussed above. The red curve depicted in Fig. 4.15 would be generated again, allowing for the determination of an acceptable total duration of false alarms over the entire acquisition period. The duration-time and SOPAS thresholds could then be applied accordingly. Furthermore, to account for the possibility of fiber damage occurring as a result of massive events, a straightforward enhancement to the algorithm, such as monitoring the $S_0[n]$ parameter associated with the received power, can enable the detection of fiber cuts.

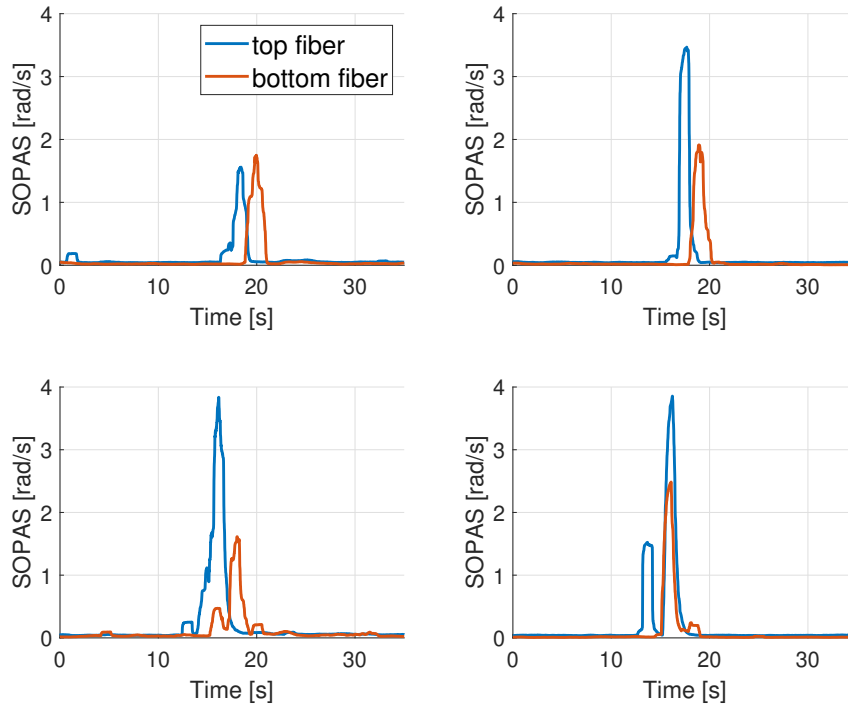


Fig. 4.17 SOPAS measured during four different launches in the two-fiber configuration.

Two-fiber detection system

Since our proposed system is LI, information on SOP variation can be obtained only at the fiber output, and the perturbations in each point of the fiber are integrated over its entire length; thus, event localization cannot be implemented. However, in the previous section, we discussed a multi-fiber configuration of our system as a possible solution for simultaneously improving the spatial resolution and reducing the probability of false alarms. Monitoring several different fibers deployed in different portions of the site enables a rough estimation of the position of the detected event, and it allows alarm triggering only when it has been detected in more than one portion. As shown in the previous section, the system can also be made more cost-effective by using an optical switch to sequentially interrogate the different fibers, which would allow for the use of a single polarimeter. However, in this first validation of the multi-fiber configuration, we added an optical splitter at the laser output and deployed two SSMFs, each 40 meters long, connected to two dedicated polarimeters with a synchronized time base. The fibers' layout on the gully is depicted in Fig. 4.16. Similar SOPAS measurements as in the previous paragraph have been carried out during the fall of the same 6 small and 1 larger spherical masses. Four SOPAS

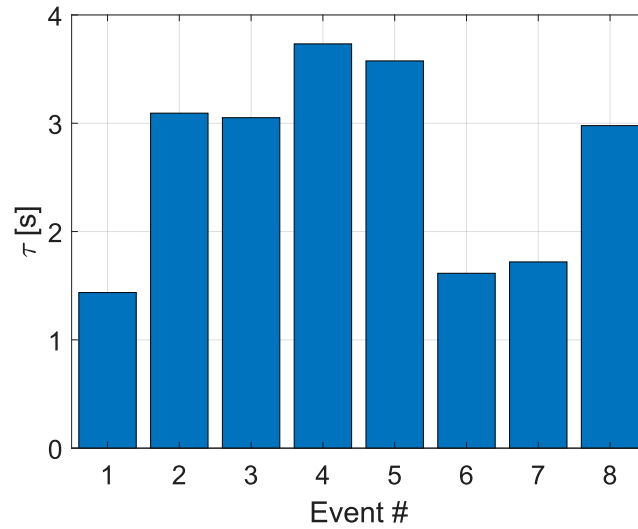


Fig. 4.18 Bar plot showing on the y-axis the delays computed by means of cross-correlation in between the SOPAS traces acquired on the two fibers. The related events are identified just as numbers on the x-axis.

traces are shown in Fig. 4.17 for four different events. As the two portions of the gully monitored by the two fibers are displaced by a few meters, the SOPAS time evolution shows two different peaks a few seconds apart. The first peak shows a clear detection of the event on the top (blue) fiber, whereas the second peak shows that the emulated mass transport event has moved downhill onto the second fiber. The overall system performance, in terms of false alarm reduction, can be greatly improved by generating an alarm only when the SOPAS falls above the threshold on both fibers. Moreover, the angular speed peaks are always delayed by an amount of time that depends on the known distance between the two fibers (about one to two seconds in our experiment), thus an estimate of the speed of the sensed event can be obtained by computing the cross-correlation between the two measured SOPAS traces. The results concerning the time-delay estimate τ of the same event occurring on the two fibers are shown in Fig. 4.18, where eight repetitions have been considered. The numbers obtained for τ are coherent with what has been observed when performing the experiments, delivering estimates ranging from 1.44 to 3.58 seconds. Values inside this range depend both on the actual speed of the masses and on where they actually hit the fiber. Considering an average distance of two to three meters between the point where the masses touch the first fiber and the second, the mean speed values would be around 0.8 and 1.3 m/s, similar to a walking person's velocity,

which is reasonable. By adding more monitored fibers in the same space, or just better displacing two so that the space uncertainty is reduced, the τ estimate accuracy would be enhanced. False alarm probability, by means of a proper algorithm, would be further reduced in this scenario.

4.2.4 Discussions and conclusions

This section presents an experimental on-field demonstration of a realistic polarization-based optical fiber sensing system, for the early warning of potentially dangerous mass transport phenomena in mountain scenarios. The system has been characterized under different configurations and operating conditions. First, we ensured that the section of installed fiber used to connect the interrogator to the monitoring site would not, in normal conditions, cause false alarms due to ordinary events such as vehicular traffic or people and animals passing by. We characterized the SOP angular speed evolution in time, showing that a low SOPAS level can be maintained also for long observation times and for all the tested fiber layout configurations, including a sensing fiber up to 80 m long. The system proved to be sensitive to common circumstances such as walking over a semi-exposed section of the fiber cable, but we also showed that resulting SOPAS levels are well below what can be reasonably expected to be the effect of intense debris flows on the SOP variation.

Moreover, we have emulated rockfall events by dropping a set of spherical masses from the top of the gully and let them roll over a sensing fiber 40 m long. Our findings show that the generated SOPAS peaks are about two orders of magnitude higher than the average noise level measured for both 40 m and 80 m long fibers, thus confirming that a threshold-based algorithm can efficiently distinguish regular operating conditions from hazardous events that would result in much higher SOP variations and longer duration time than those that we were able to induce in our experiments.

Lastly, we implemented a two-fiber solution to demonstrate the potential for improved system performance in terms of robustness to false alarms. We again emulated rockfalls on the gully where two fibers were deployed in two different areas. By using one polarimeter for each of the fiber we were able to detect the same rockfall occurrence on the two fibers separately. This would allow triggering an alarm only when the event is detected, also on the second (bottom) fiber, thus further reducing the probability of false alarms. Furthermore, this study further

opens the way for an even more efficient solution where more than two fibers are monitored by the same polarimeter, thanks to a low-cost (hundreds of €) optical switch at the polarimeter input. This configuration enables a rough estimation of the event location when the fibers are installed in different portions of the same site, or a considerable cost reduction when different fibers are used to monitor different sites with the same hardware components.

The fibers' configuration tested in this section was a worst-case for the characterization of the background noise and could be subject to serious damage in the case of a rockfall event. We envision that a future development of this sensing system should probably employ buried fiber cables over the gully, so that environmental noise can be further reduced, without really affecting the sensitivity to real events, which would be much more intense than small masses rolling over the site, which we used in our experiments. Another option can be to install the fiber longitudinally along the mountain slope at the cost of maybe reduced sensitivity (see Section 4.1), to prevent damage due to massive debris flowing along the center of the gully. Moreover, the whole fiber can be divided into different shorter spans joined together through fiber connectors and alternated with fiber sections crossing the gully transversally to improve detection. Using this configuration, a flowing mass might only affect portions of the fiber and not the whole installation. One or a few fiber spans only would need to be replaced, thus reducing re-installation efforts and costs.

4.3 Experimental Characterization of a Deployed Early-Warning System for SOP-Based Monitoring of Debris Flows in Mountain Scenarios

After having analyzed the SOP-based detection system in a somewhat ideal and isolated laboratory condition (Section 4.1), and then discussed a first approach, scaling to a real world scenario (Section 4.2), we had the chance to collaborate with another company for the development of an interrogator and software able to implement the same detection algorithm, SOPAS-based, discussed above. The main goal was to acquire data to be processed in a several-month/one-year timeframe, in the same gully of Section 4.2, to get the necessary statistical relevance to assess the working condition of the system. On a longer timeframe, the final, calibrated version

of the interrogator would have been connected to a traffic light installed on the road in Fig. 4.10 and to an SMS text messages/e-mail application for alarm purposes. We managed to install a functioning version of the interrogator in Fig. 4.1, with a more market-oriented vision, allowing us to record and process a larger amount of data. Nevertheless, the whole process of installing the actual fibers and the debugging process of the software running in the interrogator took much longer than expected, leaving, unfortunately, with only a very limited portion of available data to process. Moreover, given the once-per-year typical frequency of the debris flows to happen in the gully, we were unlucky enough not to have been able to record any actual disruptive event, which could have been the final test for our system.

In the first stages of the installation, a combination of out-of-the-ordinary storms and consequent debris flows destroyed the surrounding area and consistently changed its topology [119]. The river on the side of the road, passing by the interrogator, overflowed because of heavy rains. The road had to be rebuilt from scratch, and the initial position where the interrogator was (meant to be) installed (see Fig. 4.10a)) was no longer available. This event was never observed before, and thus not predicted or predictable. Nevertheless, the fiber configurations, which we will discuss below in detail, perfectly survived the event, confirming that the system could be resilient to more ordinary hazards. The final version of the interrogator was still in the installation process, which is why we have no recordings of the event and why we decided to move it to another safer position, supplied by solar panels. This major setback further delayed the data acquisition.

We present here the recorded data, which (preliminary) confirm the discussion made in Section 4.2. The monitoring system is still installed and running to this day.

4.3.1 Experimental setup and processing algorithm

The experimental testbed shown in Fig. 4.19 concerns the real and final installation of the SOP-based monitoring system, which we studied in the previous sections. Four fiber circuits (shown in photos highlighted with different colors in Fig. 4.19) are installed throughout the length of the gully, mostly transversely. Circuit #1 (in orange in Fig. 4.19) is longitudinally installed along the gully. This optical fiber circuit is reported for completeness, but was not active. Circuit #2 (in purple in Fig. 4.19) is not buried but installed on the vertical side of an artificial dam-like structure, a weir. Circuit #3 (in green in Fig. 4.19) is buried in between Circuit #4

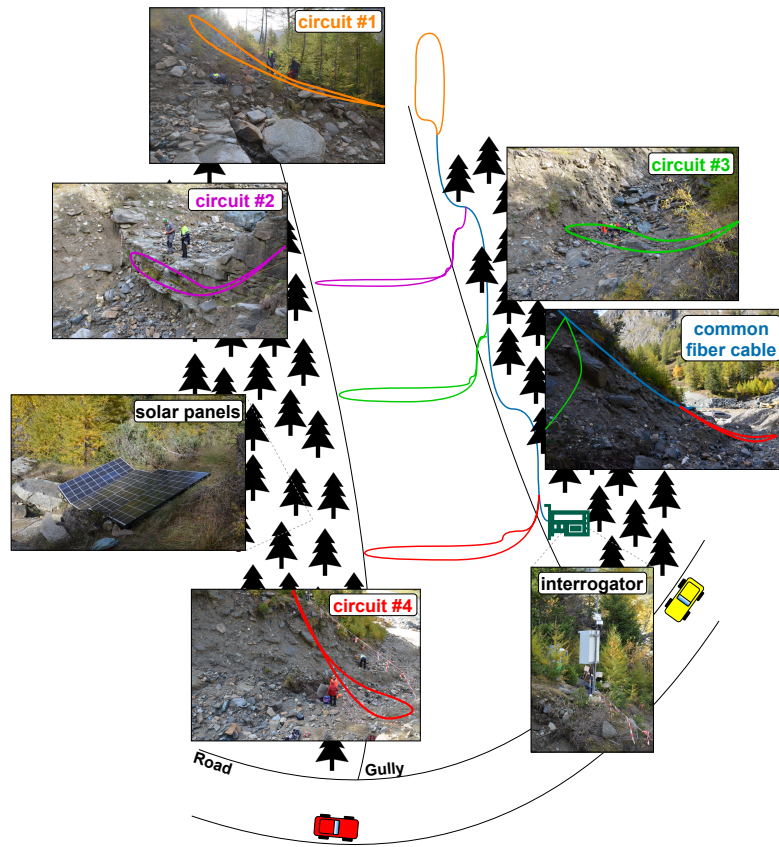


Fig. 4.19 Experimental setup of the monitored gully, including photos of the actual fiber installations, interrogator, and solar panels. Red, green, purple, yellow, and blue lines refer to circuits #4, #3, #2, #1, and common fiber cable.

and Circuit #2, at about 30 meters distance from both of them. Circuit #4 (in red in Fig. 4.19) is positioned at a 40 meter distance from the main road, buried. By buried, we mean a few centimeters, on average, below the terrain surface. The blue line in Fig. 4.19 is the common multi-fiber cable, carrying the optical fiber circuits on the common path along the gully length. The system comprises solar panels to supply the interrogator, where all the necessary hardware is positioned. As depicted in Fig. 4.19, the interrogator and solar panels are placed in safe positions on the higher sides of the gully, where flowing mass events cannot damage them. The gully is about 3 to 5 meters deep, depending on the altitude. Fig. 4.20a) shows the main components of the interrogator hardware, similar to the one discussed in the previous sections. Each circuit is connected to a pair of fibers inside the multi-fiber

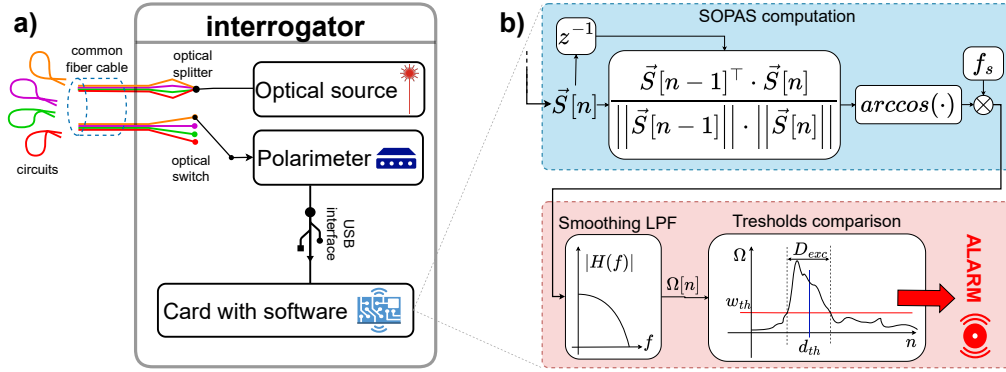


Fig. 4.20 a) Simplified interrogator scheme. b) Proposed processing and alarming algorithm running on the card connected to the polarimeter.

cable that carry the optical signal from the laser (upstream direction) and back to the polarimeter (downstream direction) in a loop-back configuration (equivalently to the RT fiber pair discussed in Section 4.2). A total of eight fibers of the multi-fiber cable are thus used. The same optical signal is fed in upstream to all four circuits through a 1x4 optical splitter. In downstream, the circuit to be monitored is selected through an optical switch placed at the polarimeter input. The idea was to reproduce the same circuit-localization and danger evaluation done in Subsection 4.1.4, by interrogating several fibers at the same time. Nevertheless, at the moment of the experiments depicted here, that was still not available. The total length of each circuit ranges from 200 m for Circuit #4 to 400 m for Circuit #1. The employed external cavity laser (ECL) launch CW power is 17 dBm, whereas the received power is above -4 dBm for each circuit. The interrogator is placed over a pole fixed to the ground by a set of iron strings for enhanced robustness to weather-induced spurious vibrations. The interrogator box is temperature-controlled and water-resistant. Besides the optical devices, it contains all the necessary hardware for data transmission to an outside server and for alarm communication to a pair of traffic lights on the road. The sampling frequency of the system is $f_s = 100$ S/s, and the SOPAS is monitored. As a reminder, we show again in the light-blue rectangle in Fig. 4.20b) how it is computed. The red rectangle describes a proposed algorithm to deliver alarms based on thresholds. After filtering (simple moving average filter, with window fixed to 100 samples, i.e., $T_{mov} = 1$ second), the $\Omega[n]$ time evolution is compared to:

- SOPAS threshold w_{th} , over the $\Omega[n]$ signal, which may exceed it if a potentially hazardous vibrational event is detected by the fiber circuit under test.

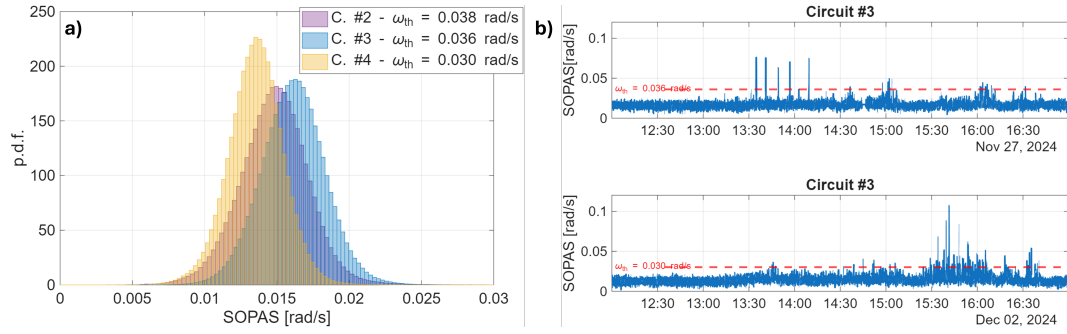


Fig. 4.21 a) pdfs of consecutive 12 hours acquired, per circuit. b) SOPAS evolution recorded during anomalous noisy hours for circuits #3 and #4.

- Time threshold d_{th} , on the duration. Whenever the SOPAS exceeds ω_{th} , it remains above threshold for a time D_{exc} , as specified in Fig. 4.19b). If this duration exceeds the d_{th} time threshold, the occurrence is classified as a dangerous event, and an alarm is triggered. In fact, dangerous flowing mass events should have a bursty behavior, where each burst lasts tens of seconds, whereas false alarms are anomalies with a much shorter duration.

In this work, since no real dangerous event occurred, each time the condition $\Omega[n] \geq \omega_{th}$ is satisfied together with $D_{exc} \geq d_{th}$, we will refer to exceedances happening. Consequently, each time an exceedance is recorded for a specific pair of ω_{th} and d_{th} , the system is subject to false alarms. The goal of this section is then to find the optimal system working condition so that the false alarm occurrences can be minimized. The choice of d_{th} is critical to deliver timely alarms, and should be kept low. In the following, it will be kept below 2 seconds, so that the alarm would be triggered at most two seconds after the SOPAS threshold exceedance, which is also affected by the time average window length.

4.3.2 System detection results

Starting late November 2024, we recorded SOPAS samples from the different circuits. Since noise, intended as anything not related to dangerous events but that couples to the fibers and makes the SOPAS change, is dependent on external conditions and fiber displacements, this section reports an interesting case study for 12 straight hours, acquired at different times for circuits #2, #3, and #4. Since parallel monitoring is not yet available (as we envisioned in Subsection 4.1.4), samples were acquired from

23-11-24 at 00:00 for circuit #2, 27-11-24 at 00:00 for circuit #3, and 30-11-24 at 12:00 for circuit #4. Around November 20th, after a snowfall, the monitored gully was covered by a thick layer of ice and snow. This scenario is quite common since temperatures in the area can reach about -10°C . Fig. 4.21a) shows the pdfs of the recorded, time-averaged, SOPAS samples in the 12-hour time window. The three distributions depict a very stable and comparable noise level between the circuits, with very few outliers: more than 99.9% of the SOPAS samples lie below 0.03 rad/s for all of them. This confirms a quite steady behavior of the SOP when ice covers the gully, as expected. Defining $P_{99.9\%}$ as the 99.9th percentile of the distributions in Fig. 4.21a), as a general rule of thumb, the detection threshold on the SOPAS values is fixed to $\omega_{th} = 1.5 \cdot P_{99.9\%}$, with the values per circuit shown in the legend of the same figure. With these thresholds, the recorded time when $\Omega[n] \geq \omega_{th}$ is in between 0 and 2 seconds, depending on the selected circuit. Focusing now on circuits #3 and #4, which are both buried, no noticeable variations were recorded in the presence of strong snowfalls, which occurred several times, making us infer some insensitivity to this kind of event. The only noticeable anomalies are depicted in Fig. 4.21b), recorded outside the 12-hour histograms of Fig. 4.21a), where the SOPAS exceeds ω_{th} for tens of seconds for circuit #3 and almost one hour for circuit #4. We underline that this behavior is difficult to relate to any known external condition, such as animal activity in the gully (which has been recorded several times by cameras), but has not been recorded in the presence of any snowfall or rainfall. However, it strongly characterizes the noise level of these two circuits. In this case, a simple fixed threshold on SOPAS value is less effective, as it would lead to false alarms for several minutes, which is hardly acceptable. As discussed above, introducing a second threshold on the exceedance duration D_{exc} , could enhance the detection performances. In Figure 4.22, two detection maps for the two circuits #3 and #4 show the number of exceedances per ω_{th} and d_{th} parameters pair, considering the whole 12 hours dataset used for the pdfs in Fig. 4.21a), where no anomalous behavior is recorded, and the SOPAS behavior in Fig. 4.21b). For low threshold values, the majority of exceedances have short duration ($D_{exc} \leq d_{th}$), whereas the trend is inverted when the threshold is increased. This is reasonable since a small ω_{th} leads to taking into account short noise peaks, oscillating around the threshold. This is confirmed by the majority of exceedances being below $d_{th} = 0.5$ seconds. The maps show that, for circuit #3, to eliminate false alarms, any ω_{th} value can be selected provided that d_{th} is larger than about 1.3 seconds. This leads to exactly 0 exceedances

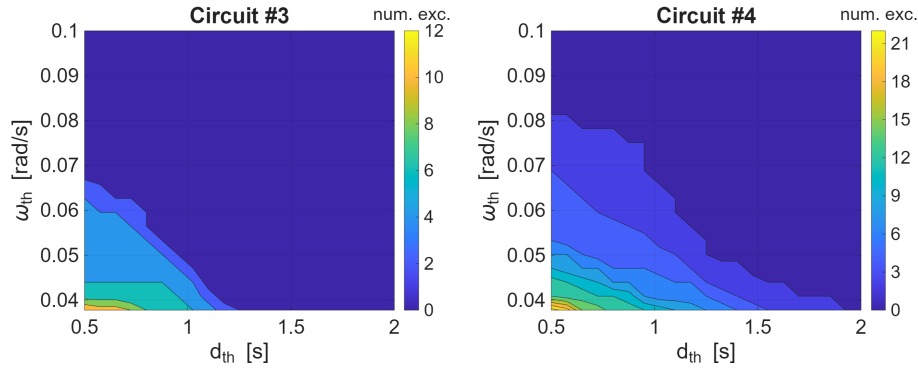


Fig. 4.22 Exceedances detection maps for circuits #3 and #4.

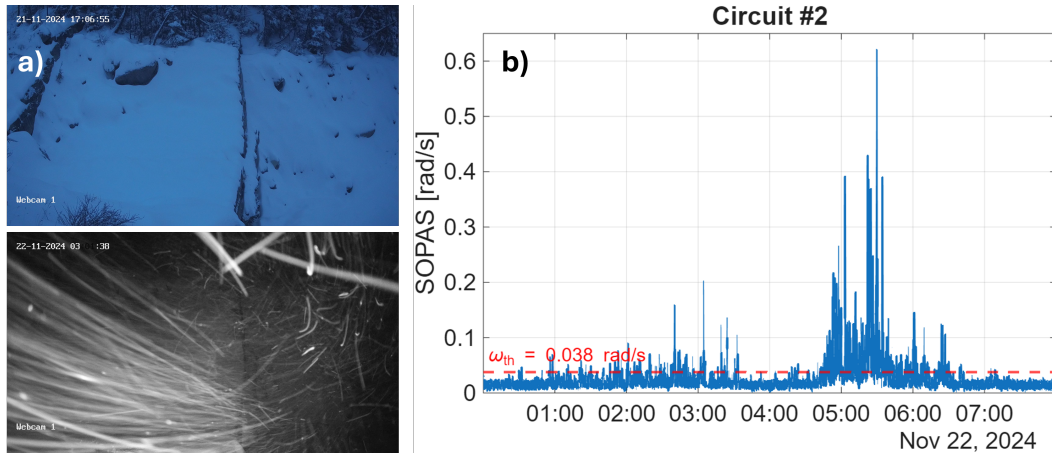


Fig. 4.23 a) The upper photo shows the gully on circuit #2 with a snow layer in quiet conditions, the lower photo shows the occurrence of an intense snowfall on the same spot. b) SOPAS evolution recorded on circuit #2 during an intense snowfall.

(i.e., 0 false alarms). For circuit #4, the background noise level is slightly higher, but more than half of the parameter pairs in the map could lead to the no false alarms condition. Although this is not exhaustive since longer recordings should be studied, it gives a comprehensive idea of the working principle and performance of the system. Actual performance evaluation with real-life events will give a more complete idea of the actual detection performances of these two circuits. Through the years, several sensors have been installed in this gully and recorded the occurrences of actual hazardous flowing masses: the recorded duration is much longer, as we envisioned and as demonstrated by literature [102], than the one shown in the maps, with much higher intensity, realistically leading to much higher SOPAS values.

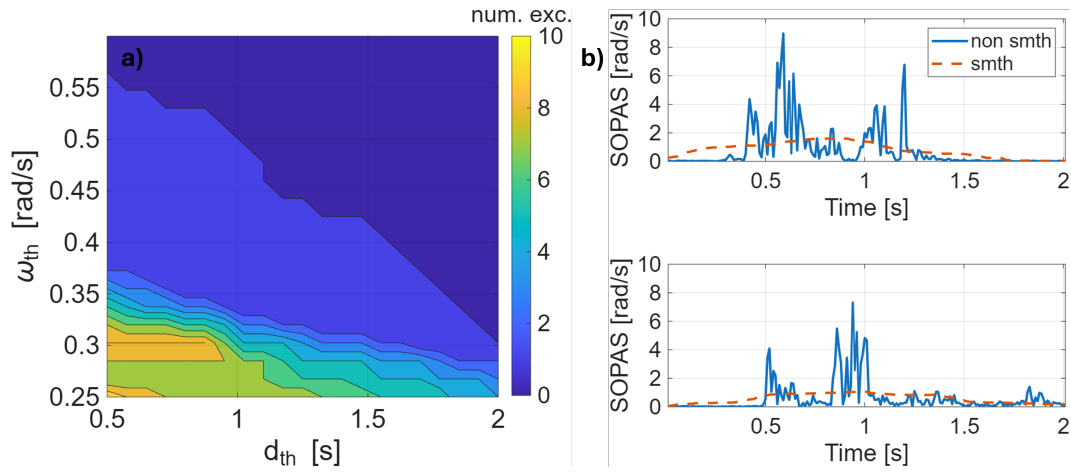


Fig. 4.24 a) Exceedences detection map for circuit #2. b) Simulated flowing mass event response on SOPAS, non-smoothed (blue line, “no smth”) and smoothed (orange dashed line, “smth”).

In circuit #2, the situation is quite different. This fiber cable is not buried, but completely exposed, fixed on the dam-like weir structure. Fig. 4.19a) shows the fiber displacement as seen by the front, without snow, while Fig. 4.23a), upper photo, shows the same structure as seen from above and with snow. In the same figure, the photo below shows the occurrence of a very intense snowfall, generating the SOPAS variations reported in Fig. 4.23b). Unlike the other buried circuits, circuit #2 is extremely sensitive to external weather conditions: a threshold value of 0.038 rad/s, delivering 0 seconds of false alarm in the 12 hours recorded to generate the pdfs in Fig. 4.21a), is now too low and completely immersed in noise, generating hours of alarms. The detection scenario in this case changes completely: even with d_{th} values near 2 seconds, with ω_{th} around 0.038 rad/s, the number of exceedences never reaches 0, and decreases, with increasing duration thresholds to a few tens at most. To reach a number of exceedences and a map layout similar to the ones of circuits #3 and #4, the SOPAS threshold values need to be increased in the range from 0.2 rad/s to 0.6 rad/s, as shown in Fig. 4.24a), that is, one order of magnitude larger. This is due to the very different layout and installation of this fiber circuit. Moreover, being exposed, the fiber could be more subject to the effect of flowing masses, to which the buried circuits are maybe less sensitive: as mentioned in the final subsection of Section 4.1, fiber depth is something that surely needs larger investigation. To characterize the effect of a flowing mass on this circuit, we tested the fall of gravel and sand on the fiber. The results are reported in Fig. 4.24b), for two occurrences.

The blue curve shows the original SOPAS trace, while the orange dashed line shows the time-averaged trace, with SOPAS values up to 2 rad/s in correspondence with the event. An actual flowing mass would hit the fiber continuously for much longer than two seconds [118]. These events have been recorded at least once a year in this gully, occurring in bursts of tens of seconds. As such, they would produce time-averaged SOPAS values much longer and much larger than the 1-2 rad/s measured during our tests. Considering the map in Fig. 4.24a) then, a threshold value with ω_{th} being in between 0.4-0.5 rad/s and $d_{th} > 1.2$ seconds, would allow for consistent detection performances reducing the number of false alarm due to external intense snowfall, as shown by the recorded data.

4.3.3 Discussions and conclusions

We discussed a unique SOP-fiber-based detection system installed in a mountain environment within an active gully subject to intense, hazardous flows. Preliminary data analysis indicates notable effects on the SOPAS arising from the external environment, although these do not appear to be critical for the system's detection performance. Despite having different circuits with different noise characteristics, a simple intensity threshold ω_{th} and duration threshold d_{th} can achieve good detection performance and resilience to false alarms. The results reported in this work are nevertheless still preliminary: a distributed study over several months is necessary, as well as characterization of truly dangerous event occurrences.

4.4 Chapter Conclusions

At the very beginning of this chapter, we discussed the main drawbacks of the most standard mountain engineering techniques to monitor the environment for hazards. The comparison with SOP monitoring, in this scenario, seemed promising since several flaws could be at least mitigated by it (see Table 4.1). Through this chapter, we went from a reduced-scale setup to a real installation of an actual SOP-based sensing system, to understand the limits, pros, and cons of the technique.

Concerning the question marks raised in Table 4.1, the reliability of the fiber system was to be studied. We demonstrated how, in all the scenarios where the sensing system was deployed, the events to be detected were always detected with

a reasonable margin, delay time, and algorithm complexity. The SOPAS is an extremely simple approach that does not need sophisticated electronics or software to be implemented and seems to be, in this context, reliable. Despite having introduced in Chapter 3 the SOP-PSDG, it would maybe not have been, in this case, the perfect fit, as it's more complex and requires advanced electronics, suitable for an already high-end hardware such as the one in the coherent transceivers. As we specified in Subsection 3.2.4, since the SOPAS metric is non-adaptive, it should be employed in scenarios where the event to be detected is in general more intense than the usual noise level, which seems to be true in the mountain scenario. Moreover, differently from the urban/submarine environment, the peculiarity of a tens of seconds long, bursty behavior of typical flowing masses events can also be exploited to differentiate between alarm/no alarm conditions, making the SOP-based sensing system reliable in all the scenarios studied. Nevertheless, we acknowledge that to really assess the complete reliability of this system, much longer acquisitions need to be studied, also involving the recording of true hazards.

As discussed in Chapter 1 and Section 3.4, SOP sensing allows for very long distances to be covered, at the cost of localization incapability. This is an important difference with respect to the legacy geotechnical sensors, which have more of a “point sensing” behavior, with decreased coverage. Even if the actual gully is usually a few hundred meters long, making the useful sensing length much shorter than the one required for Chapter 3, we demonstrated how, with the use of an optical switch, the coverage can potentially be extended to more than one gully. Moreover, with the same approach, we could estimate the speed (and consequent danger) of a flowing mass event, enhancing reliability, and have rough localization. The power supply can be in an event-safe area, from where the sensing fibers dispatch (exactly as we did in Section 4.3).

We also acknowledge that one of the main drawbacks of the system can be related to the installation. The cost associated with it can be high, but it can be mitigated. Firstly, optical fibers are rather inexpensive: one cable containing around 50 fibers can cost around 1 EUR/m. Despite having used laboratory-grade equipment to build the interrogator prototype, the cost of the polarimeter can be scaled down from 12 k€ to less than 5 k€, at the expense of lower power sensitivity, SOP noise, and sampling speed. These factors can all be disregarded since we have never worked with extra-low received powers (minimum was -4 dBm), and the events to be detected are so intense that polarization noise can maybe be negligible. The

Table 4.2 Comparison between the proposed monitoring system and existing solutions [106–109, 120, 102, 105].

Method	Characteristics	Pros	Cons
Geophones, accelerometers, infrasonic sensors, and seismometers	Measures the vibrations or sound waves associated with the debris propagation	Easy and safe installation	Limited reliability/accuracy, requires supply on site, calibration, and interpretation
Ultrasonic and Doppler radar sensors	Measures the level variations at a specific point along a channel/gully	High reliability/accuracy	Applicable for narrow channels only, need to hang sensors over the channel, high risk of damage during the event, requires supply on site, visual impact
Wire, pendulum, and impact sensors (i.e., electromechanical systems)	Installed on specific check points (trigger lines), detects the arrival of debris/snow masses	Reduced costs, high reliability/accuracy	High risk of damage during the event, need to hang sensors over the channel, requires supply on site, environmental impact
Photocells and high-resolution infrared cameras (i.e., optical systems)	Manual or automatic identification of the debris flows/avalanches transit	Visual acquisition	Limited reliability/accuracy, limited visibility in case of bad weather and night, high risk of damage during the event, requires supply and installation on site
Remote Doppler radar sensors	Detects the initiation of avalanches on wide areas	Only one measurement point, reduced risk of damage	Very expensive, needs a visible scenario, requires supply at the installation point
Fiber-optic SOP sensing	Monitors ground vibrations related to debris flow propagation along channels	Reduced risk of damages, limited cost, high reliability/accuracy, supply required only at the polarimeter, no visual impact	Need to bury the fiber along the slope

sampling speed necessary is around 100 S/s, very low. Another cost factor is the need to replace damaged fiber in the event of a particularly strong, catastrophic hazard. Nevertheless, by placing the interrogator in safe areas, the only thing to be substituted would be the fibers. This comes with reinstallation costs, which are anyway less than the hardware costs. Moreover, the catastrophic event described at the beginning of Section 4.3 didn't break any fiber, making the chance of reinstallation even lower. A fiber cut would also correspond to a drop in the received power at the polarimeter, another trigger to generate the alarm. Recent studies also investigated a standalone SOP sensing system exploiting S_1 Stokes parameter only, which only requires two photodiodes to be computed [121, 12], making the system much more inexpensive.

The sensitivity change should be, of course, studied.

A system with these characteristics could really represent a valid alternative to current early warning and detection systems available on the market. A comparison of pros and cons is summarized in Table 4.2 with respect to the most common sensors. The proposed system combines apparently high reliability with the robustness and durability required in a mountain environment at a cost comparable to that of the least expensive alternatives. Another suitable alternative in this case would be remote radar Doppler, which, however, would require full and clear visibility of the scene from the installation point and would be substantially more expensive, in the end. A comparable fiber sensing technique that could be employed is DAS or, more generally, ϕ OTDRs, since Brillouin-based sensors have too long response times to be suitable. Nevertheless, the overall costs and complexity of the system could probably be higher (~ 12000 €, plus all the real-time processing hardware and alarm detection system, which is more complicated and thus expensive). The hardware needed is overall more expensive, and the detection algorithm should be developed from scratch, in this case, adding to the overall expenses. Moreover, a specific data management plan is also required since, being resolved in space, the size of the information generated is huge.

Chapter 5

Distributed Acoustic Sensing Coexistence with Telecommunication Systems

The previous chapters addressed LI techniques, with particular emphasis on the state of polarization and its integration with the current telecommunication infrastructure. We delved into the details of SOP sensing, both in coherent systems and as a standalone solution, in the mountain scenario. As detailed in Chapter 1, DAS, as part of the LR techniques, is a dedicated sensing approach, designed to accurately detect and localize fiber axial strains [5, 45] in various scenarios [8, 41, 122]. DAS has achieved significant commercial success in important niche applications, such as oil and gas pipeline monitoring, and is gaining increasing relevance in geophysical applications [40, 122, 41, 8]. The basic working principle of DAS systems is detailed in Chapter 2.

However, considering coexistence with data channels, the requirements of the telecommunication side are often opposite to those of the sensing part. This mismatch poses significant issues for the integration of the sensing system with the already deployed network infrastructure. In particular, the high pulse peak power employed, together with the pulsed behavior of the most standard DAS systems, generate nonlinearities that are quite difficult to limit and to study.

In this chapter, we present an investigation of the coexistence of DAS systems with standard telecommunication ones. Section 5.1 provides guidelines on the integration of chirped-pulse DAS with intensity-modulated and direct-detected (IM-

DD) systems, along with a physical interpretation of the results. Section 5.2 focuses on coexistence in coherent communication systems, utilizing a standard non-chirped DAS sensing hardware. Our goal is to also investigate whether the high power levels involved can trigger spontaneous Raman scattering (SRS) in the L-band.

The matter presented in this chapter is partly based on the works reported in [123–125]. The notations used to discuss the DAS parameters (e.g., pulse durations, chirp bandwidth) are slightly different from those used in Chapter 2, and will be reintroduced here.

5.1 Experimental and Simulative Study on IM-DD Transmission and Large Chirped-Pulse DAS Coexistence

As mentioned in Chapter 2, DAS can operate with coherent or direct detection, similarly to telecommunication systems. With coherent detection, perturbations can be tracked by monitoring the phase variation of the Rayleigh backscattered signal. By recovering the complex optical field, matched filtering (MF) can be applied, allowing for long modulated signals (instead of short pulses) to be sent into the fiber and recovering the impulse response in post-processing. Such an operation provides flexibility in system parameters, enabling both long-range operation (beyond 100 km [126–128]) and improved spatial resolution [129, 130]. Long haul operation using MF and optical repeaters compatible with the telecom infrastructure has also been recently pursued, demonstrating operation over 1000 km [72, 131]. For coherent detection, the use of ultra-narrow-linewidth lasers is a mandatory system requirement, as the phases of the backscattered traces need to be coherent, being unfortunately one of the main reasons for the DAS's high CAPEX cost.

On the other hand, using direct detected (DD), single-shot linear measurement DAS systems are also possible with the use of chirped-pulse ϕ OTDR [60]. CP- ϕ OTDR presents fundamentally different trade-offs than traditional phase-measuring DAS, excelling in large strain detection [132, 66], and long-term (> 24 hours) operation [133, 134, 67]. While operation in up to 100 km has been demonstrated [61], the highest performances are traditionally reported at shorter distances (typically at up to ~ 50 km). The complexity is also reduced (at the cost of increased signal

processing effort, due to cross-correlations computation [61]), given the simpler DD scheme used (single DD photodetector/digitizer), and the fact that laser stability requirements can be relaxed by 1-2 orders of magnitude (e.g., operating with 1 MHz laser linewidths [135]). This makes DD CP- ϕ OTDR an ideal candidate for monitoring of access/metropolitan links. We remark that CP- ϕ OTDR has been widely used in the last decade and is a commercially available technology. The interested reader is invited to read the extended review of the technique, available in [61], where the finer details, advantages, and trade-offs of the technique are analyzed in depth.

Note that the DAS and telecommunication data compatibility requirements are also fundamentally different between the two operations: with coherent detection DAS and use of MF, a lower peak power can be used, but overlapping during a higher percentage of time (duty cycle can in fact be close to 1 [136]). With DD DAS, higher peak power is used, but overlapping during shorter periods (duty cycles typically of 10^{-3} - 10^{-4} [137]). Recent research on the coexistence of DAS and telecommunication systems [7, 72, 137] has shown that high-peak-power pulses can induce Kerr effects on data wavelengths, achieving coexistence under specific conditions that depend significantly on the system configurations.

Regarding the used optical bandwidth, whilst in telecommunications the use of tens of GHz has become standard use, so far, DAS operation (both academic and commercial) has been mostly limited to operations below 1 GHz (due to an increase in cost/complexity which does not match the traditional DAS applications). In this regime, pulses can essentially be approximated as a single frequency signal when studying nonlinearities arising in DAS [62] and coexistence [137]. However, fundamentally, telecommunications and DAS can operate at similar bandwidths, and an increase in optical bandwidth is known to allow for an increase in DAS performance. As an example, using DD CP- ϕ OTDR with 8 GHz optical chirp, the measurable single-shot strain variation was increased to $\pm 3\mu\epsilon$ (two orders of magnitude higher than traditional phase-measurement DAS for the same spatial resolution) at kHz operation [66]; and long-term (> 24 hours) high sensitivity (n ϵ [66], mK [67]) measurements were demonstrated. In this regime, with optical bandwidths of 10 GHz that can no longer be approximated as a single central frequency pulse, the impact of nonlinearities in DAS has only recently been described in detail [67], and, to the best of our knowledge, no co-existence studies have yet been performed.

In this section, we will focus specifically on the coexistence between large chirped-pulse DAS and IM-DD data transmission on the same fiber, both operating at

similar optical bandwidths (5 GHz optical chirp, 10 Gbit/s), and both envisaged for DD operation over a few tens of km. The possible scenario of application is the one analyzed in [7]: metropolitan single span, inter-data center or access networks, which are still largely based on legacy IM-DD transceivers. In these scenarios, typically covering a few tens of km, CP- ϕ OTDR can give excellent sensing and localization capabilities. Moreover, the ITU-T DFOS initiative [7] discussed above is pushing for incorporating the sensing signal into the ITU-T grid in access or metro DWDM legacy systems, highlighting the growing interest in this topic.

We present here results employing frequency spacings ranging from 50 GHz to 400 GHz between co-propagating data and sensing channels, varying the DAS peak power, and adjusting the receiver optical filter bandwidth, as outlined in Section 5.1.1. We also emphasize in Subsection 5.1.2 the physical interpretation of the propagation effects on the data signal, analyzed for both co-propagation and counter-propagation. A major addition is the confirmation of our findings through detailed time-domain split-step simulations, in Subsection 5.1.3, which suggest system-level solutions for enhancing coexistence. Subsection 5.1.4 concludes the section with final discussions.

5.1.1 Experimental setup

In this subsection, we describe the experimental setup illustrated in Fig. 5.1a), which we used to investigate the coexistence of large chirped-pulse DAS and telecommunication IM-DD systems.

On the DAS side, we experimentally implemented the chirped pulse generator only, without analyzing the reception of the backscattered traces (it was, anyway, shown in [138, 137] that data impact on DAS performance is minimal, provided that appropriate optical filters are used). The DAS chirped pulses are generated employing a narrow-linewidth (~ 100 Hz) ultra-stable laser (referred to as “DAS laser” in Fig. 5.1a)), with central wavelength $\lambda_0 = 1550$ nm ($f_{DAS} = 193.414$ THz), which is then modulated using an I/Q (in-phase/quadrature) Mach-Zehnder modulator (MZM), driven on its two electrical arms by an AWG. The pulse intensity was shaped as a 4th order Super-Gaussian, with full-width-half-maximum (FWHM) duration $\tau = 80$ ns. Proper sinusoidal signals, Super-Gaussian-shaped, generate the optical chirp inside the pulse, which ranges from starting frequency $\nu_0 = -1$ GHz to final frequency $\nu_f = -6$ GHz, thus with bandwidth $\Delta\nu = 5$ GHz. The inset of Fig. 5.1a) shows the (ideal) real and imaginary parts of the generated chirped pulse,

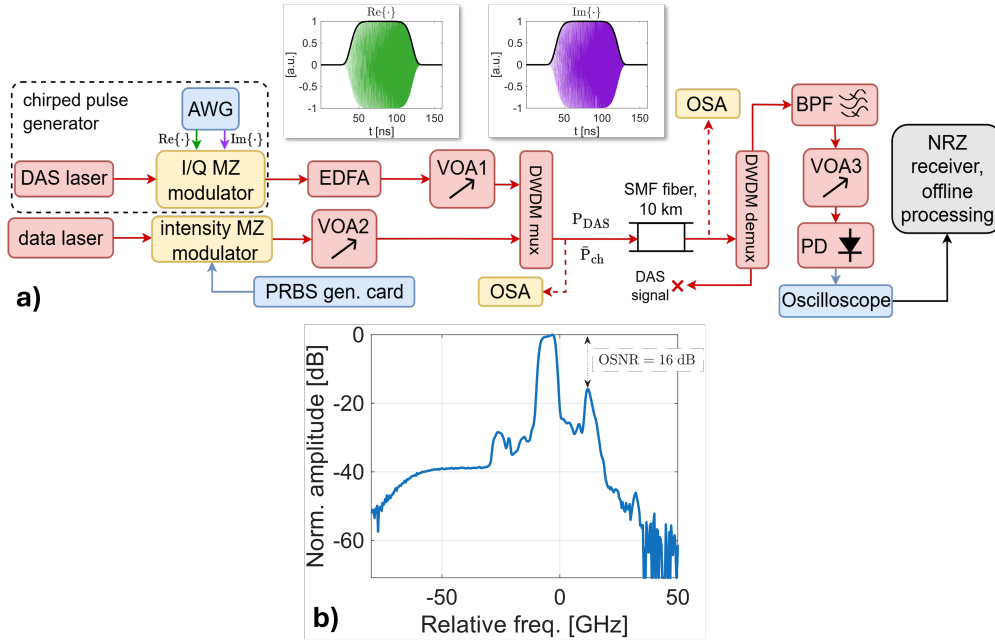


Fig. 5.1 a) Experimental setup used for the coexistence analysis of the DAS pulse with data channels propagating in a 10 km SSMF. The inset shows the real (green) and imaginary (purple) parts of the complex chirp, driving the I/Q MZM. The black line is the Super-Gaussian intensity envelope. b) Transmitted spectrum of the large chirped-pulse DAS alone, normalized to its maximum.

and its Super-Gaussian intensity envelope (black continuous line). The electrical signals sent to the AWG were also pre-distorted to compensate for the driver and the limitations of the MZM electrical frequency responses, resulting in less than 1 dB variation from v_0 to v_f amplitude. The DAS signal was sent once every $\sim 3.2 \mu\text{s}$, to match the data pseudo-random bit sequence (PRBS) periodicity, as detailed further on, corresponding to a DAS duty cycle of $\sim 2.4\%$. Commercial DAS duty cycles are much smaller, but our choice was motivated by the need to simplify the experimental signals post-processing (i.e., by using shorter signal acquisition windows) and by the fact that, as mentioned above, we are not evaluating the DAS sensing-related performance, but only its impact on data channels. After its generation, the DAS pulse was amplified by an EDFA, its peak power P_{DAS} regulated by a variable optical attenuator (VOA1 in Fig. 5.1a) and measured right before fiber propagation. The DAS peak powers used for this study varied between ~ 20 dBm to ~ 29 dBm, as it is the most commonly used power range for short-metro fibers. Note that, for SSMF fibers (with effective lengths of ~ 20 km), pulse peak powers are capped due to the effects of MI at ~ 23 dBm [62, 61]. However, for shorter fibers, peak

powers can be increased in inverse proportion to the fiber's length (e.g., ≥ 30 dBm for 5 km fibers, [46]). It should be noted that for the particular case of CP- ϕ OTDR technology, a lower signal-to-noise-ratio variability with peak power is expected than in phase-measuring DAS, as long as the trace visibility is maintained (i.e., nonlinear effects are avoided) and enough signal-to-noise-ratio is available to avoid large errors [139]. To ease readability, in the remainder of this section, the optical spectra will always be plotted with respect to a relative frequency axis where conventionally 0 GHz corresponds to the DAS laser central optical frequency f_{DAS} .

On the telecommunication side, the IM-DD non-return-to-zero (NRZ, PAM2) data transmission was generated using a commercial PRBS generator card, set at 10 Gbit/s and using a PRBS sequence with $2^{15} - 1$ bits period, resulting in a periodicity of $T_{PRBS} \sim 3.2 \mu s$. This signal electrically drives an intensity MZM, optically fed by a tunable distributed feedback (DFB) laser, referred to as “data laser” in Fig. 5.1a). The average data signal power is set by means of VOA2 to $\bar{P}_{ch} = -2$ dBm, allowing for acceptable ROP, measured right at the fiber input (see Fig. 5.1a)). A 10 km SSMF G.652 was used as the fiber link under test, emulating the short-reach single span scenarios outlined in this chapter's introduction. Different frequency separation values Δf of the data carrier from the DAS central frequency f_{DAS} have been considered: 50 GHz, 100 GHz, 200 GHz, 400 GHz. To this end, a dense wavelength-division multiplexing (DWDM) multiplexer (DWDM mux) has been used to merge the DAS and data signals at the fiber input. In contrast, a DWDM demultiplexer (DWDM demux) has been used to separate them at the fiber output. The DWDM mux/demux has a pass band of 80 GHz.

Fig. 5.1b) shows the measured normalized average transmitted optical spectrum of the chirped pulse, measured right before fiber propagation, thus after the DWDM mux. The resolution bandwidth of the OSA was 0.01 nm (1.25 GHz). As mentioned above, 0 GHz refers to the DAS central frequency f_{DAS} . The 5 GHz chirp content is visible in Fig. 5.1b) on the left side (from $\nu_0 = -1$ GHz to $\nu_f = -6$ GHz). For reasons that will become clearer later in this section, it is useful to comment on the optical noise that is present on this transmitted DAS pulse spectrum. Here we define a the OSNR as the difference in dB between the pulse spectral peak (arbitrarily normalized to 0 dB in Fig. 5.1b)) and the (non-flat) surrounding optical noise. We observed two main optical noise sources:

1. *EDFA ASE noise*. This is the relatively flat spectral component, mainly visible around -50 GHz in Fig. 5.1b), and present in the whole DWDM mux 80 GHz

band. The related OSNR is about 40 dB. This noise contribution is always active, even outside the DAS pulse occurrence.

2. *I/Q modulator spurious noise effects.* The combination of the AWG electrical signal source and the following I/Q modulator used in our experiments generates some spurious harmonics on either side of the main lobe in Fig. 5.1b). The strongest harmonic is located at about +10 GHz from the DAS center frequency and generates a “local” OSNR of about 16 dB, whereas the other significant harmonic, located at –25 GHz, has OSNR = 30 dB. This spurious noise source is only present inside the DAS pulse.

It should be noted that in our experiments, when we vary P_{DAS} through VOA1, the two aforementioned noise contributions vary accordingly.

After fiber propagation and channels separation through DWDM demux, the modulated data signal is further filtered through an optical band-pass filter (BPF) with the same central frequency as the data channel and bandwidth B_{rx} . The role of this filter is quite important and will be discussed later. Different B_{rx} values have been tested, specifically $B_{rx} = 14$ GHz, 20 GHz, 30 GHz, and 50 GHz. The resulting total optical filtering on the data signal at the fiber output, which is given by the cascade of the DWDM demux and the BPF, provides an effective DAS channel suppression of more than 60 dB. This means that any linear optical crosstalk from DAS pulse onto the data signal is excluded.

On the data signal receiver side, we used VOA3 to change the ROP P_{rx} reaching the photodiode (PD), thus allowing BER measurements for different P_{rx} values. The electrical signal from the PD is then digitized through a real-time oscilloscope and processed offline through a standard NRZ DD receiver, computing the BER through the error counting technique. As a benchmark for our experimental analysis, i.e., without DAS signal, we set $P_{rx} = -20$ dBm to obtain $BER \simeq 10^{-4}$. We will refer to this baseline as BER_{noDAS} for the considerations in the next subsections.

5.1.2 Experimental results

We present here the experimental results, underlining the main effects involved. The next paragraphs will show the resulting impact on the data channel from both spectral and time-domain perspectives, and discuss the BER degradation as a function of different system parameters.

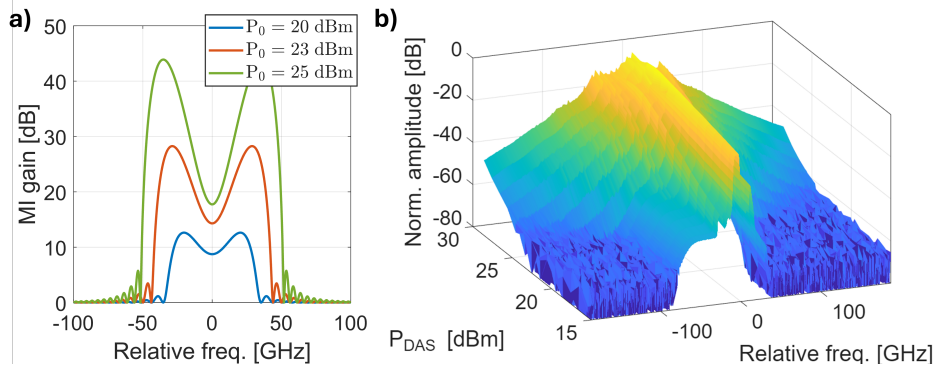


Fig. 5.2 a) Theoretical MI gain curve [63, 140] generated by a single frequency source, considering $\gamma = 1.3 \text{ W}^{-1}/\text{km}$, $\beta_2 = -22 \text{ ps}^2/\text{km}$ and a 10 km SSMF fiber. b) Received spectra obtained after fiber propagation versus different P_{DAS} , when the chirped pulse alone is propagated. The graph is normalized to the maximum value among all the measured spectra.

Considerations on nonlinear effects resulting from the propagation of the DAS signal alone

As it is known from nonlinear optics theory [63], modulation instability (MI), also called parametric gain (PG), is one of the main impairments generated by high-peak-power pulse propagation in optical fibers, responsible for a very peculiar in-band amplification around the central frequency of the pulsed signal. In the context of DAS, it is known to be one of the main effects for high power pulses, typically limiting P_{DAS} to around 23-25 dBm [62] in practical applications. To grasp MI key features, Figure 5.2a) illustrates the MI gain that a single frequency pulse propagation would generate [140] centered at f_{DAS} , showing the strong dependency that the gain and the frequency position of the main lobes have with increasing pulse peak powers P_0 . Particularly, the angular frequency Ω_{max} at which the MI gain has its two symmetric maxima (i.e., the lobes' positions) is described by Eq. 5.1

$$\Omega_{max} = \pm \left(\frac{2\gamma P_0}{|\beta_2|} \right)^{1/2}, \quad (5.1)$$

where γ is the fiber Kerr nonlinear coefficient, and β_2 the group velocity dispersion constant. In Fig. 5.2a), the fiber is considered to be 10 km long, with $\gamma = 1.3 \text{ W}^{-1}/\text{km}$ and $\beta_2 = -22 \text{ ps}^2/\text{km}$, typical values for a telecommunication SSMF fiber. Eq. 5.1 and Fig. 5.2a) highlight that a higher peak power corresponds to a broader and more intense noise amplification. This may become critical for the coexistence with the

telecommunication channels, particularly close to the DAS pulse, as the crosstalk generated by the MI could induce distortions on data. While Fig. 5.2a) shows the theoretical MI gain, Fig. 5.2b) shows the spectra as recorded by the OSA, in our experimental setup, after the 10 km fiber and for different P_{DAS} values, when the chirped pulse was transmitted alone. The graph in Fig. 5.2b) is normalized (as in most of the other spectral curves reported in this section) to set the maximum to 0 dB. The presence of the MI effect is quite evident, since the received spectra broadens with increasing peak power, and consequently, the in-band noise (due to both I/Q MZM harmonics and ASE) increases. This effect can be observed with a DAS peak power starting at 21 dBm.

Spectral and time domain measurements on data signal

We will now examine the spectral and time-domain distortions caused by the MI-crosstalk on the data signal, based on experimental results obtained when both DAS and data channels are active. To this purpose, Fig. 5.3 shows the spectrum of data co-propagated with the DAS signal, recorded at the fiber output before the optical filtering, in the case of $\Delta f = 100$ GHz channel frequency spacing. This figure illustrates how the MI effect on DAS can affect the data signal when the spectral separation is small enough for it to fall within the DAS MI-generated bandwidth. In this case, two detrimental effects take place:

1. the DAS transmitter intrinsic noise (see previous paragraph and Fig. 5.1b)) is strongly enhanced by MI, thus reducing the OSNR around the data channel;
2. MI (which can also be interpreted as a “local” spectral gain) amplifies the data signal in a complex and nonlinear way, thus distorting the data signal in the time domain.

In the remainder of this section, we will refer to “MI-crosstalk” as the sum of these two effects, induced by the DAS signal propagation on the data channel. From a system viewpoint, the impact of the first effect (optical noise enhancement) on data can be partially reduced by employing a narrow receiver optical filter with variable bandwidth B_{rx} , centered at the central frequency of the data channel. In the following, we discuss the impact of narrowing B_{rx} .

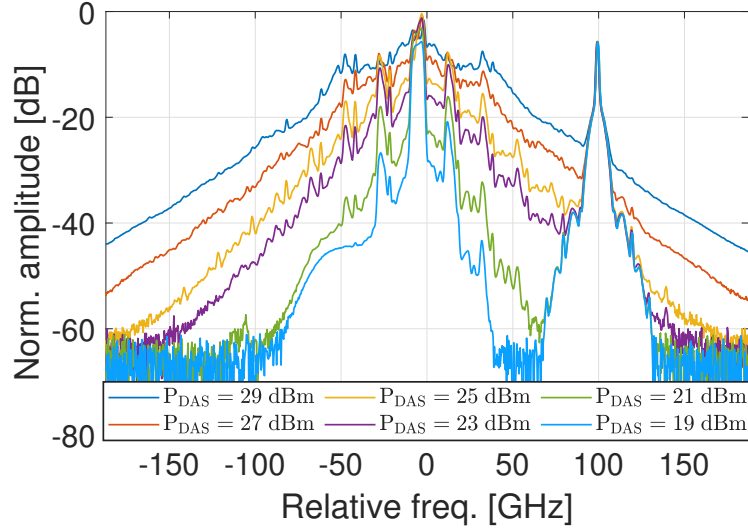


Fig. 5.3 Average spectra of the co-propagating large chirped-pulse DAS and $\Delta f = 100$ GHz spaced data channel recorded by the OSA right after fiber propagation for different P_{DAS} .

To obtain a first-order time-domain analysis of the MI-crosstalk impact on data, we recorded the photodiode current intensity I through the RTO and offline-processed it. As an example, the raw data signal intensity I versus time is reported in the inset of Fig. 5.4a), for $P_{DAS} = 23.5$ dBm, zoomed around the DAS pulse occurrence. Notice that the long term mean value was removed. It is useful to remind here that we intentionally synchronized our system to generate one DAS pulse for each PRBS data sequence, so that the relative time-position of the pulse is time-synchronous with each PRBS sequence. In the following figures, we show the offline-processed signal $\langle I \rangle$ obtained as follows. First, we “chopped” the received I over 50 time-windows, each with duration T_{PRBS} . Then, we evaluated the average I over these recorded 50 PRBS repetitions. This averaging is fundamental to strongly reduce the impact of the underlying random noise. Figure 5.4 shows the evolution of $\langle I \rangle$ versus time, zooming in on a symmetric 150 ns window centered around the DAS pulse with 80 ns time duration, for different P_{DAS} values. The resulting $\langle I \rangle$ waveforms (which we also AC-coupled to remove their long term mean) clearly show that, during the MI-induced interaction with the DAS pulse, the received data signal can be strongly distorted, depending on P_{DAS} values. Different P_{DAS} , spanning from 23.5 dBm to 29.2 dBm, have been reported, while Fig. 5.4 refers to a) $\Delta f = 50$ GHz, b) $\Delta f = 100$ GHz and c) $\Delta f = 200$ GHz. The B_{rx} value is fixed to 14 GHz.

Interestingly, from Figs. 5.4a-b), two main effects are worth of attention: the impact of proximity to the DAS central frequency and the shape of the crosstalk

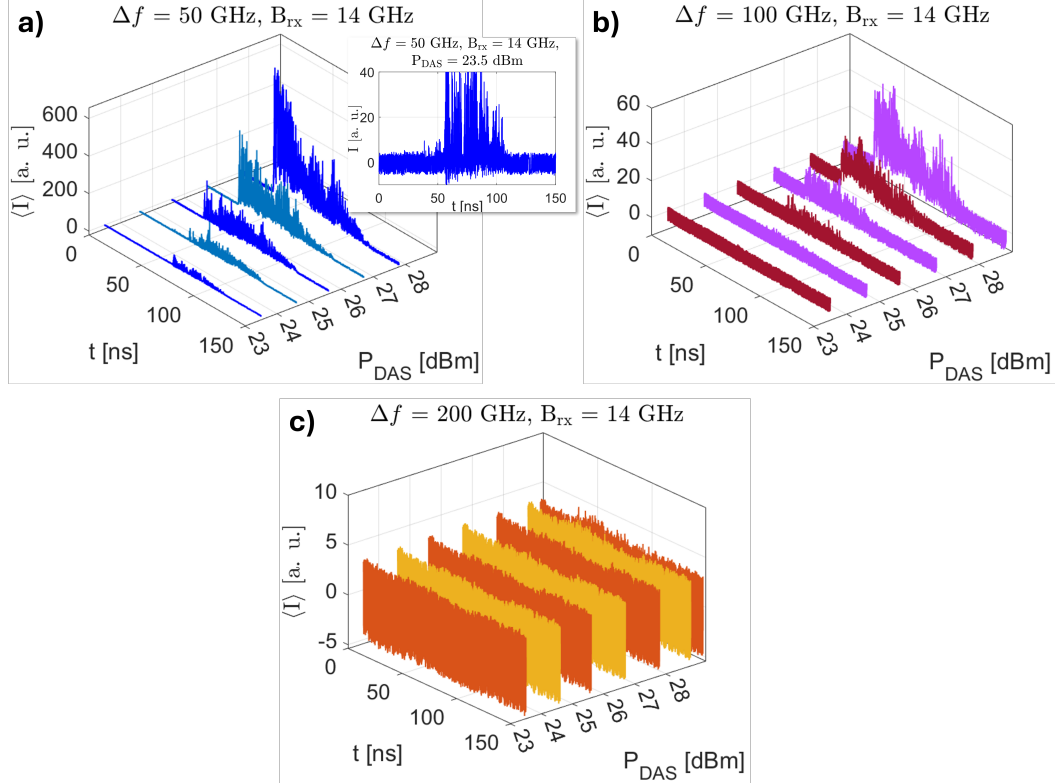


Fig. 5.4 Data signal average intensity $\langle I \rangle$ evolution along the pulse co-propagation for $B_{rx} = 14$ GHz when a) $\Delta f = 50$ GHz, b) $\Delta f = 100$ GHz and c) $\Delta f = 200$ GHz, versus P_{DAS} . Different colors are only used to provide contrast between lines and enhance readability. Inset in a) represents the non-averaged intensity I evolution for the case with $\Delta f = 50$ GHz, $B_{rx} = 14$ GHz and $P_{DAS} = 23.5$ dBm.

induced on the data channel. Regarding the first one, with $\Delta f = 50$ GHz, the effect of MI starts to occur already at $P_{DAS} = 23.5$ dBm, with non-negligible distortion corresponding to 4 times the data peak-to-peak swing I_{pp} (see Fig. 5.4a) and inset). Moreover, using (somehow extreme) high-peak-powers around $P_{DAS} = 28$ dBm, $\langle I \rangle$ increases approximately by 60 times the data stream I_{pp} , and thereby indicating a strong effect of the MI-crosstalk. For the same $P_{DAS} = 23.5$ dBm, $\Delta f = 100$ GHz in Fig. 5.4b) does not show any sign of distortion, which starts to be comparable with $\Delta f = 50$ GHz if employing a $P_{DAS} \sim 3-4$ dB higher. In Fig. 5.4a), the case at pulse peak power ~ 29 dBm was not recorded, as it could damage the PD, while it is shown in Fig. 5.4b). At the highest recorded P_{DAS} , the effect reduces by an order of magnitude when the separation is increased from 50 GHz to 100 GHz (60 a.u. for the $\Delta f = 100$ GHz case), demonstrating the effectiveness of using larger frequency spacings to decrease the amount of MI-induced crosstalk. This is made even more

explicit in Fig. 5.4c), for the case with $\Delta f = 200$ GHz. The data waveform distortion is completely absent for $P_{DAS} < \sim 29$ dBm, and weakly appearing for higher peak powers. This is slightly noticeable in the two most right waveforms ($P_{DAS} > 28$ dBm), around 50 ns. The second physical effect concerns the imbalanced shape of the crosstalk during the pulse co-propagation (i.e., the central 80 ns of the total 150 ns), clearly visible in Figs. 5.4a-b). Because of the linear change of central frequency inside the pulse, due to chirp, the MI-generated spectrum, as seen in Fig. 5.3 for a fixed P_{DAS} , broadens inside the $\tau = 80$ ns, by a factor $\Delta\nu$. This leads to a time-dependent crosstalk over the data stream, which explains the clear imbalance, for both Δf values in Figs. 5.4a-b), of the $\langle I \rangle$ values from the beginning to the end of the pulse co-propagation. This effect is particularly intense for high $P_{DAS} \geq 26$ dBm. For the $\Delta f = 200$ GHz case in Fig. 5.4c), the crosstalk is too weak to make the imbalance noticeable.

Similar observations were made in our experiments for the other filter bandwidths B_{rx} and 400 GHz frequency spacing.

Bit error rate evaluation

In order to observe the effect of the DAS pulse propagation on the data transmission performance, in this paragraph, we present the experimental BER measurements. Before proceeding, we point out that:

- the baseline BER without pulse interaction is the typical one for non-optically pre-amplified direct-detection receivers, thus mostly being limited by the Gaussian-like noise introduced by the transimpedance amplifier placed after the photodiode;
- in the presence of DAS pulse interaction, the evolution of BER in our setup will be non-stationary over time, since we clearly showed in the previous paragraph that the MI-crosstalk is present only inside the DAS pulse time window. However, when present, it can be very strong, requiring the estimation of a sort of “time-resolved” BER. To do this, we resort to a similar approach employed to evaluate the $\langle I \rangle$ metric. For more information on this experimental derivation on time-resolved BER estimation, the interested reader can refer to this previous work of ours (see Fig. 1c)) in [141], which anyway was related to a different transmission scenario).

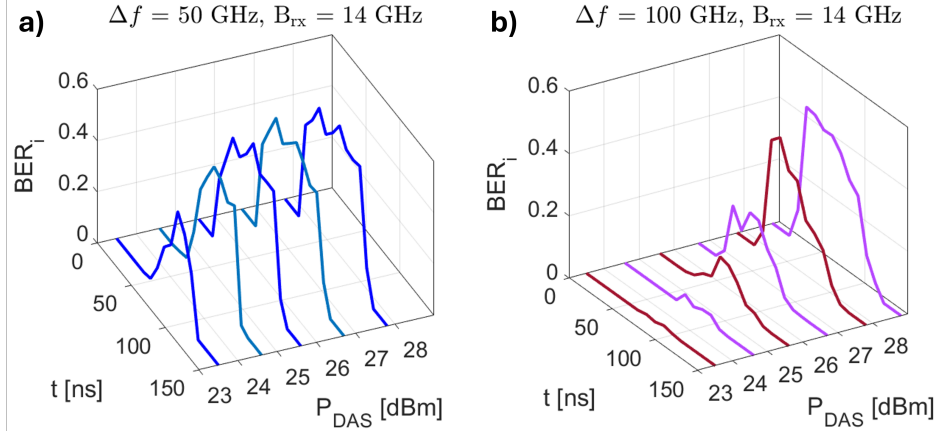


Fig. 5.5 Instantaneous BER time-evolution along the pulse co-propagation with data for $B_{tx} = 14$ GHz, when a) $\Delta f = 50$ GHz and b) $\Delta f = 100$ GHz, versus P_{DAS} . Different colors are only used to provide contrast between lines and enhance readability.

We start by reporting in Fig. 5.5 the “instantaneous” BER (BER_i) for the same cases of Figs. 5.4a-b) ($\Delta f = 50$ GHz, 100 GHz, and $B_{tx} = 14$ GHz). The BER_i time evolution has been computed considering consecutive windows of 100 bits each (i.e. 10 ns) for each of 50 PRBS periods (i.e. 5000 bits per window). We then centered the plots in Fig. 5.5 around the same 150 ns of Fig. 5.4a-b).

The results reported in Fig. 5.5a) shows that MI can be so strong for $P_{DAS} \geq 24.6$ dBm that BER_i reaches 0.5 when the DAS pulse is on, a situation that would made the data transmission to go completely out of service. The scenario significantly changes in Fig. 5.5b) which analyzes a larger spacing $\Delta f = 100$ GHz. A comparable effect with $\Delta f = 50$ GHz at $P_{DAS} = 24.6$ dBm can be noticed when $P_{DAS} \sim 28$ dBm, i.e. ~ 3 dB higher. In this case, since crosstalk is weaker (see Fig. 5.4b)), the BER_i does not show any saturation at any of the considered peak power levels. Interestingly, the $\langle I \rangle$ shape imbalance in Fig. 5.4b), particularly for $P_{DAS} \geq 27$ dBm, completely reflects the BER_i evolution in Fig. 5.5b). The broadening of the MI spectrum due to the chirp induces a higher number of errors at the rising edge of the pulse than at the falling edge, forcing a time dependency of the BER along the 80 ns of pulse co-propagation with the data channel. We envision, still to be verified by further experiments and numerical simulations, that this may depend on the frequency content of the pulse. In this case, a fixed τ with larger Δv would present even weaker distortions versus the end of the pulse co-propagation.

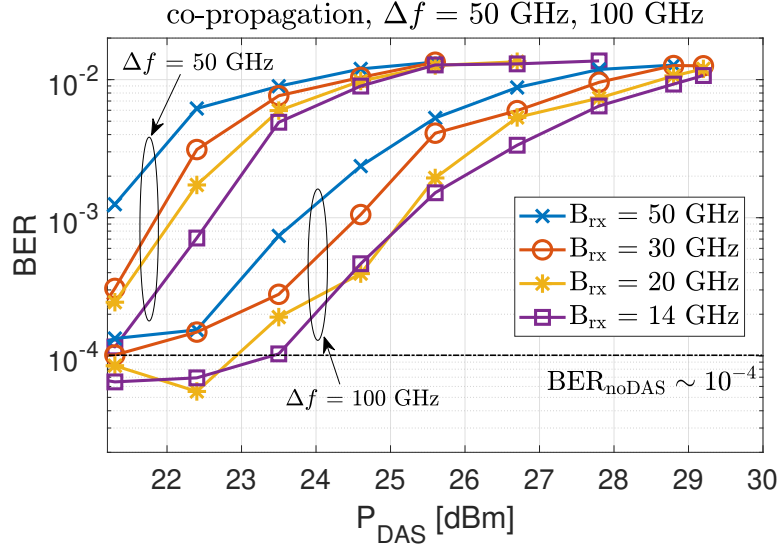


Fig. 5.6 BER curve versus P_{DAS} values when co-propagating data and chirped pulse, for $\Delta f = 50$ GHz and $\Delta f = 100$ GHz. Four different optical filter bandwidths have been tested for both cases.

Figures 5.6, 5.7 show the BER (averaged on the full received experimental time window, equal in this case to about $200 \mu s$, i.e. more than 60 PRBS periods), as a function of P_{DAS} for different conditions of channel frequency spacing Δf and optical filter bandwidth B_{rx} . BER curves are shown in Fig. 5.6 for $\Delta f = 50$ GHz and 100 GHz, in Fig. 5.7a) for $\Delta f = 200$ GHz and in Fig. 5.7b) for $\Delta f = 400$ GHz. The black dashed line labeled BER_{noDAS} represents the baseline BER value when no DAS pulse is sent into the fiber, serving as a reference point for comparison. To have a quantitative estimation of the maximum acceptable P_{DAS} levels allowing co-existence, we define the following power metrics:

- P_{th} is the value of P_{DAS} for which the resulting BER is $\simeq BER_{noDAS}$, i.e. the power level above which the BER versus P_{DAS} curve has an inflection point: this power level would serve as the threshold after which the effect of DAS pulse co-propagation affects the average BER;
- $P_{FECfail}$ is the P_{DAS} value where the BER curve crosses 10^{-2} , which we consider as the BER threshold before FEC.

In Fig. 5.6, for 100 GHz frequency separation and $B_{rx} = 14$ GHz, $P_{th} \sim 23.5$ dBm, and decreases by more than 2 dB when employing $B_{rx} = 50$ GHz. The $\Delta f = 50$ GHz

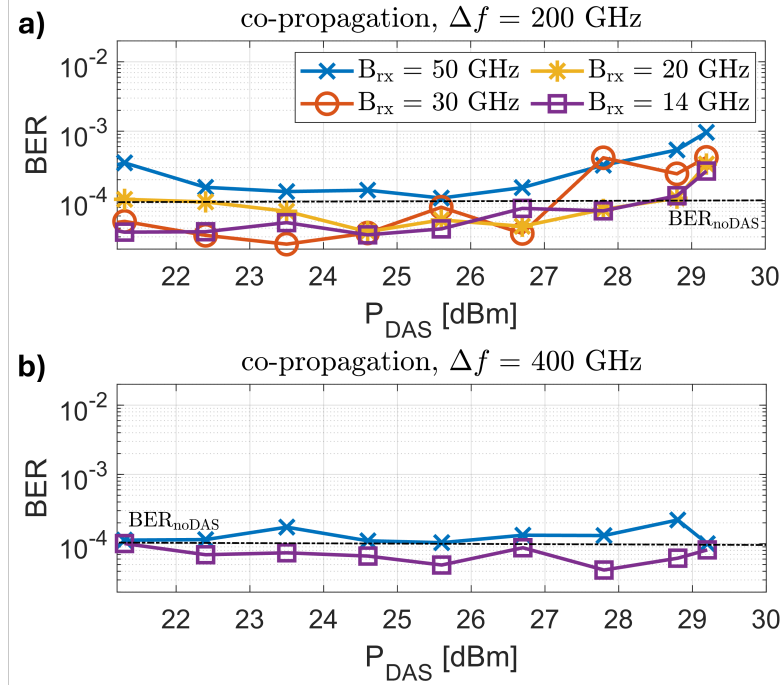


Fig. 5.7 BER curve versus increasing P_{DAS} values when co-propagating data and chirped pulse, for a) $\Delta f = 200$ GHz and b) $\Delta f = 400$ GHz. Four different optical filter bandwidths have been tested for the former, while only two for the latter. Legend is shared between a) and b).

frequency spacing case is much more critical, as the P_{th} is almost always below the considered range of P_{DAS} . Moreover, for $B_{rx} = 14$ GHz, $P_{FECfail} \sim 25$ dBm, 3-4 dB lower than the $\Delta f = 100$ GHz case. Despite the effect of using narrower B_{rx} clearly shows strong improvement on the BER values (in the $\Delta f = 50$ GHz case, even one order of magnitude for $P_{DAS} = 22$ dBm when varying B_{rx} from 50 GHz to 14 GHz), large chirped-pulse DAS coexistence with $\Delta f = 50$ GHz spaced data channel is still quite challenging. Conversely, using increasing frequency spacings demonstrated advantages for the coexistence of the two signals, with a reduced impact of DAS pulse on the co-propagating data channel, in line with what was discussed above and shown in Fig. 5.3. In particular, Figures 5.7a-b) show the BER as a function of P_{DAS} when the DAS and data channel are spaced by 200 GHz and 400 GHz, respectively. Despite a slight effect noticeable for $\Delta f = 200$ GHz, when using high DAS peak powers above $P_{DAS} \sim 28$ dBm, the consequences for the data channel are limited, for any of the B_{rx} value tested. Referring to Fig. 5.7b), for the $\Delta f = 400$ GHz case, there is no observable data transmission impairment for any P_{DAS} tested. Figures 5.7a-b) confirm that coexistence with data channels spaced by 200 GHz or 400 GHz from

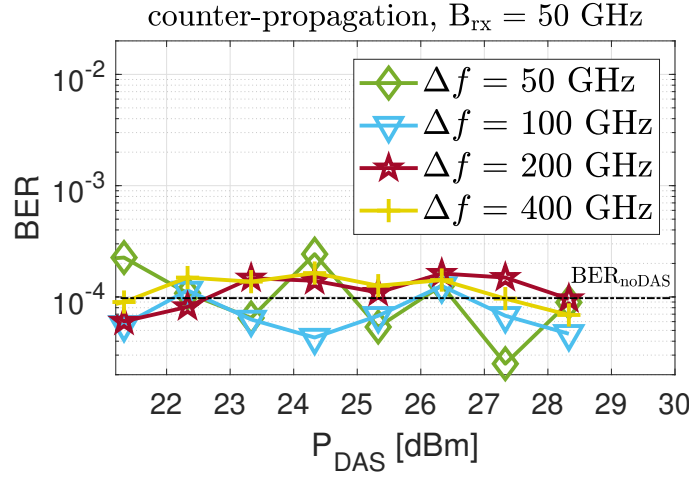


Fig. 5.8 BER curve versus increasing P_{DAS} values when counter-propagating data and chirped pulse, for different Δf and same optical filter bandwidth B_{rx} .

the sensing signal can be reliably ensured. Take also into account that, when dealing with a real DAS system, the repetition period is much larger (of the order of ms), leading to a weaker effect on the average BER curves, but to an identical one in terms of instantaneous BER (see Fig. 5.5).

To fully address the scenario of coexistence, we also tested a counter-propagation configuration, where DAS and data signals travel in opposite directions. The rationale for trying also the counter-propagating case is related to the fact that MI is strongly dependent on phase matching conditions between the involved propagating signals, so that it is well known that MI basically disappears for the counter-propagating case [63] (just like four-wave mixing or cross-phase modulation). The used experimental setup is identical to the one presented in Fig. 5.1a), except for the DAS signal, which is now injected at the receiver side through the DWDM demux and propagates towards the DWDM mux. An isolator was also added at the data laser output to prevent damage. We used the same set of parameters studied for the co-propagation, such as the same Δf values, optical filter bandwidths B_{rx} , and the same ranges for P_{DAS} values. The results with $B_{rx} = 50$ GHz at all tested frequency spacings are reported in Fig. 5.8. The BER as a function of the P_{DAS} shows no significant crosstalk induced on the data channel, with transmission performance comparable to the case when no DAS signal is present in the system at $BER_{noDAS} = 10^{-4}$. These results experimentally confirms the disappearances of any relevant nonlinear effects in this case. All the other receiver optical filter bandwidths (30 GHz, 20 GHz, 14 GHz)

Table 5.1 P_{th} and $P_{FECfail}$ values for co-/counter-propagating signals, considering all the tested B_{rx} and Δf . N.C. is short for “no consequences” recorded on the BER, for those parameters.

Setup	Δf	B_{rx}	P_{th}	$P_{FECfail}$
co-prop.	50 GHz	14 GHz	21.2 dBm	25 dBm
		20 GHz	< 21.2 dBm	25 dBm
		30 GHz	< 21.2 dBm	24.5 dBm
		50 GHz	< 21.2 dBm	24 dBm
	100 GHz	14 GHz	23.5 dBm	29 dBm
		20 GHz	23 dBm	28.8 dBm
		30 GHz	21.2 dBm	28 dBm
		50 GHz	< 21 dBm	27 dBm
	200 GHz	14 GHz	28.8 dBm	> 29.2 dBm
		20 GHz	28.8 dBm	> 29.2 dBm
		30 GHz	27 dBm	> 29.2 dBm
		50 GHz	27 dBm	> 29.2 dBm
	400 GHz	14 GHz	N.C.	N.C.
		20 GHz	N.C.	N.C.
		30 GHz	N.C.	N.C.
		50 GHz	N.C.	N.C.
counter-pr.	N.C.			

have also been tested with similar results to Fig. 5.8, but not reported due to space limitations.

To provide a summary of all the tested conditions, we summarized in Table 5.1 the main working conditions for all the different parameters. In particular, Table 5.1 shows the (approximate) values of P_{th} and $P_{FECfail}$ for each Δf , B_{rx} , and for both co-propagating and counter-propagating techniques. Considering the standard $P_{DAS} \leq 23$ dBm for DAS systems, a $\Delta f = 100$ GHz data channel would not be affected by co-propagation with the sensing signal, if using $B_{rx} = 20$ GHz or 14 GHz ($P_{th} \geq 23$ dBm in these cases). Instead, a $\Delta f = 50$ GHz spacing is critical, resulting in a maximum admissible $P_{DAS} \leq 21.2$ dBm when the narrower $B_{rx} = 14$ GHz filter bandwidth is used. The conditions where we experimentally verified reliable coexistence are with $\Delta f = 400$ GHz or counter-propagation, where no consequences have been recorded on the data channel, for any P_{DAS} . Employing $\Delta f \geq 200$ GHz, the effect of crosstalk is so small that even larger B_{rx} up to 50 GHz can be employed. In this case, P_{th} is usually more than 27 dBm. Table 5.1 also highlights that filtering is crucial, but a larger Δf is more effective in reducing crosstalk. While increasing Δf

from 50 GHz to 100 GHz raises $P_{FECfail}$ by 4 dB, fixing Δf and narrowing B_{rx} shows variation of $P_{FECfail}$ of 1 dB for 50 GHz spacing and 2 dB for 100 GHz spacing. This happens because the crosstalk distortion on the data channel at $P_{FECfail}$ is at its highest point, and the filter's effectiveness limited.

5.1.3 Numerical simulations

The scenarios outlined in the previous section for the co-propagation experiment have also been examined through detailed time-domain split-step numerical simulations. These simulations not only confirm the results obtained but also provide deeper insights into the key nonlinear interactions between the DAS signal, the data signal, and noise. Furthermore, they allow for the exploration of a broader range of parameters, including the investigation of additional optical filtering options.

We numerically simulated the same DAS pulse used in the experiments, with identical intensity shape, chirp content, duration, and the same range of peak powers. In particular, ten DAS pulses are generated along the 10 Gbit/s data stream, thus the total simulated time window is equal to $\sim 32 \mu s$, again with 2.4% duty cycle. The shorter simulation window compared to the experiments was a compromise between CPU computational time and accuracy, and, as we will show later, still allows us to obtain results that can be compared to the experiments (i.e., the same BER saturation level and similar average spectra). The fiber length considered for the simulations is again 10 km, and only the optimal $B_{rx} = 14$ GHz optical filter bandwidth was tested. Flat noise from the transimpedance amplifier (TIA) was added to the received signal, and its power spectral density was adjusted to have the same sensitivity curve for BER_{noDAS} as in the experiments. As detailed in Section 5.1.1 when discussing Fig. 5.1b), the two extra optical noise contributions coming from the DAS transmitter branch are the *I/Q modulator harmonics* and the *ASE noise* (generated by the EDFA used in the DAS transmitter). As shown in Fig. 5.2a), MI intensifies this optical noise, with the resulting main lobes frequency position depending on the pulse peak power according to Eq. 5.1. While ASE noise can be easily added in simulations, the peculiar shape of the harmonics in Fig. 5.1b) is more complex to be emulated. The harmonics are specific to our experimental setup, we thus decided to neglect them. Instead, we focused on testing various levels of ASE noise. This approach allowed us to intentionally generate a wider range of transmitted-side OSNRs than the one present in our setup. By doing this, we aimed to gain a clearer understanding

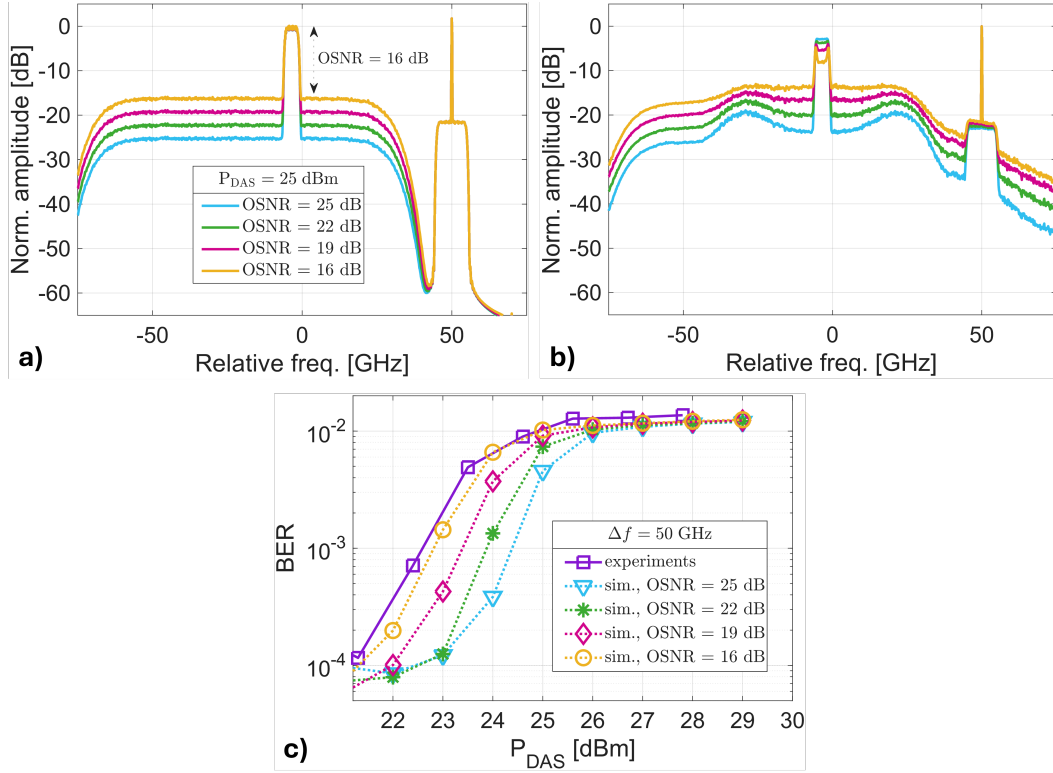


Fig. 5.9 Spectra of transmitted DAS pulse + data a) before and b) after fiber propagation with $\Delta f = 50$ GHz data channel, when considering different OSNR values, for $P_{DAS} = 25$ dBm. All spectra have been normalized to the maximum value when transmitting $P_{DAS} = 25$ dBm. Graph c) shows the BER as a function of the P_{DAS} for both experiments and numerical simulations for different OSNR values.

of the general impact of optical noise levels, which are subsequently influenced by the nonlinear effects in the optical link. In particular, in our simulation, ASE noise is generated as usual as a flat complex white Gaussian noise and it is then passed through a Super-Gaussian filter of nominal bandwidth $B_{tx} = 100$ GHz. We chose this value for the flat ASE noise to reasonably fit the overall experimental noise sources bandwidth (see Fig. 5.1b) and related discussion). Moreover, the filtered ASE noise was positioned around the DAS pulse to match the experiments. The resulting transmitted spectra are reported in Fig. 5.9a) for 50 GHz frequency spaced data channels. Here, $P_{DAS} = 25$ dBm, while the ASE noise level was tweaked to have different OSNRs of 25 dB, 22 dB, 19 dB, and 16 dB. We then propagated the signals in Fig. 5.9a) and recorded the received spectra in Fig. 5.9b) at the fiber output. In both Figs. 5.9a-b) all spectra are normalized to the maximum of the DAS pulse transmitted spectrum, so that Fig. 5.9a) shows the DAS pulse spectra maxima

at 0 dB. Notice that the received spectra depict the two MI lobes on either side of f_{DAS} , such as those predicted by the theory in Fig. 5.2a). Figures 5.9a-b) confirm our earlier observations. Although optical noise is minimal on the data channel due to the transmitter side optical filtering, it increases after fiber propagation because of strong MI caused by high-peak-power DAS pulses. Specifically, Figure 5.9b) illustrates that, as the OSNR decreases, the MI-induced optical noise around the data channel rises significantly.

We also analyzed the BER performance in simulation, as shown in Figure 5.9c). This figure illustrates the BER evolution versus P_{DAS} for a frequency separation of $\Delta f = 50$ GHz, incorporating various OSNR values varied in 3 dB increments: for OSNR = 25 dB the BER starts to rise at $P_{DAS} \sim 23$ dBm, 2 dB higher than the case for OSNR = 16 dB. In other words, the effect of MI on the data channel is triggered for lower P_{DAS} values if the OSNR is decreased. These results lead to a possible design rule: the lower the optical noise generated by the DAS transmitter setup, the higher P_{DAS} can be allowed. We also point out that the curve for OSNR=16 dB matches our experimental BER curve, where the same 16 dB OSNR was observed between the DAS pulse and the highest I/Q modulator harmonic (see Fig. 5.1b)). In the remainder of this section, we will show results for OSNR=16 dB only. The BER curves for experiments and simulations when $\Delta f = 50$ GHz, 100 GHz, and $B_{rx} = 14$ GHz are shown in Fig. 5.10a). The agreement with experiments is very good in the 50 GHz case, whereas small discrepancies can be observed in the 100 GHz case for $P_{DAS} \geq 25$ dBm. This can be attributed to a non-perfect reproduction of the shape of the noise in the numerical simulations. A flat ASE noise (such as the one we have in simulation) amplified by the MI could generate a flatter spectrum for increasing P_{DAS} . This leads to an almost perfect match between experimental and simulation BER when $P_{DAS} < 24.6$ dBm, but to a mismatch at higher peak power, as if the tails of the MI-amplified noise spectrum were still intense. Overall, the reasonable match of the experimental and numerical simulation BER curves with OSNR = 16 dB means that the MI crosstalk on the data channel can be reliably predicted.

The inset of Figure 5.10a) shows the BER evolution versus fiber length L , assuming $P_{DAS} = 24$ dBm, $\Delta f = 100$ GHz and the same OSNR and B_{rx} of the main figure, obtained through simulations. As expected, the effect of MI-crosstalk on the data effect saturates around $L \sim 25$ km, which is the usual fiber length where the effect of nonlinearities is stronger. For lengths $L \geq 25$ km, the recorded BER values remain one order of magnitude lower compared to those recorded under worse

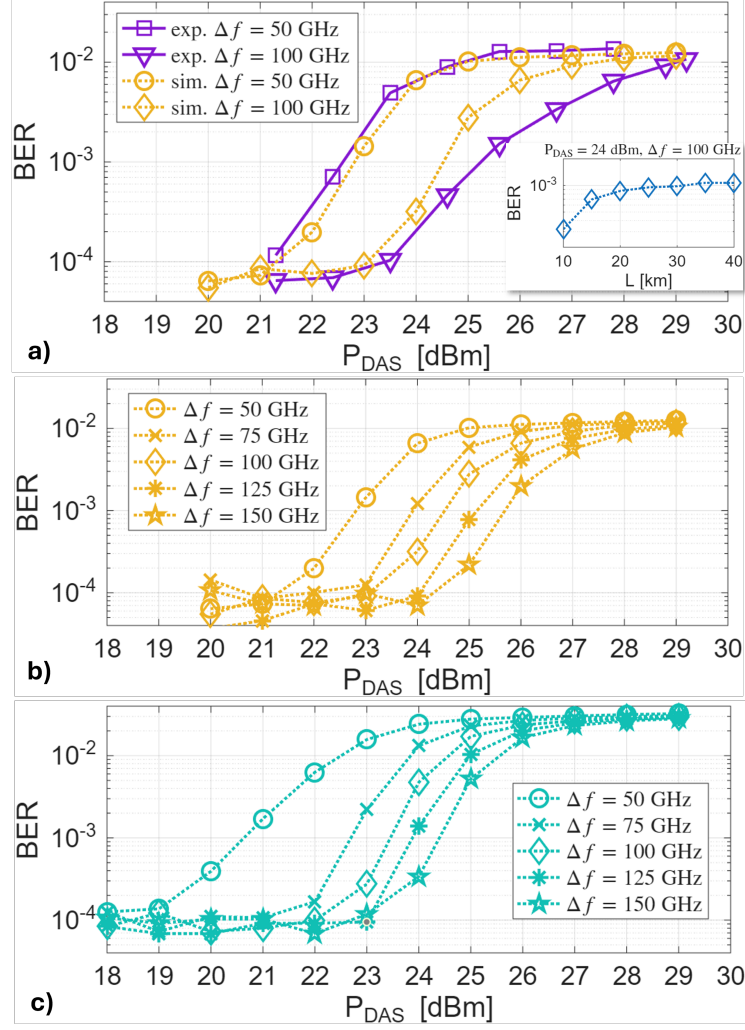


Fig. 5.10 BER curves versus P_{DAS} for a) $\Delta f = 50$ GHz and 100 GHz with $B_{rx} = 14$ GHz for both experiments, and simulations. Inset shows the simulated BER versus fiber length, when $P_{DAS} = 24$ dBm and $\Delta f = 100$ GHz. Simulation-only BER curves for increasing Δf values from 50 GHz to 150 GHz in steps of 25 GHz are shown in b) for the PAM2 and c) for the PAM4 modulation formats. All the simulations have been obtained setting OSNR = 16 dB.

conditions (higher P_{DAS} , wider B_{rx} , lower Δf) at $L = 10$ km, which saturates at 10^{-2} . Figure 5.10b) shows the BER curves varying Δf from 50 GHz to 150 GHz in steps of 25 GHz. These simulation results further confirm the importance of using larger frequency spacings, as the BER shows increasing tolerance to the DAS peak power for increasing Δf . This results in more than 3 dB higher admissible P_{DAS} when Δf is increased from 50 GHz to 150 GHz, at $BER = 10^{-4}$. To provide a more comprehensive scenario we also ran, just for this specific case, numerical

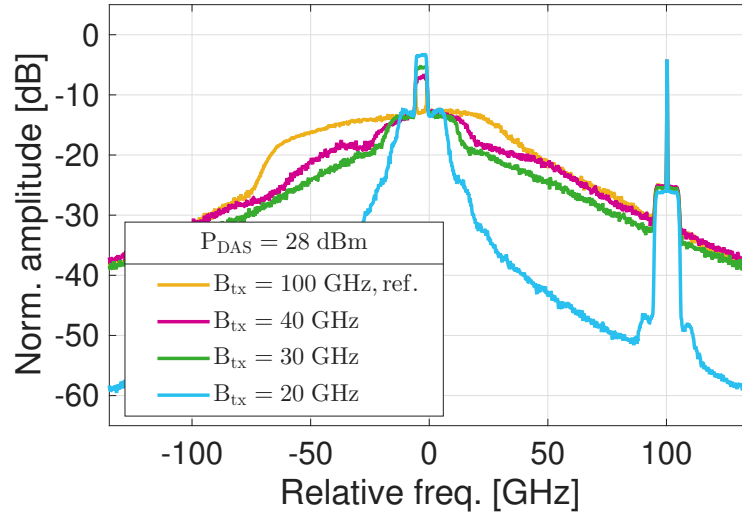


Fig. 5.11 Spectra of the received DAS + 100 GHz spaced data channel when considering $P_{DAS} = 28$ dBm and varying B_{tx} . The yellow curve refers to the reference case with 100 GHz wide noise bandwidth employed to emulate the DWDM.

simulations changing the modulation format to PAM4, spanning the same Δf range of Fig. 5.10b). The average BER versus P_{DAS} curves are reported in Fig. 5.10c). The DAS peak powers range has been increased to include 18 dBm and 19 dBm, to show where the effect of DAS is negligible for this modulation format. As expected, the penalty on the PAM4, introduced by the co-propagating sensing signal, is higher than the PAM2 case. Particularly, the MI-induced crosstalk starts to have consequences on the PAM4 average BER for P_{DAS} values 1-2 dB lower than the PAM2 modulation format analyzed until now. Additionally, the BER curves for the PAM4 saturates at a slightly higher BER value than the PAM2 case.

As shown in Table 5.1, a proper optical filtering at the receiver can help reduce the amount of noise and limit the onset of MI, thus reducing the generated crosstalk on the data channel. We also investigate the possibility of introducing filtering on the DAS signal to restrict the noise bandwidth at the transmitter side. In Fig. 5.9, the Super-Gaussian shape of the filter has bandwidth $B_{tx} = 100$ GHz, and it is not centered around the chirped signal because we wanted to emulate, as closely as possible, the experimental scenario. To try to improve the performance, we made further investigations, centering the filter around the DAS pulse and testing narrower bandwidths B_{tx} : 40 GHz, 30 GHz and 20 GHz. Fig. 5.11 shows the resulting spectra after fiber propagation, when co-propagating with a $\Delta f = 100$ GHz-spaced data channel and employing $P_{DAS} = 28$ dBm. Spectra are normalized with respect to the

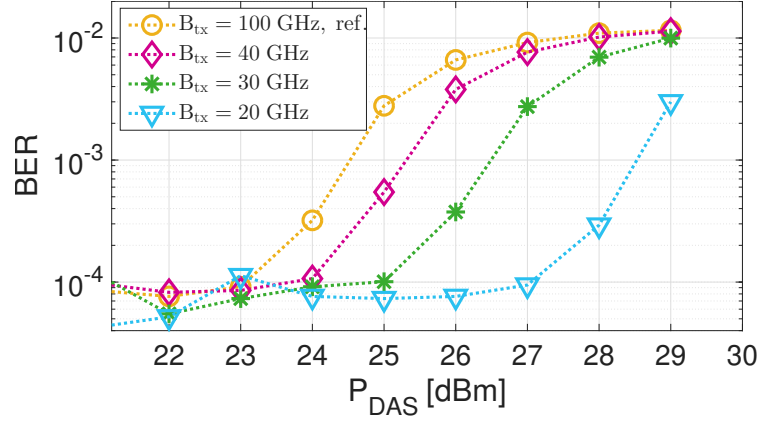


Fig. 5.12 BER curves versus P_{DAS} obtained in numerical simulations, when employing narrower optical filter bandwidths B_{tx} at the transmitter side, around the DAS channel. The yellow curve refers to the reference 100 GHz wide noise bandwidth employed to emulate the experimental DWDM.

related transmitted spectrum maximum of the DAS pulse (as was done for Figs. 5.9a-b)). The difference, in terms of crosstalk, is small between $B_{tx} = 40$ GHz and the reference $B_{tx} = 100$ GHz case, and slightly enhanced when further decreasing the bandwidth to $B_{tx} = 30$ GHz. A significant difference is instead present when employing $B_{tx} = 20$ GHz, which is likely shaping the noise to a too small bandwidth for the main lobes of the MI gain to properly amplify it. The related BER curves for the different conditions analyzed in Fig. 5.11 are shown in Fig. 5.12, reporting an important enhancement of the BER for decreasing B_{tx} .

5.1.4 Discussions and conclusions

This section discusses in detail the coexistence of large chirped-pulse DAS and IM-DD systems on the same fiber, primarily focusing on the impact on data channels. Our findings identified Kerr-related MI, caused by propagation of high-peak-power pulses from DAS, as the main impairment affecting data transmission. We investigated the impact of the variation of numerous parameters, which enabled us to summarize the following “system guidelines” for designing future fiber links where the coexistence of DAS and data transmission is necessary.

- **Counter-propagation.** The experimental setup in which the DAS pulse is transmitted in the opposite direction with respect to the data shows negligible

nonlinear effects on the data channels. Thus, when possible from a network architecture viewpoint, this should be the preferred option.

- **Co-propagation.** When, on the contrary, co-propagation is a must from an architectural viewpoint, the signals' coexistence has been demonstrated both experimentally and through numerical simulations, but only after a careful selection of the main transmission parameters. Given that the MI-induced crosstalk is the main impairment on data, the 50 GHz spacing should be avoided (unless DAS peak power can be kept very low, such as below 20 dBm), while 100 GHz spacing allows DAS peak power up to ~ 23 dBm, a value that is compliant with the one often used in commercial DAS systems. If 150 GHz or 200 GHz (or higher, such as 400 GHz) spacing is acceptable from an architectural viewpoint, then this is the preferred system option, allowing DAS peak power above 28 dBm with negligible impact on data. These conclusions on large spectral spacing would become even more relevant for a longer fiber link (we addressed 10 km in this work) or for multi-span optically amplified scenarios where one DAS is inserted in each span (just like what is done today for the optical supervisory channel, OSC).
- **Transmitter and receiver filters, in co-propagation.** The transmitted side noise, if possible, should be kept as low as possible, as MI intensifies it. Narrow optical filtering on the transmitter side, around the DAS pulse, has also been shown to limit the MI onset. Similarly, strong optical filtering on the receiver side, around the data channel, reduces the amount of MI-crosstalk, improving the coexistence of the two signals.

Even though it is not addressed in this work, we point out that a possible strategy for co-propagation would be to position the DAS signal completely off-band, i.e., several nanometers away from the data wavelengths. The only limitation of this approach would be the onset of Raman nonlinearity, which reaches its maximum when the “pump and probe” signals are about 12 THz apart. These considerations are outside the scope of this section, but may lead to an interesting future research work.

In our further studies, we also plan to address the coexistence of DAS with dual polarization-quadrature amplitude modulation (DP-QAM) coherent telecommunication systems [142]. In this scenario, the impact on data would be more complex, since coherent detection is also phase-sensitive. In addition to MI, cross-phase modulation nonlinearity may also become relevant.

5.2 Experimental Investigation on Pulsed DAS Coexistence with DWDM High-Speed Coherent Transmission in C and L-bands

We discussed above and in the previous chapters how joint communication and sensing in a shared optical fiber infrastructure enable simultaneous high-capacity data transmission and real-time environmental monitoring. In particular, integrating DAS systems with DWDM transmission provides a cost-effective way to enhance both network performance and situational awareness [143], using a single C-band wavelength for DAS without waste in spectrum and without requiring dark fibers dedicated only to sensing. However, DAS–DWDM coexistence introduces physical-layer impairments and nonlinear effects that must be carefully managed. As we showed for a single IM-DD channel, the high-power DAS probe can interact nonlinearly with neighboring DWDM channels [144]: different DAS approaches have been proposed to face this issue [145, 146]. Besides the Kerr effect in C-band, DAS could also trigger stimulated Raman scattering in L-band, causing inter-band distortion. Nonlinear interactions also depend on whether sensing and data signals propagate co- or counter-directionally. Further understanding these effects is essential for efficient spectrum sharing and optimal hybrid network deployment.

This work experimentally investigates the coexistence of high-speed C+L band DWDM transmission with a commercial coherently-received C-band non-chirped pulsed DAS. We focus on Kerr nonlinear crosstalk in C-band and investigate any Raman-induced distortion in L-band. Experiments are performed on a 20 km fiber span with added ASE noise at the receiver to evaluate DAS-induced penalties, using the required OSNR at a certain BER as a metric, to emulate optically amplified links where DAS operates on the span between two amplifiers or reconfigurable optical add-drop multiplexers (ROADMs). Both co- and counter-propagating configurations are tested at varying DAS pulse peak powers. Pre-FEC BER and FEC error counts obtained via real-time commercial coherent transponders reveal the implications of joint distributed monitoring and DWDM communications for system design and spectral planning in next-generation fiber networks.

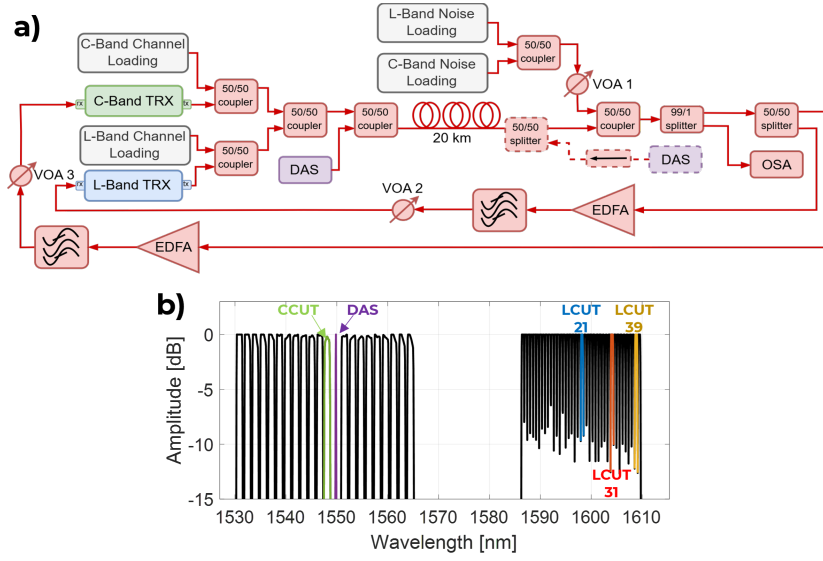


Fig. 5.13 a) Experimental setup and b) transmitted optical spectrum.

5.2.1 Experimental setup and results

The experimental setup used to investigate the coexistence scenario discussed above is shown in Fig. 5.13a). Two generations of commercial coherent transceivers are used to transmit a 118 GBaud DP-QPSK signal at 400G net bit rate in the C-band and a 69 GBaud DP-QPSK signal at 200G net rate in L-band. These modulated data-carrying signals are combined through channel loading with other dummy signals to obtain two DWDM combs with a total of 22 and 40 channels, respectively, in the C- and L-bands. As depicted in Fig. 5.13b), the C-band channel under test (CCUT) is centered at 1548.52 nm, on the 36th slot of the C-band ITU-T 100 GHz grid, whereas the L-band channel under test (LCUT) is initially at 1593.37 nm, in the middle of the generated L-band comb. The DAS central wavelength is 1550.12 nm (channel 34 of the grid), 200 GHz apart from the data channel. The two DWDM combs are combined together and then with the DAS, before propagation along a 20 km SSMF. The total optical power at the fiber input is 7.5 dBm for the C-band and 8 dBm for the L-band. This corresponds to approximately -6 dBm for each of the 22 C-band channels and -8 dBm for each of the 40 L-band channels. In the counter-propagating case, the DAS signal is introduced at the output of the SSMF and propagates in the opposite direction to the data (dashed boxes in Fig. 5.13a)). At the receiver side, ASE noise loading is applied on a bandwidth of 500 GHz around both CCUT and LCUT to vary the received OSNR by means of a variable optical

attenuator (VOA 1, see Fig. 5.13a)). A 99/1 tap is used to monitor the spectrum and measure the OSNR on a bandwidth equal to the baud rate. Lastly, a 50/50 optical splitter is used to send the whole comb on two different paths, where it is amplified, properly filtered to isolate the CUT, attenuated through VOA 2 and VOA 3 to control the received optical power, and detected by the two receivers. The CCUT and LCUT are filtered out of the comb with a 200 GHz and 100 GHz filter, respectively.

As we expect data traffic to be hindered by Kerr nonlinear effects in the C-band and by Raman effect in the L-band, we also vary the frequency separation between the DAS and the CCUT and the central wavelength of the LCUT. Fig. 5.13b) shows the normalized spectra of the C+L band DWDM combs, highlighting the position of the CCUT (green) 200 GHz apart from the DAS (purple), and the three investigated positions of the LCUT, respectively placed on channel 21 (blue), 31 (red) and 39 (orange) of the generated 40-channel L-band comb. By increasing the separation of the LCUT wavelength from the DAS from 43.25 nm to 50.05 nm and then to 58.64 nm, the LCUT was shifted closer to the Raman gain peak (~ 13 THz from the pump, in silica fibers). For each CUT, pre-FEC BER and post-FEC errors were

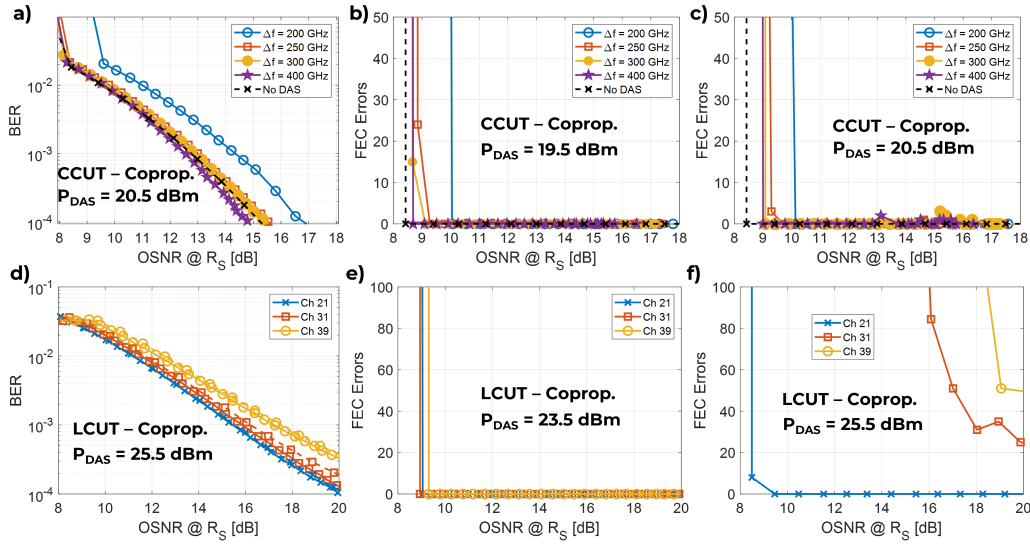


Fig. 5.14 Co-propagation case. a) BER vs OSNR for 400G DP-QPSK CCUT and different spectral spacings Δf when $P_{DAS} = 20.5$ dBm (solid) and without DAS (dashed), and corresponding FEC errors vs OSNR for CCUT when P_{DAS} is b) 19.5 dBm and c) 20.5 dBm. d) BER vs OSNR for three 200G DP-QPSK LCUT when $P_{DAS} = 25.5$ dBm (solid) and without DAS (dashed), and corresponding FEC errors vs OSNR for all LCUT when P_{DAS} is e) 23.5 dBm and f) 25.5 dBm.

measured versus OSNR while varying the spectral distance from the DAS, as shown

in Fig. 5.14. Post-FEC errors were collected over 1 second for the CCUT and 60s for the LCUT. Given the 1 kHz DAS pulse repetition rate, we believe these measurement times are enough to obtain a meaningful statistic, including 1000 and 60000 DAS pulses of 100 ns duration each, respectively. We decided to increase the recording window to increase the chances of including fluctuations generated by the Raman effect, if any. The DAS pulse propagation-induced Kerr effect, affecting the neighboring C-band channels, is well known (see, in a different context, Section 5.1), intense and noticeable, even in short recording windows, while we were not sure about the possible SRS.

In the C-band co-propagating case reported in Fig. 5.14a-c), the pre-FEC BER curves for DAS pulse peak power $P_{DAS} = 20.5$ dBm show a slight improvement when increasing the Δf frequency distance from 200 GHz to 250 GHz and up to 400 GHz, but do not highlight any clear effect of the DAS presence. Keep in mind that a rigid shift like the one in Fig. 5.14a) could also be due to the different central wavelength of the CCUT employed. However, the nonlinear crosstalk due to the pulsed DAS signal co-propagating with the data channel can be observed by measuring the accumulated FEC errors. We refer to the FEC threshold as the BER value, typically around $\sim 2 \cdot 10^{-2}$, which makes the coherent receiver go “out of service”. In this case, the BER curve saturates to something in between $3 \cdot 10^{-2}$ and 10^{-1} , depending on the transceiver employed, and the number of FEC errors accumulates indefinitely, meaning that there is no chance for the transceiver to recover the data (i.e., the DSP is not working properly). More in detail, Fig. 5.14b) shows an increase in the FEC error count only for OSNR values corresponding to pre-FEC BER above FEC threshold, in the range 8-10 dB, when P_{DAS} is set to 19.5 dBm. This is a sufficient power level for the commercial DAS employed (Coherentia) to ensure monitoring sensitivity of about $12 \text{ p}\epsilon/\sqrt{\text{Hz}}$ over the considered 20 km span. A slight increase to $P_{DAS} = 20.5$ dBm (Fig. 5.14c)) causes a few FEC errors to occur at much higher OSNR values, and at any Δf . In such conditions, the internal DSP of the commercial card fails to correctly retrieve information, even though only for brief moments during the DAS pulse duration, thus effectively leading to a drop in data integrity. Similarly, in the L-band case shown in Fig. 5.14d-f), the pre-FEC BER curves measured for LCUT at different wavelengths when $P_{DAS} = 25.5$ dBm are perfectly superimposed to the curves without co-propagating DAS pulses, indicating no apparent impairment on data transmission due to the sensing signal. However, the FEC errors in Fig. 5.14f) highlight a large number of FEC fails for the same

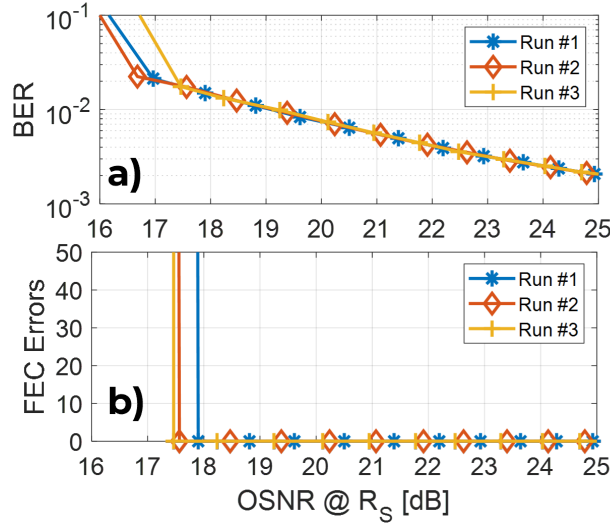


Fig. 5.15 a) Three BER vs OSNR measurements for 800G DP-16QAM CCUT in the counter-propagation case, and b) corresponding FEC errors when $P_{DAS} = 27.5$ dBm. Runs #1, #2, #3 refer to 1-second-long consecutive acquisitions.

$P_{DAS} = 25.5$ dBm. Interestingly, the number of FEC errors for a given OSNR level increases as the LCUT is moved towards the long wavelength range, as expected for a Raman-related effect, leaving transmission on the shorter wavelength LCUT still possible. Moreover, no errors for pre-FEC BER below FEC threshold (OSNR greater than 9 dB) are observed at $P_{DAS} = 23.5$ dBm (see Fig. 5.14a)), showing a threshold P_{DAS} for the onset of possibly Raman-induced distortion in between 23.5 dBm and 25.5 dBm, higher than the ~ 20 dBm for the Kerr effect in the C-band.

In the counter-propagating case, the nonlinear interaction time between the data channels and the DAS pulses is strongly reduced by the rapid walk-off. As a result, no effect of the DAS is observable on the data traffic, neither on the pre-FEC BER nor on the FEC errors, as shown in Fig. 5.15a-b) in the case of ultra-high speed communications with an 800G DP-16QAM modulated CCUT and the highest achievable $P_{DAS} = 27.5$ dBm. In this case, we considered single-channel transmission on both the C and L-bands and increased the total measurement time for the CCUT to 3 seconds by repeating the 1-second acquisition three times (Runs #1, #2, #3), to have a statistically more reliable estimation.

Table 5.2 Table summarizing all the obtained results. We depicted with green circles the cases where no FEC errors were recorded at any OSNR level, and with red crosses when at least one FEC error was measured. Specifically, four Δf values from 200 GHz to 400 GHz for the C-band, and the three LCUT central wavelengths (1593.37 nm, 1600.17 nm, and 1608.76 nm) for the L-band (separated by “/”). The acronym BUT stands for band under test.

Setup	BUT, net bit rate	P_{DAS} [dBm]								
		19.5	20.5	21.5	22.5	23.5	24.5	25.5	26.5	27.5
Co-prop.	C-band, 400G	o/o/o/o	x/x/x/x	x/x/x/x	x/x/x/x	x/x/x/x	x/x/x/x	x/x/x/x	x/x/x/x	x/x/x/x
	L-band, 200G	o/o/o	o/o/o	o/o/o	o/o/o	o/o/o	o/x/x	o/x/x	x/x/x	x/x/x
Counter-pr.	C-band, 400G	o	-	o	-	o	-	o	-	o
	C-band, 800G	o	-	o	-	o	-	o	-	o
	L-band, 200G	o	-	o	-	o	-	o	-	o
	L-band, 400G	o	-	o	-	o	-	o	-	o

5.2.2 Discussions and conclusions

We characterized the coexistence during simultaneous propagation of DAS sensing signal and high-speed DWDM traffic, both in C- and L-bands. Table 5.2 shows a summary of all the performed measurements, highlighting with green circles the cases where no FEC errors were recorded at any OSNR level (neglecting the ones related to the FEC threshold), and with red crosses when at least one FEC error was measured. For the co-propagation case, the symbols refer to the four Δf values from 200 GHz to 400 GHz (with 50 GHz step) in the C-band, and to the three LCUT central wavelengths (1593.37 nm, 1600.17 nm, and 1608.76 nm) in the L-band. Our findings show that coexistence is always feasible when counter-propagation can be implemented, even at very high transmission speed and P_{DAS} up to 800 Gbps and 27.5 dBm, respectively. On the other hand, in the case of co-propagation, the maximum admissible P_{DAS} is restricted to below 20.5 dBm for the adjacent C-band data channel, primarily due to Kerr nonlinearity. In the same case, for the L-band CUT, the power level is limited to below 25.5 dBm due to some nonlinear effects which could be related to the Raman effect. Further experimental/numerical simulation confirmations are needed to truly address the latter.

In conclusion, the counter-propagating case should not be critical in any practical conditions, since we show basically no penalty on DWDM data for P_{DAS} levels that are significantly higher than the typically used one, while the co-propagating setup appears as much more critical and thus its implementation should be analyzed in detail through a case-by-case study. For instance, compared to our 20 km experiments,

longer span systems will have a longer Kerr-effect nonlinear effective fiber length, typically reaching the maximum theoretical value $L_{eff} \simeq 22$ km for $\alpha = 0.2$ dB/km, and thus nonlinear impairment would be stronger than in our 20 km span experiments (where $L_{eff} \simeq 14$ km, for an estimated $(22 \text{ km}/14 \text{ km}) \simeq 2$ dB reduction in nonlinear power threshold).

5.3 Chapter Conclusions

The previous sections provided an overview of the coexistence between the most common telecommunication systems, including both legacy (but still widely used) IM-DD systems, as well as more standard systems, particularly for long-haul and ultra-high capacity infrastructures, coherent communication technologies, with typical DAS equipment.

The DAS technology that we employed when studying the IM-DD was first, academically, introduced in 2016 [60], and, despite being an ϕ OTDR, it does employ a different working principle when coming to the detection and measurements of the axial strains and temperature changes happening along the fiber. The fact that it exploits DD at the receiver also makes it comparable in complexity with IM-DD systems, justifying the study in Section 5.1. Nevertheless, we were mainly interested in discussing the effect that high-peak-power chirped pulses have on the neighboring IM-DD data channel, more than on the actual effect that the latter has on the DAS. Our conclusion suggests that coexistence is primarily limited by MI, which feeds on the in-band noise surrounding the DAS signal. By keeping the peak power below 23 dBm (which is typically true for CP- ϕ OTDRs) and also reducing the in-band noise, both in spectral occupancy and OSNR, the crosstalk on the data channel may be mild. Moreover, narrow filters around the data channels and large frequency spacings would strongly help reduce the data distortion. Similar conclusions were derived in completely different telecommunication systems, coexisting with DAS. In this case, the situation comprised coherent transceivers in the C- and L-bands, running at very high speeds, especially for the C-band (800G), coexisting with a more typical non-chirped DAS hardware. As shown in the BER curves reported in this study, it was basically impossible to characterize the induced nonlinearities by just looking at the BER penalty: the duty cycle was too small to induce the amount of errors necessary to affect the average BER. For this reason, we employed

the FEC errors metric, which proved to be a much more reliable value to test data resilience. Notice that vendors, even when BER values are acceptable and below the FEC threshold, do not tolerate FEC errors, which should always be kept exactly zero. Despite being complex to compare with the IM-DD system coexistence study, since the repetition rate is not the same and the DAS systems employ a different working principle, the Kerr-induced nonlinearities are the main impairments for both cases. MI is surely generated by the standard DAS employed in Section 5.2, but we demonstrated that, with peak powers below 22-23 dBm and $\Delta f > 100$ GHz, it should not really affect the data channel. Moreover, simulations and experiments of Section 5.1 were carried out in somewhat non-ideal conditions, which would be optimized (i.e., pulse better equalized, I/Q MZM harmonics suppressed, higher OSNR) in a commercial device such as the one used in Section 5.2, leading to a probably weaker MI-induced crosstalk in neighboring channels. Nevertheless, the study carried out with coherent systems showed consequences (i.e., FEC errors > 1) with peak powers higher than 20.5 dBm, in the C-band, even with > 200 GHz of frequency spacings. This is because, for IM-DD systems, the main DAS-generated nonlinear impairment is the MI-induced crosstalk, since data channels are not modulated in phase. Cross-phase modulation and four-wave mixing are surely generated by high-power signal propagation, and surely affect the CCUT, which is (also) phase-modulated since the system is coherent, leading to FEC errors, even if the working condition seems to be “better” than the one employed in the IM-DD case. We also need to specify that we are currently studying the effect that a chirped-pulse signal would have on the coherent data channel, and envision a possible difference: since the pulse has a phase content (i.e., the chirp), the phase effect on the channels may be different and needs careful study. Our works also demonstrated that, placing the DAS pulse really far (in frequency) from the actual comb, which is a solution that, based on the results of Section 5.1 and 5.2 on the C-band, would make perfect sense, needs to be carefully studied, as the Raman effect could impair the L-band channels and affect the receiver performances. One of the most important messages delivered by this chapter is that counter-propagation of telecommunication and sensing signals has always shown no impairments, at least on the data channel side, resulting in one of the most promising approaches when discussing coexistence with DAS, where applicable.

Further investigation is needed for the consequences that data channels have on the DAS equipment, which has not been tested in either of the two works discussed here. When co-propagating, the extra-small portion of backscattered light coming

from the data channels may distort the DAS pulse, affecting the sensing performance. This has also been experimentally evaluated by us in some experiments carried out as the very final part of this PhD and not reported in this thesis. For example, [138, 137] shows zero consequences on the sensing side, generated by the data signals. The true concern would come from the counter-propagating scenario, where the telecommunication channels would come right in the direction of the DAS backscattered trace, and could interfere with the sensing performance. We are currently investigating this scenario, and preliminary outcomes result in the DAS system not being affected at all, even in this condition.

Chapter 6

Thesis Conclusions

This PhD thesis reviewed the main options that have been investigated (and are currently under investigation, in some cases) in recent years, in the ISAC context. The state-of-the-art analysis proposed in Chapter 1 examined different available options to enable sensing in telecommunication networks, all perfectly valid and, for the most part, experimentally demonstrated (e.g., interferometric techniques, forward phase). Nevertheless, this thesis aimed to demonstrate that SOP-based sensing is among the easiest and most compatible techniques when coexisting with the telecommunication side. Coming to the conclusions of this whole work, it becomes necessary to distinguish between two terms that, through this thesis, have been used equivalently: *integrated* or *added* to the telecommunication system. State of polarization and forward phase are the only two physical parameters that may be exploited for sensing purposes, and are inherently integrated in coherent communications: the DSP already provides an estimate for the two parameters needed for data demodulation. Potentially, a simple software upgrade that outputs the related samples would enable the optical networks' external events sensitivity, basically at zero cost. Particularly, we showed how this is absolutely true for SOP, but not completely for forward phase: in this case, an ultra-stable laser would be needed, as the phase variations generated by hazards need to be distinguishable from the fluctuations generated by laser phase noise, typical in telecommunication systems where the lasers employed have linewidth of the order of several tens of kHz at least. Employing the phase as the sensing measurand must then have advantages justifying the cost of replacing all the hardware equipment initially thought for telecommunication only, which is not low at all: ultra-stable lasers can cost more

than ten thousand euros, which has to be scaled to all the coherent transceivers, making it basically unbearable. Our results demonstrate that, at least in metropolitan scenarios, there is no advantage in employing optical phase in place of SOP, as the sensing performances are worse. It should also be considered that this may not be true for submarine cables, where several works have demonstrated impressive reliability and detection capability of the forward phase. In this context, monitoring a reduced number of cables, and thus adding suitable lasers only for some specific hardware, may allow forward phase monitoring to scale better than in a metropolitan scenario. The same consideration holds for interferometric techniques, mentioned in Chapter 1.

This leaves space to SOP-based monitoring as the easiest way to enable sensing on optical networks, being the only measurand to truly be integrated with no need for external hardware to enable sensing. The only upgrade, which would be required by any other added/integrated sensing method, is a real-time algorithm that extracts the polarization samples and processes them to deliver timely warnings. This thesis investigated the issues related to the latter, proposing different ways to process SOP, also depending on the application scenario (e.g., metropolitan/mountain). We have extracted SOP samples from a commercial coherent receiver in our laboratory, demonstrating the feasibility of the approach and addressing the dependency on the telecommunication scenario's different parameters. At the time when we carried out the studies in Chapter 3, the capability of commercial transceivers to output SOP samples was still at an early stage, and some issues would have made it difficult to process the data reliably, for this reason, we decided to use a polarization analyzer to emulate the coherent receivers' DSP. We remind that a polarimeter cannot be added to monitor polarization in this kind of system, as the light is, on average, unpolarized. Recently, several companies have started to integrate SOP sensing in their devices, specifically pluggables, which record the related samples for further processing in a much more reliable way than a couple of years ago, when we carried out these works, and at a much higher sampling rate (around some kHz). This truly enables, even on a commercial and mainstream level, the use of the coherent communication infrastructure to monitor the fiber cables' surrounding environment.

Despite having discussed several times the simplicity of this approach, we should mention that it is valid for coherent systems, which are densely installed in both terrestrial and, especially, submarine systems, but the situation changes for IM-DD systems (e.g., passive optical networks, PON), where, since the transmitted signals

are not modulated in polarization and usually kept to a shorter distance (around 10-20 km), the DSP is much simpler and does not recover neither SOP nor forward phase samples: the only available options would be to either add DAS or, to remain within the same family, add a polarimeter. Phase sensing/interferometric techniques, also in combination with SOP, have been explored [147, 121, 29]. The advantages of enabling polarization sensing, in terms of costs and scalability, still need to be studied, as PONs work in a time-division-multiplexing manner, where each user is granted a time window where it can transmit, i.e., a different signal and a different polarization signature. Extrapolating SOP from the different users would thus allow to differentiate events happening in different branches of the PON, delivering rough localization capabilities. Also, a single polarization analyzer would monitor the SOP for different users, i.e., different fiber branches, which scales well on wide networks. The software able to do this, anyway, is not straightforward and requires detailed study, to which several companies and research groups are currently giving attention. Despite having a huge sensing range (SOP monitoring has been demonstrated on several submarine/suboceanic links), events' localization is still a critical point for polarization sensing, which is, to this day, still under investigation.

In this thesis, we also investigated the use of a standalone system, based on SOP monitoring, installed in a mountain environment, which should deliver timely alarms when a debris flow, landslide, rockfall, or any other flowing mass event occurs and tramples the fibers. We have discussed the whole transition from a small, in-scale model to a real installation on an active gully, which is still recording SOP samples to this day. Despite having delivered reliable results and demonstrated notable advantages when compared to traditional mountain engineering techniques, the absolute sensing system reliability, especially versus false alarms in a blind scenario, is still to be well addressed, as no true hazard has ever been recorded. Standalone sensing systems based on SOP and not connected to any telecommunication hardware are nevertheless being studied by other research groups, for example [12], in several contexts. One of the most recent trends involves monitoring the Stokes parameter S_1 alone, in place of the whole Stokes vector, since it is the simplest parameter of the three to recover, needing only (up to) two photodiodes, which would make the system even cheaper. Of course (as very well detailed in [12]), this comes at the cost of a reduced sensitivity of the sensor.

Distributed acoustic sensing is, on the other hand, an ad hoc sensing system that has to be completely added to the existing telecommunication infrastructure: as

Table 6.1 Comparison of the main characteristics of SOP and DAS sensing techniques.

Characteristic	DAS	SOP
<i>Telecom. systems compatibility.</i>	Potentially compatible, under certain conditions, as an <i>addition</i> to the already installed telecom. hardware.	Perfect compatibility, SOP sensing is <i>integrated</i> in coherent communication systems. For IM-DD infrastructures (mainly PON), a polarimeter and dedicated SOP extraction software must be added.
<i>Hardware/software req.</i>	Mostly different from the telecom. one; requires ultra-stable and narrow-linewidth lasers, pulse generation, and dedicated data processing.	Completely overlapping for coherent systems; requires a software upgrade to extract, store, and process SOP sample to detect hazards (already available for recent transceivers).
<i>Sensitivity/reliability</i>	Extremely sensitive, accurate, and reliable in measuring $n\epsilon$ strain and mK temperature variations. Ad hoc sensor.	Reliable as a detector for fluctuations generated by external agents. Measurements are not directly translatable to strain/temperature.
<i>Cost</i>	High cost, $\sim$ tens of k€.	Completely free in the case of coherent communication systems.
<i>Range</i>	< 100 km is the standard. Raman amplification should be employed above ~ 35 km.	Demonstrated for a whole transoceanic link (thousands of km).
<i>Localization</i>	Highly accurate (even < 10 m), inherent in the OTDR working principle.	Complex and non-intrinsic. Could be span-based for transoceanic links, with accuracy of tens of km. Cross-correlation/triangulation techniques have not yet been fully demonstrated in a real environment.

discussed for the forward phase monitoring, above in this Chapter, this, of course, creates problems mainly related to costs when upscaling the system to a wider infrastructure. This also happens because, as mentioned several times throughout this thesis (see Chapters 2 and 5), the requirements to enable fiber sensing when employing DAS are basically opposite with respect to the telecommunication side, meaning that converting the latter into a sensing system can be complicated. Nevertheless, the sensing performances delivered by the studied DAS ϕ OTDR- or CP- ϕ OTDR-based systems are of another reliability level with respect to the SOP. While the latter can mainly be used as a detector, which qualitatively monitors, tracks, and detects external events, it doesn't really measure what is happening to the fiber in terms of strains and/or temperature variation, which DAS can do accurately. Moreover, localization capabilities are of the order of less than tens of meters, which is an important added value with respect to SOP sensing. This comes at the cost of an expensive technology (tens of k€), which is hard to add to the telecommunication system,

but not impossible. We demonstrated how, under specific constraints related to the peak powers employed and suitable data channel spacings, the Kerr- and (possibly) Raman-induced nonlinearities can be mitigated on the telecommunication side. In particular, counter-propagating telecommunication channels and sensing signals did not generate any impairment on the data. The effect on the DAS performances still needs to be investigated; published results [138, 137] report no worsening on the sensing side.

Table 6.1 shows a comparison between the two main sensing techniques studied in this work: DAS, which we remind must be *added* to the telecommunication infrastructure, and SOP, which, instead, is *integrated* in coherent systems. The table makes it clear how the two systems have opposite characteristics, which could make them suitable for use in different, non-necessarily-overlapping contexts: the comparison should not serve as a way to determine which technology is better, but rather to envision the two systems' deployment across a wide range of scenarios, where sometimes SOP is more suitable, and sometimes DAS is. This is also valid for the other techniques, in the ISAC context, mentioned in Chapter 1; still, we focus here on the two approaches primarily investigated in this thesis. Given the sensing capabilities of DAS, together with the complexity of scaling its deployment over large network infrastructures, we envision its most effective application in scenarios where a clear need for hazard detection already exists and optical fibers are already deployed for communication purposes. The cost and complexity of DAS do not justify a ubiquitous deployment across all fiber links, its use should be limited to selected infrastructures. In such contexts, the installation costs and the challenges related to coexistence with data channels, potentially affected by high-peak-power pulses, are justified by the significant benefits of enabling distributed sensing. This could be relevant in offshore environments, where DAS can provide early tsunami warnings, as well as in submarine systems, where it enables earthquake detection and localization, a key requirement for timely alert generation [136, 72]. Moreover, DAS proves especially valuable when events are localized along the fiber and precise spatial information is required. When efficient scalability is needed, SOP's intrinsic integration with existing communication systems makes it particularly suitable for metropolitan networks, where it can enable city-wide monitoring of external events. Such capability could enhance the resilience of optical infrastructures, for instance, by improving the detection of fiber cuts or spoofing attacks over short links. Despite these perspectives, a major limitation still hinders widespread adoption: the lack

of robust processing algorithms capable of reliably interpreting sensing data. In this context, the development of centralized processing frameworks (acting as a “brain” for the network) represents a crucial step toward making SOP-based sensing a practical and reliable solution, mainly in metropolitan areas. Events localization is also something to be further investigated, and that would surely enable wider adoption of the technique. In contrast, when perturbations extend over large portions of a link [31, 12, 73], the need for accurate localization becomes less critical: in submarine scenarios, SOP-based sensing could be a complementary solution. Finally, the joint use of DAS and SOP sensing is largely unexplored but could deliver interesting results, enhancing the reliability of the two systems. Their complementary characteristics could be leveraged to overcome their inherent limitations, particularly in long-haul and submarine links, where DAS provides accurate but range-limited measurements, while SOP offers global sensitivity over extended links. The integration of sensing functionalities into optical fiber infrastructures has the potential to transform communication networks into pervasive monitoring systems: while significant challenges still need to be fully addressed, the use of DAS and SOP (mainly, but with the potential inclusion of other LI techniques) goes in the direction of intelligent, self-aware, and resilient optical networks.

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Appendix A

Polarization

A.1 Polarization Ellipse Equation Derivation

From the Eq. 2.3, using some basic trigonometric formulas, we can rewrite the x - y electric field time evolutions as in Eq. A.1. For the sake of simplicity of notation, we will drop the unit vectors $\hat{x}$ and $\hat{y}$.

$$\begin{aligned} E_x(t) &= E_1[\cos(\omega t) \cos(\varphi_1) - \sin(\omega t) \sin(\varphi_1)] \\ E_y(t) &= E_2[\cos(\omega t) \cos(\varphi_2) - \sin(\omega t) \sin(\varphi_2)] \end{aligned} \quad (\text{A.1})$$

The idea is now to find a formula that states the relationships between $E_x(t)$, $E_y(t)$, δ , E_1 , and E_2 . Thus, first of all, we include $E_x(t)$ in the expression of $E_y(t)$, following Eqs. A.2.

$$\begin{aligned} \frac{E_x(t)}{E_1} &= \cos(\omega t) \cos(\varphi_1) - \sin(\omega t) \sin(\varphi_1) \\ \sin(\omega t) \sin(\varphi_1) &= \cos(\omega t) \cos(\varphi_1) - \frac{E_x(t)}{E_1} \\ \sin(\omega t) &= \frac{\cos(\omega t) \cos(\varphi_1)}{\sin(\varphi_1)} - \frac{E_x(t)}{E_1 \sin(\varphi_1)} \end{aligned} \quad (\text{A.2})$$

The expression for $\sin(\omega t)$ can now be substituted in $E_y(t)$, in Eq. A.1, obtaining the Eqs. in A.3.

$$E_y(t) = E_2 \left[\cos(\omega t) \cos(\varphi_2) - \frac{\cos(\omega t) \cos(\varphi_1)}{\sin(\varphi_1)} \sin(\varphi_2) + \frac{E_x(t)}{E_1 \sin \varphi_1} \sin(\varphi_2) \right]$$

$$\frac{E_y(t)}{E_2} \sin(\varphi_1) = \cos(\omega t) \cos(\varphi_2) \sin(\varphi_1) - \cos(\omega t) \cos(\varphi_1) \sin(\varphi_2) + \frac{E_x(t)}{E_1} \sin(\varphi_2) \quad (\text{A.3})$$

Because of $\sin(\delta)$ being equal to $\sin(\varphi_2 - \varphi_1)$, it can be rewritten through trigonometric formulas as $\sin(\delta) = \cos(\varphi_1) \sin(\varphi_2) - \cos(\varphi_2) \sin(\varphi_1)$ and substituted in Eq. A.3. Rearranging the terms, we obtain the relationship in Eq. A.4.

$$\cos(\omega t) \sin(\delta) = \frac{E_x(t)}{E_1} \sin(\varphi_2) - \frac{E_y(t)}{E_2} \sin(\varphi_1) \quad (\text{A.4})$$

The same procedure, can be followed to extract $\cos(\omega t)$ in place of the sine, in Eq. A.2. By substituting the cosine in the following equations, we get an expression similar to Eq. A.4 but with the sine on the left side, as shown in Eq. A.5.

$$\sin(\omega t) \sin(\delta) = \frac{E_x(t)}{E_1} \cos(\varphi_2) - \frac{E_y(t)}{E_2} \cos(\varphi_1) \quad (\text{A.5})$$

Because of the Pythagorean identity, $(\cos(\omega t) \sin(\delta))^2 + (\sin(\omega t) \sin(\delta))^2 = \sin^2(\delta)$. Eqs. A.4 and A.5 can then be written as in Eq. A.6.

$$\begin{aligned} & \left(\frac{E_x(t)}{E_1} \right)^2 \sin^2(\varphi_2) + \left(\frac{E_y(t)}{E_2} \right)^2 \sin^2(\varphi_1) - 2 \frac{E_x(t) E_y(t)}{E_1 E_2} \sin(\varphi_1) \sin(\varphi_2) + \\ & + \left(\frac{E_x(t)}{E_1} \right)^2 \cos^2(\varphi_2) + \left(\frac{E_y(t)}{E_2} \right)^2 \cos^2(\varphi_1) - 2 \frac{E_x(t) E_y(t)}{E_1 E_2} \cos(\varphi_1) \cos(\varphi_2) = \\ & = \sin^2(\delta) \end{aligned} \quad (\text{A.6})$$

Through the Pythagorean identity, gathering the squared sines and cosines, Eq. A.6 can be simplified as in Eq. A.7.

$$\left(\frac{E_x(t)}{E_1} \right)^2 + \left(\frac{E_y(t)}{E_2} \right)^2 - 2 \frac{E_x(t) E_y(t)}{E_1 E_2} \cos(\delta) = \sin^2(\delta) \quad (\text{A.7})$$

Equation A.7 represents an ellipse lying on the $E_x(t)$ - $E_y(t)$ plane, proving that the most general shape that is described by the tip of the electric field vector actually is

elliptical. From the same equation, substituting $\delta = n\pi$, we obtain Eq. A.8

$$E_x(t) = \frac{E_1}{E_2} E_y(t) \quad (\text{A.8})$$

which is the equation of a line with angle $\arctan(\frac{E_2}{E_1})$, thus linear polarization. Enforcing the conditions $\delta = n(\pi/2)$ and $E_1 = E_2$ we instead obtain A.9

$$E_x(t)^2 + E_y(t)^2 = E_0 \quad (\text{A.9})$$

where $E_0 = E_1 = E_2$, which is the equation of a circle, thus circular polarization.

A.2 Stokes Parameters Fundamental Condition

By substituting Eq. 2.7 in Eq. 2.6, one obtains

$$\frac{1}{2} + \frac{1}{2} - \cos^2(\delta) = \sin^2(\delta) \quad (\text{A.10})$$

which is the Pythagorean identity. Let's now multiply everything by $4E_1^2E_2^2$, which leads to

$$2E_1^2E_2^2 + 2E_1^2E_2^2 - (2E_1E_2\cos^2(\delta))^2 = (2E_1E_2\sin(\delta))^2 \quad (\text{A.11})$$

and now sum and subtract $E_1^4 + E_2^4$, obtaining

$$2E_1^2E_2^2 + 2E_1^2E_2^2 + E_1^4 + E_2^4 - E_1^4 - E_2^4 - (2E_1E_2\cos^2(\delta))^2 = (2E_1E_2\sin(\delta))^2 \quad (\text{A.12})$$

Since $2E_1^2E_2^2 + E_1^4 + E_2^4 = (E_1^2 + E_2^2)^2$ and $2E_1^2E_2^2 - E_1^4 - E_2^4 = -(E_1^2 - E_2^2)^2$, everything can be rewritten as in Eq. A.13,

$$(E_1^2 + E_2^2)^2 + (E_1^2 - E_2^2)^2 - (2E_1E_2\cos(\delta))^2 = (2E_1E_2\sin(\delta))^2 \quad (\text{A.13})$$

which is exactly Eq. 2.8.

A.3 Stokes Parameters Relationship with Ellipticity and Orientation

Stokes parameters can also be expressed in terms of ψ and χ . The definition in Eq. 2.9 can be substituted in Eq. 2.5, to obtain Eq. A.14.

$$\begin{aligned} \tan(2\psi) &= \frac{S_2}{S_1} & S_2 &= S_1 \tan(2\psi) \\ \Rightarrow \\ \sin(2\psi) &= \frac{S_3}{S_0} & S_3 &= S_0 \sin(2\chi) \end{aligned} \quad (\text{A.14})$$

and then the fundamental condition in A.14 can be enforced.

$$\begin{aligned} S_0^2 &= S_1^2 + S_2^2 + S_3^2 = S_1^2 + S_1^2 \tan^2(2\psi) + S_0^2 \sin^2(2\chi) \\ S_0^2(1 - \sin^2(2\chi)) &= S_1^2(1 + \tan^2(2\psi)), \text{ where } \tan(2\psi) = \frac{\sqrt{1 - \cos^2(2\psi)}}{\cos(2\psi)} \\ S_0^2(\cos^2(2\chi)) &= S_1^2 \left(1 + \frac{1 - \cos^2(2\psi)}{\cos^2(2\psi)} \right) \\ S_1^2 &= S_0^2 \cos^2(2\psi) \cos^2(2\chi) \end{aligned} \quad (\text{A.15})$$

At this point, we could write everything gathering S_0 , and exploiting some easy trigonometric formulas, to obtain S_1, S_2, S_3 as in Eq. A.16.

$$\begin{aligned} S_1 &= S_0 \cos(2\chi) \cos(2\psi) \\ S_2 &= S_0 \cos(2\chi) \sin(2\psi) \\ S_3 &= S_0 \sin(2\chi) \end{aligned} \quad (\text{A.16})$$

This is the definition shown in Eq. 2.11.

Appendix B

Hints on Localization Using SOP over a Bidirectional Link

The idea proposed in [26] and developed in [35] involves an optical fiber infrastructure that can be schematically represented as in Fig. B.1. We will refer to the dashed blue box when discussing the West-side optical transceiver, and to the dashed red box when discussing the East-side optical transceiver. For this reason, the West-side transmitter and receiver use the TX_W and RX_W notation, respectively. The same applies to the East-side, represented with TX_E and RX_E . Vibrations and mechanical stresses having an impact on the SOP, are in Fig. B.1 referred to as *perturbation*. The link separating the East and West side transceivers is a bidirectional one and is represented as if the fibers selected are contained inside the same cable of the same length L . This is a very important, typically true condition, since if some mechanical stress is induced over the cable, it will most probably be coupled to both fibers with the same intensity and, more importantly, similar shape. The latter really depends on the SOP-derived metric that is used for the cross-correlation operation, which needs proper discussion and has not been treated in this thesis. The quantities z_W , z_E , refer to the length that the light needs to travel from one side to the other, after the perturbation. The subscript is W if considering the perturbation coupled to the SOP traveling from W to E . The opposite case holds for the subscript E . For example, supposing that the perturbation is happening where depicted in Fig. B.1, z_W would be the distance separating the East transceiver hardware with respect to the perturbation. On the opposite, z_E would be the distance separating the perturbation from the West transceiver. In both cases, the remaining length on the link would be $L - z_W$ and

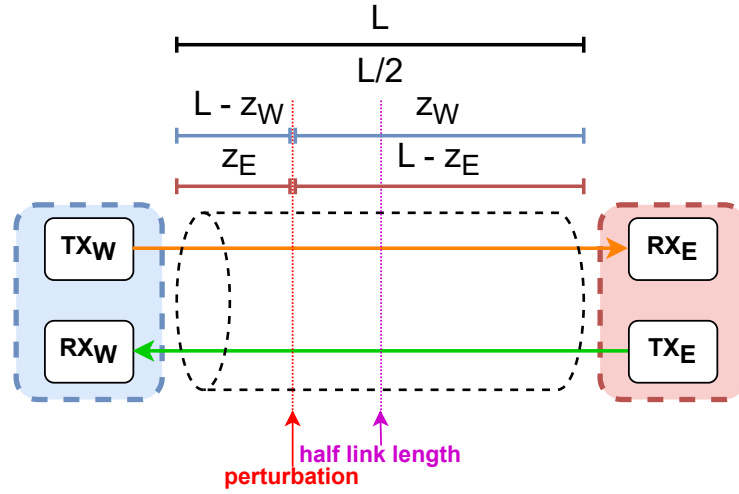


Fig. B.1 Schematic representation of a coherent transceiver's bidirectional link. East and West side quantities have been highlighted in red and blue, respectively.

$L - z_E$, respectively.

For the following discussion to be consistent, we need some specific assumptions, listed in the bullet points below.

- **East and West transceivers are perfectly synchronized in time and can exchange information.**
- **The length L of the fibers contained inside the cable is the same for the E - W and W - E links, and both W and E transceivers know it. The fiber is arranged as a straight line.**
- **The polarization noise is absent, or so low that it can be neglected and does not provide errors in localization.**

This localization method relies on the time of flight (TOF) experienced by light when traveling from the perturbation to RX_E and from the perturbation to RX_W . In particular, the perturbed SOP will reach the W or E receivers with different delays, depending on where the perturbation happened along the link (unless it happens at $L/2$). These delays cannot be directly recovered, but it is possible to estimate their time difference. Relying on the assumptions made in the bullet points above, the propagation delays experienced by the two transceivers detecting the same

perturbation are shown in Eq. B.1,

$$\begin{aligned}\tau_W &= z_W/c_0 \\ \tau_E &= z_E/c_0\end{aligned}\tag{B.1}$$

where τ_W is the TOF from be the perturbation to RX_E , and equivalently for τ_E . The value c_0 is the speed of light inside the fiber. The two propagation delays must sum up to $\tau_L = \tau_W + \tau_E$, where τ_L is the time that light takes to propagate over the L km long fiber link. Relying on the assumption that the two receivers are perfectly synchronized and can exchange SOP data instantaneously, the cross-correlation operation between the acquired SOP traces would provide the time difference in between τ_E and τ_W , as depicted by Eq. B.2.

$$\begin{aligned}R[k] &= SOP_W[n] \star SOP_E[n] \\ \Delta\tau_{W,E} &= |\tau_W - \tau_E| = |\arg \max (R[k])| \cdot T_s, \quad k = 1, \dots, N\end{aligned}\tag{B.2}$$

Here, $R[k]$ is the cross-correlation function ($\star$ the related operation), while the SOP_W and SOP_E are one-dimensional SOP-derived time-traces containing the perturbation. We again underline that the outcomes of the algorithm depend on which SOP-derived metric is chosen. T_s is the sampling period, while n represents the n -th sample on the SOP time-evolution, and k the k -th sample over the total N of the cross-correlation function. The time difference between the two delays can be easily recovered through the $\arg \max(\cdot)$ operation on the $R[k]$ function. The use of the absolute value on the τ_W and τ_E difference prevents the delay from being negative (it mathematically could be, as it depends on where the perturbation happens, fixing the order of the signals being correlated, as in Eq. B.2). Conventionally, we could express everything in terms of z_W only, thus obtaining Eq. B.3.

$$\begin{aligned}\tau_W &= z_W/c_0 \\ \tau_E &= z_E/c_0 = \frac{L - z_W}{c_0} \\ \Delta\tau_{W,E} &= |\tau_W - \tau_E| = \left| \frac{2z_W - L}{c_0} \right|\end{aligned}\tag{B.3}$$

Because of the absolute value properties, Eq. B.3 can be written as Eq. B.4,

$$c_0 \Delta \tau_{W,E} = \begin{cases} 2z_w - L, & L \leq 2z_w \\ L - 2z_w, & L > 2z_w \end{cases} \quad (\text{B.4})$$

where the case $c_0 \Delta \tau_{W,E} = 2z_w - L$ matches what is depicted in Fig. B.1, as $z_w \geq L/2$. For this reason, this convention will be the one taken into consideration for the following discussion. Considering the opposite case (thus, $z_w < L/2$) will lead to the same final results. Because of the convention used, $\tau_E < \tau_W < \tau_L$ holds.

Introducing in Eq. B.4 the sampling period T_s , we can make the z_w estimate $\hat{z}_w$ explicit for the case $z_w \geq L/2$. We then obtain the expression in Eq. B.5.

$$\hat{z}_w = \frac{\Delta \tau_{W,E} c_0 + L}{2} = \frac{k T_s c_0 + L}{2}, \quad k = 1, \dots, N \quad (\text{B.5})$$

Since the cross-correlation function $R[k]$ is sampled with T_s spacing as well, the $\Delta \tau_{W,E}$ value must be an integer multiple k of it. This creates a quantization error in the localization outcomes delivered by this method, which, ideally, would be reduced with decreasing T_s . Of course, in a non-ideal scenario, a sampling frequency increase corresponds to a SOP noise worsening, making the relationship between T_s and the localization error more complex. The estimate $\hat{z}_w$ has then an uncertainty of, ideally, $\pm T_s c_0$.

The condition in Eq. B.6 regarding the sampling frequency should always be true to guarantee localization at any point of the fiber link, implying to always have > 1 sampling period between the recorded perturbed traces; otherwise, the time-delay information would be lost.

$$T_s < \Delta \tau_{W,E} \quad (\text{B.6})$$

Clearly, it is impossible to have it true in any case, as it depends on the unpredictable position of the perturbation along the link. This method will thus always have a blind length z_b , where it delivers wrong results, defined in Eq. B.7,

$$z_b = 2 \cdot T_s \cdot c_0 \quad (\text{B.7})$$

with $z_b/2$ on the W , and $z_b/2$ on the W side. In other words, this is the minimum length after which, fixed T_s , the two delay differences become distinguishable. A decrease in T_s would then also mean a shorter blind length with increased localization

range, fixed L .

As described in the text and listed in the bullet points above, this model is to be considered in perfectly ideal conditions and would suffer notable impairments, which would impinge on the estimation error, if deployed in a real-life scenario. Treating the latter is outside the goal of this thesis, and has been investigated in several works concerning the topic.