Efficient Multi-Event Localization from Rayleigh Backscattering in Phase-Sensitive OTDR Systems

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Abstract: We introduce a phase-OTDR multi-resolution approach to detect mechanical events through telecom fibers. Perturbations are first coarsely localized from a subset of high-reflecting backscatters, followed by a low complexity localization refinement.

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1. Introduction

Coherent Phase-OTDR has emerged as a promising distributed sensing approach to detect low-energy mechanical events occurring along an optical fiber [1]. It can be applied over Standard Single Mode Fibers (SSMF), as those used in deployed telecommunication networks, thanks to the capture of the Rayleigh backscattering by means of a coherent receiver. Detection of multiple mechanical events over 25km of SSMF is demonstrated in [2] with a native spatial resolution of 0.8m. However, in a real time monitoring perspective, the amount of data to handle for covering the entire monitored fibre is massive. To tackle this issue, the paper introduces a technique that first detects any mechanical event at a low computing cost with a loose spatial resolution. The event localization is then further refined by means of a multiresolution scheme.

2. A multi-resolution approach for accurate event localization

We developed in [3] a Distributed Acoustic Sensing (DAS) interrogator that jointly probes the optical line on two polarization axes by means of tailored sequences built from complementary Golay codes that modulate a narrow-linewidth laser source. This probing technique gives access, after detection of the backscattered information with a dual-polarization coherent receiver followed by dedicated correlation-based signal processing, to the optical phase estimation along the Fibre Under Test. The used symbol rate f_{Symb} yields the native spatial resolution $S_r = c_f/(2F_{symb})$, where $c_f \approx 2.10^8$m/s is the light velocity in the SSMF core. With f_{symb} typically set between 100MHz to 1GHz, the fiber is discretized into 0.1 to 1m-long segments from which the differential phases are extracted to get the phase evolution between segments. The phase estimation is done periodically from the continuously transmitted codes with a period equal to $T_{code}=N_{code}/F_{symb}$ where N_{code} is the number of symbols that form the code. Hence, we obtain a space-time map of the optical phase at each of the fiber segments and can accurately detect events over a bandwidth $BW=1/(2.T_{code})$. The interrogator and experimental setup are shown in the left part of Fig.1.

With such a phase-OTDR system, fibers may be monitored over several tens of kilometers (25km is demonstrated in [2]) to detect and potentially localize numerous independent mechanical events. However, the number of segments to monitor can increase fast (25000m/0.8m=31250 segments at f_{Symb}=125MBaud as in [2]), which hardly complies with both CPU and memory real-time implementation constraints. To overcome this issue, we introduce here a method that pre-detects potential events at a low spatial resolution before refining the localization over subsections of the sensing fiber. To do so, a permanent monitoring of differential phases runs continuously over a subset of fiber segments. To define this subset, we rely on the intensity levels of backscatters measured in static mode (no mechanical

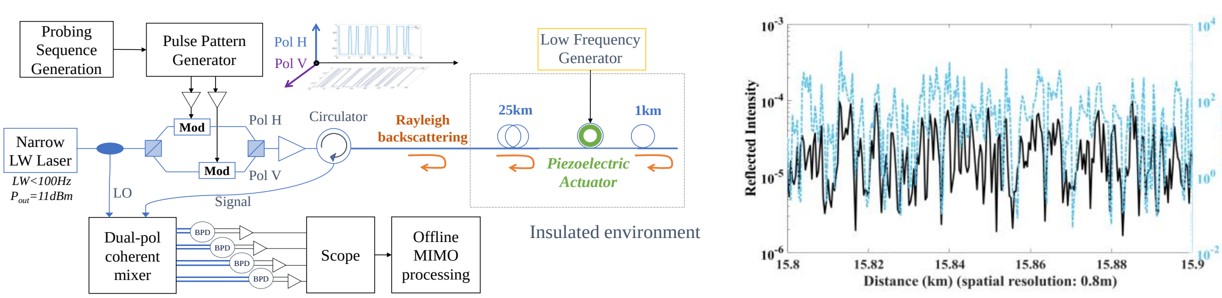

Fig.1: (Left) Experimental setup (BPD: balanced photodiodes, LW: linewidth, Mod: modulator); (Right) Rayleigh intensity pattern & inverse standard deviation of phase per segment in static mode around 15.85km.

or acoustic perturbations) and shown in the right part of Fig.1. The intensity levels measured at the native spatial resolution (0.8m in this case for f_{Symb}=125MBaud) are shown over a fiber section at 15.85km from the interrogator. Superimposed on the intensity curve is the inverse of the standard deviation of the differential phases per fiber segment (dashed line) estimated over 1s with a 1ms-long probing code. This value can be interpreted as a phase SNR. Strong variations can be seen over the distance axis and a strong correlation between the backscatter intensity and the phase SNR plots can be highlighted. This demonstrates that the higher the backscatter intensity, the higher the robustness to noise. We exploit this result to perform a selection of scatterers at a low spatial resolution $S_L=L.S_r$ by capturing the highest-reflecting segment among L adjacent ones all along the fiber. The differential phases are extracted from this subset of high-intensity segments. When one or more perturbations are detected, local analysis(-es) is (are) triggered over the segment(s) preceding the perturbation(s) at a higher resolution to localize more accurately the event(s). The spatial resolution increase may be applied iteratively to finally localize the event(s) using the native resolution S_r.

3. Experimental results

We introduce a mechanical perturbation at approximately 25km from the start of a SSMF with a piezoelectric actuator (PEA) as shown in Fig.1. A 100Hz sine wave current feeds the PEA inducing a 324nm peak-to-peak fiber elongation. The Rayleigh backscattered signal is captured by a dual-polarization coherent mixer, then a digital processing [3] extracts the optical phase evolution at each Sr=0.8m fiber segment. To avoid monitoring every fiber segment, we only process the differential phases from the highest-intensity segment each L=1000 adjacent ones. The 100Hz perturbation induced by the PEA is easily detected using an energy criterion, as shown in Fig.2 on the left, at a resolution S_L=1000S_r. The initial detected position is 25.50km. A new selection process is activated locally over the segment preceding the detected alarm using an enhanced resolution with L'=8 for example. The new localization result is shown in the right

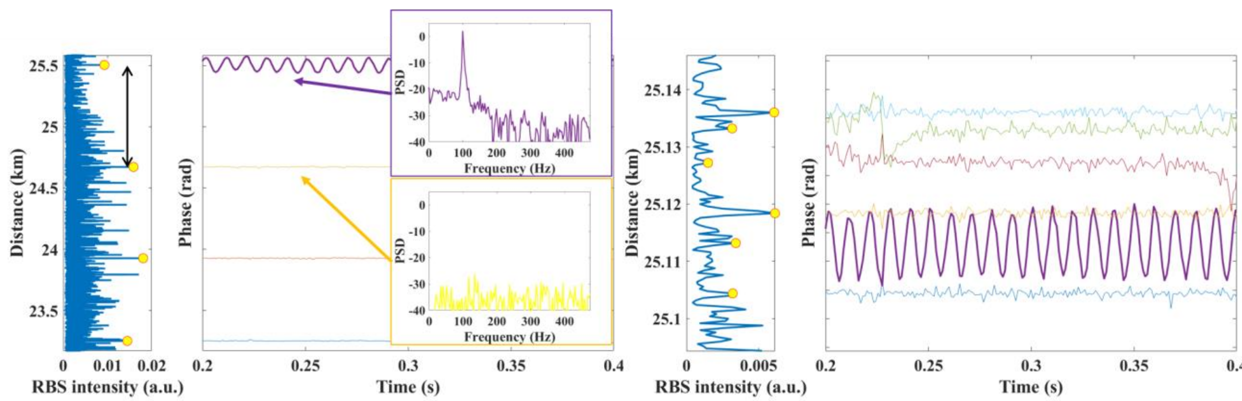

Fig.2: Event localization procedure: starting with a coarse resolution (left part with 800m-steps), the next differential phase measurement is performed with a finer step over a smaller section (highlighted by a double-arrow line) bounded by the position of the detected alarm (inset in purple) and the preceding alarm-free position (inset in yellow). A finer localization is shown on the right with 6.4m-steps.

part of Fig.2 with the event more accurately localized at 25.113km. More generally, our multi-resolution implementation handles several alarms in parallel over all the fiber, refining the localization iteratively, thus saving computation efforts compared with a permanent monitoring at the native resolution. The method illustrated here over a 25km fiber at a 0.8m native spatial resolution is applicable to any desirable resolution and fiber distance.

4. Conclusion

We described a multi-resolution method to localize events over long-distance fibers using Rayleigh scattering through a coherent phase-OTDR system. A pre-detection step, running at a low spatial resolution over a subset of high intensity backscatters, is perfected by an enhanced-resolution detection performed locally at each detected event. The proposed solution relaxes the constraints on real-time implementation by reducing the amount of monitored data.

5. References

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