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Scalable Multi-Tech Fiber Sensing on a Live Telecom Link With Polarization and Phase Monitoring / Notarstefano, F., Virgillito, E., Clivati, C., Donadello, S., Bratovich, R., Corsini, R., Hovsepyan, M., Carpentieri, F., Curri, V.. - (2026), pp. 1-4. (2026 26th International Conference on Transparent Optical Networks (ICTON) Prague (Cze) 12–16 July 2026) [10.1109/icton71309.2026.11705293].

Availability:
This version is available at: 11583/3016411 since: 2026-10-07T15:18:26Z

Publisher:
IEEE

Published
DOI:10.1109/icton71309.2026.11705293

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12 November 2026

Scalable Multi-Tech Fiber Sensing on a Live Telecom Link With Polarization and Phase Monitoring

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***Abstract*—Operational optical networks can support environmental awareness and cable-infrastructure supervision when sensing functions coexist with data traffic and remain compatible with deployed node architectures. This paper reports an overview of a live multi-technique sensing site on the Ascoli Piceno–Teramo link, where interferometric phase monitoring is operated together with a low-complexity polarization monitor based on a polarization beam splitter. The phase system provides a high-sensitivity benchmark for weak and fast mechanical perturbations, whereas the PBS-based receiver provides a scalar polarization projection obtained from standard intensity-modulated direct-detection optics and direct photodetection. Representative records from buried and aerial portions of the route are discussed to clarify the sensitivity–scalability trade-off. A vehicle-passage transient illustrates the phase response to impulsive buried-section events, while an aerial-span oscillation shows different temporal and spectral signatures in phase and PBS-SOP traces. Finally, a conceptual event-oriented processing path is outlined to show how continuous optical traces can be converted into compact supervision information.**

***Index Terms*—optical fiber sensing, state of polarization, interferometric phase sensing, live optical networks, cable safety, network supervision.**

I. Introduction

Optical transport infrastructures are no longer only passive carriers of communication services. Since deployed fibers are mechanically coupled to their surroundings, variations of strain, bending, temperature, and acoustic excitation can leave measurable signatures on the optical signals propagating through them. This observation has motivated the idea of dual-purpose networks, in which a communication system also contributes to environmental monitoring and to the supervision of its own physical layer.

This work has received support from the European Union through the Horizon Europe project SENSEI, GA 101189545, and from Open Fiber within the Fiber as a Sensor initiative.

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Distributed acoustic sensing and related back-scattering techniques provide high spatial resolution and have enabled high-impact demonstrations in geophysics and infrastructure monitoring [1], [2]. Their adoption on operational transport infrastructures, however, is not always straightforward, because cost, reach, data volume, and compatibility with multiplexed unidirectional systems can become limiting factors. An alternative class of methods, often referred to as integrated fiber sensing, relies on forward-propagating optical signals and measures the accumulated effect of perturbations along the link. In this family, coherent phase sensing offers high sensitivity and has been demonstrated on terrestrial and submarine cables [3], [4], while state-of-polarization (SOP) monitoring has attracted interest as a scalable observable that can be retrieved from data channels or simple polarization receivers [5]–[8].

The key question for terrestrial deployment is not whether one single observable is universally preferable, but how observables with different sensitivity, cost, and integration complexity can be used within the same supervision strategy. Phase measurements are well suited as a benchmark for weak perturbations, but they normally require a more demanding optical setup. Conversely, a polarization beam splitter (PBS) followed by direct detection gives access to only a partial polarization projection, yet it can be implemented with small hardware overhead and can be replicated at many network sites.

This paper presents an overview of the Ascoli Piceno–Teramo (AP–TE) multi-technique sensing site, focusing on the coexistence of PBS-based SOP monitoring and interferometric phase sensing on a live terrestrial link. The AP–TE deployment has been progressively developed as a field observatory for integrated fiber sensing, with previous work reporting the interferometric phase arrangement, the PBS-SOP sensing cards, and their WDM integration with data traffic [4], [9]–[11]. Here, we recall the elements required to interpret representative field records and discuss how the

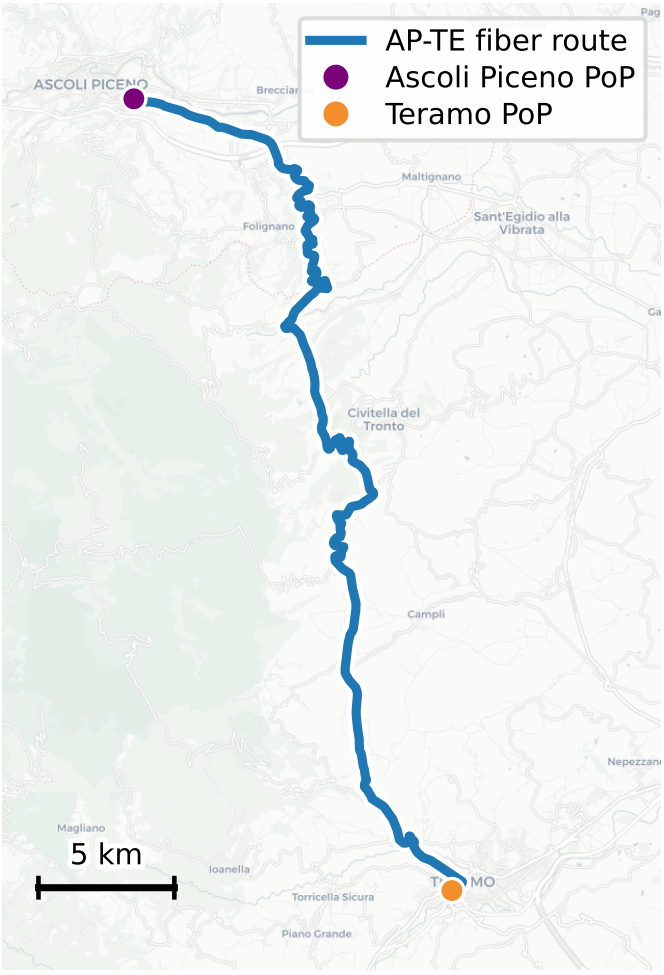

Fig. 1. Geographical layout of the AP–TE fiber route between the Ascoli Piceno and Teramo points of presence.

different sensitivity regimes of phase and PBS-based polarization monitoring can be used for cable-safety supervision and event-oriented processing. The selected examples emphasize realistic buried-section and aerial-span perturbations, while the same infrastructure remains relevant for broader environmental monitoring studies.

II. AP–TE Multi-Tech Sensing Site

The field site is deployed on a live regional network operated by Open Fiber and connecting the points of presence of Ascoli Piceno and Teramo in central Italy. The two nodes are connected by approximately 39 km of optical cable. The route is mostly installed in underground conduits following road infrastructure, with a short aerial span exposed to wind-driven and vegetation-related mechanical perturbations. This mixed installation provides a realistic terrestrial environment, where human activity, local cable coupling, and environmental forcing coexist on the same link.

Fig. 1 reports the geographical layout of the monitored route. The link carries conventional optical data traffic and hosts dedicated sensing wavelengths for interferometric phase monitoring and PBS-based SOP monitoring. The complete node-level setup, including the PBS-SOP receiver, WDM integration, acquisition chain, and phase-detection subsystem, has been described in previous AP–TE reports [4], [9]–[11]. The common deployment enables the comparison of phase and polarization-projection traces recorded under the same operational conditions.

A. Interferometric Phase Benchmark

The interferometric subsystem probes the optical path variations accumulated by a coherent carrier. Mechanical perturbations modify the fiber length and refractive index, producing a time-dependent optical phase $\phi(t)$. In the processing adopted here, the phase trace is commonly represented through its time derivative,

$$\Delta\nu(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}, \tag{1}$$

which can be interpreted as an instantaneous frequency deviation of the received optical beat note. This observable is line-integrated along the optical path rather than spatially resolved, but it provides high sensitivity to weak and fast perturbations. For this reason, in the AP–TE site it is used as the benchmark trace for interpreting lower-complexity polarization-projection measurements.

The main drawback is architectural complexity. The phase system relies on a narrow-linewidth optical source, coherent detection, and dedicated acquisition electronics for stable phase readout [9]. Although this approach is compatible with data traffic when suitable WDM planning is adopted, its cost and operational requirements make it less suitable for dense replication at every network node.

B. PBS-Based SOP Monitoring

The SOP monitor follows a deliberately simpler strategy. A standard C-band 10 Gb/s intensity-modulated direct-detection signal is used as sensing carrier. At the receiver, the selected channel is filtered and sent to a compact monitoring card. The received optical power is measured by a dedicated total-power photodiode, while a polarization beam splitter separates two orthogonal linear polarization components that are detected by two additional photodiodes. The resulting three electrical traces, corresponding to the total power and to the two PBS outputs, are digitized by low-rate ADCs and stored with software timestamps.

A convenient scalar polarization observable is obtained by normalizing the difference between the two PBS outputs,

$$s_{\mathrm{PBS}}(t) = \frac{P_H(t) - P_V(t)}{P_T(t)}, \tag{2}$$

where $P_H(t)$ and $P_V(t)$ are the two detected orthogonal polarization components, and $P_T(t)$ is the total received power measured by the dedicated power-monitor photodiode. This quantity can be regarded as one projection of the Stokes vector in the receiver reference frame. It therefore does not provide the full polarization state and its sensitivity depends on the instantaneous SOP working point. The PBS-SOP receiver should

consequently be interpreted as a reduced-dimensional monitor: perturbations are visible when they produce a sufficiently large variation on the measured polarization projection. This behavior is the trade-off for hardware simplicity. For joint processing, phase and PBS-SOP traces are time-aligned and resampled on a common 100 Hz grid. The present synchronization is sufficient for event-level comparison across observables. Finer synchronization is required when delay-based localization is targeted; dedicated synchronization approaches for such cases have been discussed in previous sensing and phase-readout work [9], [12].

III. Representative Cable-Safety Responses

The AP–TE site continuously records a heterogeneous mixture of perturbations associated with road activity, local cable coupling, environmental forcing on the aerial span, and broader low-frequency motion. The following records are used as representative cable-safety cases, rather than as a complete classification of all perturbations observed on the route. They illustrate two practically relevant regimes: short impulsive transients on buried sections and oscillatory perturbations on the aerial span.

A. Buried-Section Transients

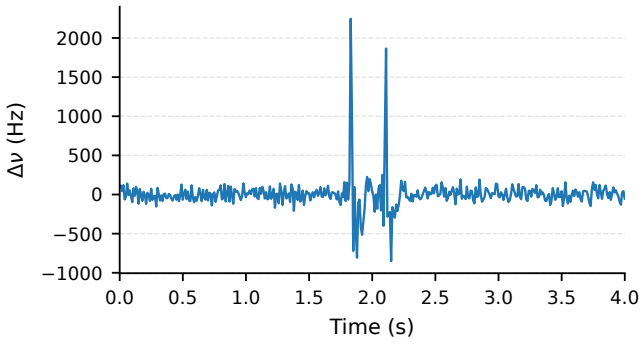

Fig. 2. Interferometric phase-derived frequency-deviation waveform recorded during a vehicle-passage event on the AP–TE link.

Short perturbations on buried sections are often governed by localized mechanical coupling between the road surface, the duct, and the cable. Vehicle passages above sensitive points, such as manholes or deteriorated road coverage, can induce sub-second transients. In the record shown in Fig. 2, the interferometric phase-derived frequency deviation exhibits a short impulsive signature associated with the vehicle passage.

The corresponding PBS-SOP record acquired over the same interval does not exhibit a comparable time-aligned signature. This behavior is consistent with the reduced-dimensional nature of the PBS measurement: the receiver observes only a scalar projection of the polarization state, and, for this event, the induced perturbation does not produce a sufficiently large excursion on the measured projection. The example is therefore used as a phase-benchmark case for impulsive buried-section perturbations, rather than as evidence of equivalent detectability across the two observables.

From an operational perspective, repeated phase-detected transients of this type may indicate local road–cable coupling, manholes, degraded pavement, or exposed duct sections.

B. Aerial-Span Oscillations

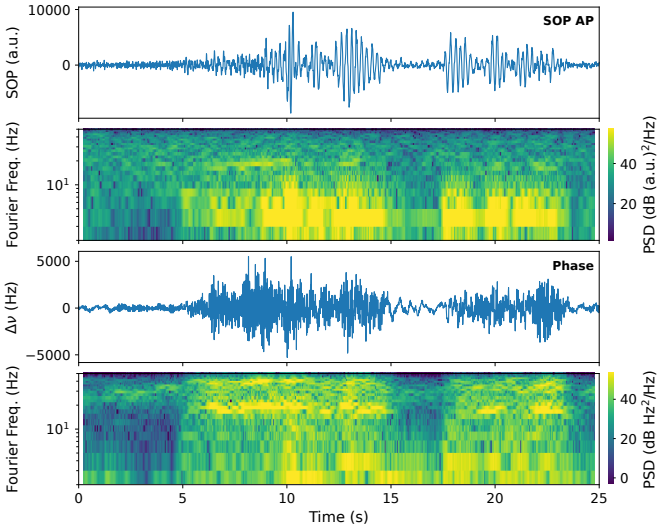

Fig. 3. Time traces and spectrograms recorded during a selected aerial-span event. From top to bottom: PBS-SOP time trace, PBS-SOP spectrogram, phase-derived frequency deviation $\Delta\nu$, and phase spectrogram.

The short aerial portion of the route provides a different mechanical scenario. Wind gusts, cable swinging, and intermittent contact with nearby vegetation can generate oscillatory signatures with persistent low-frequency components and harmonics. In this regime, time-frequency representations are more informative than raw time traces, because they reveal the persistence and spectral structure of the mechanical excitation.

Fig. 3 reports one selected aerial-span event. The phase spectrogram resolves low-frequency oscillatory components and higher-order spectral content, whereas the PBS-SOP observable exhibits a slower and less selective polarization evolution. This difference is consistent with the fact that phase and PBS-SOP measure different projections of the perturbation. Phase sensing reacts to optical-path variations accumulated along the link, while the PBS-SOP receiver records the variation projected onto its two detected polarization axes.

Aerial-span signatures are relevant to preventive maintenance because their spectral footprint can evolve when loading conditions change, for instance due to vegetation growth, snow, ice, or loosened fixtures. In this regime, the PBS-SOP channel can provide a low-overhead polarization-projection indicator when the mechanical excitation is sufficiently coupled to the measured polarization state.

The two examples in Fig. 2 and Fig. 3 are therefore used to anchor the AP–TE overview to two event families with direct operational relevance. They make the sensitivity–scalability trade-off visible without implying that the selected records exhaust the range of perturbations observed on the route.

Fig. 4. Conceptual workflow from optical-event detection to collection, interpretation, and operational support.

IV. Event-Oriented Processing for Network Supervision

Long-term phase and PBS-SOP monitoring produces continuous optical traces that are difficult to use directly in network operations. Fig. 4 summarizes the intended processing path at a conceptual level. The first step is detection, where the continuous streams are screened to select intervals that depart from the local background. This step may rely on statistical rules or unsupervised learning methods, depending on the deployment constraints, but its purpose is simply to extract candidate events from long recordings.

The collection step organizes the selected intervals together with the relevant context, such as timing information, monitored link, sensing observable, and acquisition metadata. This organization is important because phase and PBS-SOP traces do not have the same sensitivity or physical response. The phase stream provides a high-sensitivity benchmark for building validated examples, whereas the PBS-SOP stream provides a lower-overhead polarization-projection observable that can be replicated more easily across network sites.

The interpretation step converts collected records into supervision-oriented information. For the AP–TE site, examples include distinguishing impulsive buried-section transients from aerial-span oscillations, tracking the recurrence of similar signatures, and relating changes in temporal or spectral behavior to possible maintenance-relevant conditions. The final action block should be understood as operational support, such as prioritizing inspections, enriching maintenance logs, or triggering further analysis by the operator. In this sense, the processing layer acts as a compact bridge between continuous optical sensing data and operator-supervised cable-maintenance workflows.

V. Conclusion

We presented an overview of the AP–TE live multi-technique fiber sensing site, where interferometric phase monitoring and PBS-based SOP monitoring coexist with operational data traffic. The phase system provides a high-sensitivity benchmark for weak or fast perturbations, whereas the PBS-SOP monitor offers a lower-complexity polarization-projection observable that can be scaled more easily across network nodes. Representative buried and aerial cable-safety events show a clear sensitivity hierarchy: the phase trace captures the vehicle-induced transient considered here, whereas the PBS-SOP channel becomes informative when the event produces a measurable variation on its detected polarization projection. This trade-off supports a deployment strategy in which phase measurements are used to validate and characterize event families, while low-overhead polarization monitoring contributes to wider network supervision. An event-oriented processing layer can then organize detections, context, and interpretation outputs into compact supervision information for maintenance-oriented workflows.

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