Non-Intrusive DAS Coexisting in Telecom Networks

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Abstract: We describe DAS interrogation for non-intrusive coexistence with live C-band WDM channels. The scheme facilitates consistent high sensing sensitivity range >100 km. Surface vessels, seabed fishing gear and earthquakes are localized from the 2Africa network.

1. Introduction

The utility of distributed acoustic sensing (DAS) for cable protection, hazard warning and environmental monitoring has motivated the development of scalable solutions for mass deployment on fiber-optic networks. However, the solutions proposed so far has significant drawbacks in either (i) reduced transmission capacity by reserving several (typically three) WDM channels for the insertion of the DAS channel [1,2], (ii) strict limitations to the pulse peak power tolerated to avoid interference with the communication channels resulting in high BER, post-FEC errors and uncorrected blocks which in turn reduces the sensing range capability of DAS [2], (iii) allowing for counter-propagating coexistence only [1,2], or (iv) by introducing interrogation schemes with high susceptibility to laser frequency noise which increases the system self-noise, hence reducing the DAS sensitivity [3].

In this paper we suggest the L-band for DAS, taking advantage of the chromatic dispersion to avoid interaction with the WDM channels [4]. Moreover, we reduce the pulse peak power of the DAS probe pulses by utilizing the frequency swept interrogation (FSI) technique which also facilitates long-range sensing capabilities with consistent low system self-noise along the fiber [5], and furthermore allows for both co- and counter-propagating coexistence with live WDM channels. Finally, we report, to our knowledge, a first field experiment of L-band DAS interrogation in non-intrusive coexistence with live WDM channels and with consistently low system self-noise on the full 83 km shore end span of the 2Africa Marseille branch. We corroborate the data quality with example detections of man-made and environment signals.

2. Coexistence experimental setup

The field experiment was conducted at the Marseille landing on the segment to Barcelona on the 2Africa network. The fiber pair used for this trial was looped in Barcelona to keep all equipment co-located in Marseille, see Figure 1a. Four transmission channels with 75 GHz spacing, covering the range 1564.2 - 1566.0 nm, were used for the analysis, while the remainder of the 36 nm spectrum was loaded with noise. The transmission channels carried a 400 Gb/s net channel data rate with DP-16QAM modulation format, enabling a link data rate per fiber pair of 24 Tb/s.

For optimized sensing range and sensitivity, we used a DAS interrogator utilizing the FSI technique. With FSI, the ultimate spatial resolution is determined by the width of the frequency sweep, and not the pulse length. Thus, for a given spatial resolution, much more optical energy can be launched into the fiber without increasing the pulse peak power of the probe pulses which thus alleviates the impact of nonlinearities by the Kerr effect. The DAS interrogator used was the ASN OptoDAS interrogator with an 80 MHz frequency sweep, facilitating a spatial resolution down to 1.25 m, and a 100 MHz receiver sampling board giving a spatial channel separation of approx. 1.02 m, i.e. producing 81´511 sensor channels in the 83.248 km long fiber span monitored. The DAS interrogator operated at 190.0 THz (1577.8 nm), i.e. more than 1.4 THz outside of the WDM spectrum, and was connected to the transmission line by a standard C/L band filter. The 36 nm C-band spectrum remained dedicated for carrying 60 coherent WDM channels.

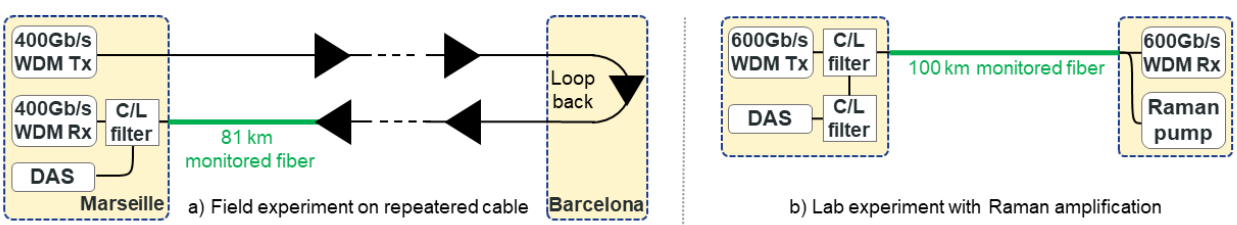

Figure 1 Experimental setup. (a) DAS coexistence on repeatered submarine cable. (b) DAS coexistence on Raman amplified link.

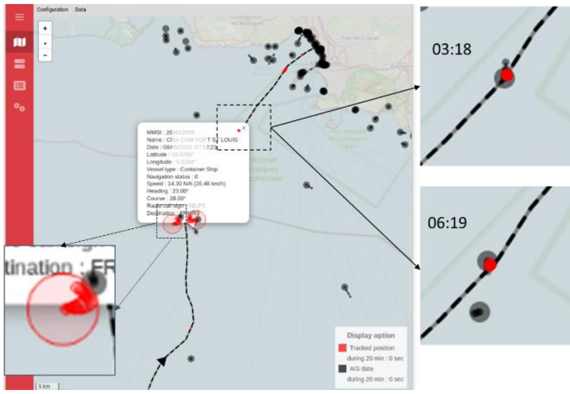

Figure 2 Left main figure shows a snapshot from the real-time monitoring dashboard where AIS data (black/grey symbols) are co-visualized with DAS detected events and tracks (red symbols) on a geographic map with the cable route (thick dashed black line). The white info box is displayed upon mouse hover to detail the vessel information. The black triangle on bottom part of cable is the repeater position containing an isolator that limits DAS sensing range. Right: Two zoom-ins show detections three hours apart when the same fishing vessel is detected to operate seabed gear while sailing across the cable (red circles).

Counterpropagating coexistence of FSI DAS at 190.0 THz was verified during a 14-day field experiment. No impact was seen in the Q^2 factor of the WDM channels that remained at 6.8 dB whatever the parameters applied for the FSI DAS interrogation pulse power and duty cycle, and the DAS system self-noise remained constant at about 10pε/√Hz with a gauge length of 8 m, throughout the 83 km fiber length, which was the same noise floor as found before enabling the WDM channels in the fiber. The consistent low system self-noise along the fiber is a result of the FSI technique not being shot noise limited (or photon starving) for fibers of this length.

Further evaluation of coexistence with FSI DAS at 190.0 THz was conducted on a 100 km link with four active 600 Gb/s PCS-16QAM wavelength channels [6]. Both counter- and co-propagation coexistence was verified with no impact to the Q^2 factor of the running channels, and while maintaining the DAS signal-to-noise ratio. More importantly, we also tested the coexistence under Raman amplification of the WDM channels. A dual stage Raman pump at 1425 nm and 1454 nm was used, with DAS in co-propagation coexistence, as shown in Figure 1b, since the link configuration with Raman amplification did not allow for connecting the C/L-band filter by the Raman amplification board. Again, the co-propagation coexistence of DAS did not impact the Q^2 factor of the WDM channels. A 2nd C/L-band filter was inserted in series with the 1st to sufficiently suppress the residual Raman pump powers to reach the DAS interrogator to obtain the same DAS data quality as in dark fibers.

3. Cable protection and seismology applications

There is a wide range of applications for DAS data from fiber optic subsea cables that are valuable for the cable operator and society. Here, we will focus on monitoring to prevent cable damage from bottom-trawl fishing [7] as well as earthquake detection [8]. Objects moving along the seabed like fishing gear or ship anchors generate surface vibrations. These signals couple to the fiber and can be characterized as propagating Scholte waves. By utilizing the distributed measurement, it is possible to locate the signal source and track the trajectory in real time. The processed positions can be displayed together with vessel locations from the automatic identification system (AIS) to enable cable monitoring teams to identify cable threats and take action to avoid cable damage. In Figure 2 we show snapshots from the real-time dashboard that plots vessel positions and DAS detected signals and alerts on a geographic map with the cable route. The interactive map can show detailed information for vessel identity and key

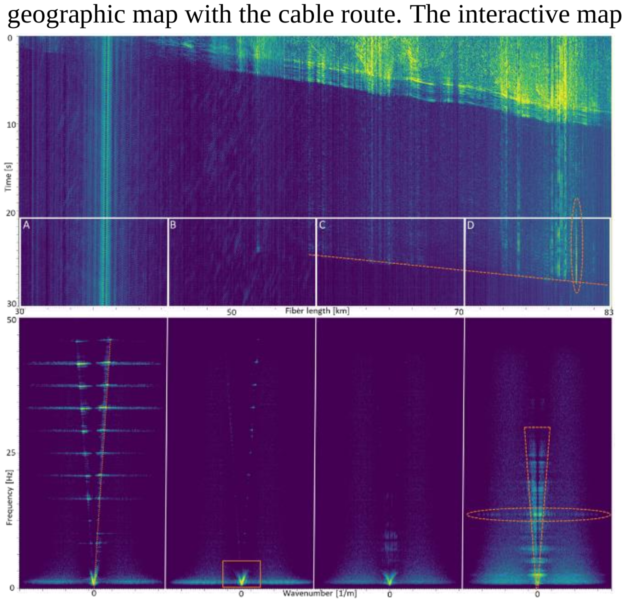

Figure 3 Example snapshot of concurrent signals: Surface vessel, earthquake, possible marine life. Top panel: Waterfall display of the measured strain [nε/$\sqrt{Hz}$] along the cable from 30 to 80 km (x-axis) over 30 seconds (y-axis). The data from boxes of 10 seconds and about 13 km annotated A-D are analyzed in the frequency-wavenumber domain in the bottom panel [nε/m$\sqrt{Hz}$] with wavenumber along the x-axis and frequency along the y-axis. Segment A shows typical surface vessel noise propagating at 1500 m/s (dotted line) and with specific harmonics. The 0.18 Hz Doppler frequency shift of the 37.4 Hz harmonic for the two wave components propagating along and against the vessel trajectory indicate a vessel velocity of 7 m/s. B and C mainly have low-frequency and slowly propagating signals (orange box) related to Scholte surface waves and oceanographic processes. In D, the P-wave phase of the earthquake is shown at high apparent velocity >4000 m/s up to 30 Hz (dashed triangle) together with a 13 Hz harmonic signal (dashed oval) believed to be related to marine life.

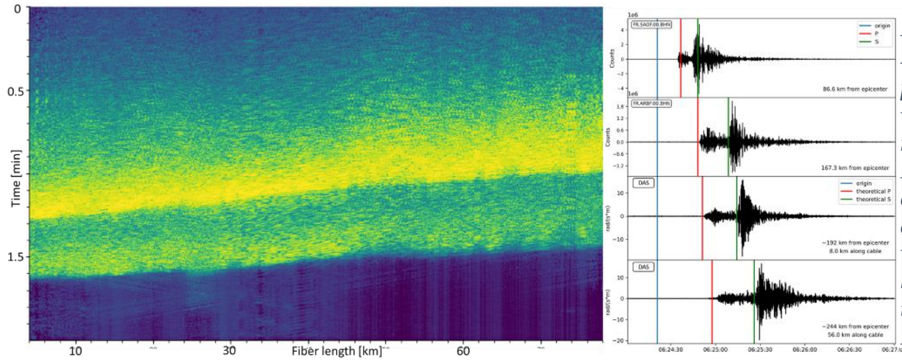

Figure 4 Left: 2023-05-16 regional M3.9 earthquake event waterfall plot [$n\varepsilon/\sqrt{Hz}$], fk-filter mute for velocities outside 2-6 km/s, and normalization per channel applied. Right bottom two traces are extracted at 8 and 56 km position along the fiber. The arrivals agree very well with theoretical values based on seismometer records, top two example stations accessed from RESIF https://seismology.resif.fr.

attributes of detections. In the two zoomed in views in the figure, taken three hours apart, a fishing vessel is detected to cross over the cable and with gear deployed on the seabed that generated alerts. If sufficient cable burial had not been ensured so that this activity represented a risk that seabed gear could snag and damage the cable, a monitoring team could contact the mariner to lift the gear and avoid the cable zone.

The dense spatial sampling of the DAS data enables processing techniques that significantly enhance data utility. As an example, we show frequency-wavenumber (*fk*) domain analysis of concurrent signals in Figure 3. The 30 seconds of recorded data have signatures from an earthquake, surface vessel noise, and possible marine life. The early detection of earthquake P-waves, which can be of small amplitude, is supported in *fk*-domain since in the deep-water environment there are few other sources characterized by high velocity > 2000 m/s (see Figure 3 D). The *fk*-domain data is thereby well suited for event-specific noise filters or to be input for machine learning algorithms. Surface vessel noise has different character in this domain. The higher frequency harmonics characteristic to the vessel can be analyzed to estimate the vessel's apparent velocity (segment A). The segments annotated B and C in Figure 3 exhibit the natural background of low-frequency ocean processes and slow surface waves that can be analyzed to characterize oceanographic conditions water flow thermal mixing. Finally, segment D also has a 13 Hz harmonic signal that was observed recurrently. While the signal character is indicative of marine life, this cable segment is at very deep water and detailed knowledge of species acoustic signatures is scarce. The submarine cable thus acts as a unique opportunity to study the deep-water environment and biology with a permanent sensor array.

Earthquakes and tsunamis have caused devastating loss of human lives, and enabling comprehensive seismological monitoring both on land and in the ocean is a crucial step to build resilience to these events. Using DAS on submarine telecom systems for seismic measurements can significantly extend coverage beyond the existing terrestrial seismic monitoring networks [9,10]. In the Mediterranean study area considered here, we characterized both teleseismic events and regional earthquakes near the south coast of France. As an example of how the strain measurements can be utilized to supplement the seismic networks, we focus on data from two cable segments that was processed to represent single-component seismometers on the ocean floor. The DAS traces can be used in combination with land seismometers to provide real-time detection and localization capabilities (Figure 4). The added DAS traces representing ocean stations will be robust with no electronics in the field and with built-in telemetry enabling real-time streaming of data just like standard seismometer stations on land. The time delays between the P and S arrivals are consistent with the catalogue location that was calculated based on an extensive network of land stations.

4. Conclusion

We have demonstrated FSI DAS operating in the L-band for non-intrusive coexistence with live C-band WDM channels on a branch of the repeatered 2Africa network. Example observations of surface vessels, seabed fishing gear, oceanographic processes and earthquakes are reported and analyzed and proves that L-band FSI DAS provides the same range and sensitivity as with DAS on dark fibers, i.e. in our experiment limited to 83 km by the 1st repeater. Furthermore, L-band FSI DAS facilitates the flexibility to operate in both counter- and co-propagation coexistence with coherent WDM traffic, and in the latter case even with Raman amplified WDM channels.

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