Digital Coherent Sensing over Deployed Fibers for Advanced Network Telemetry

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Abstract: We discuss the performance of Coherent-MIMO-DFS over deployed optical networks in various configurations and address technological challenges such as adaptation to various fiber types, disturbance identification. © 2024 The Author(s)

1. Introduction

Initially developed as a mean to monitor infrastructures such as buildings and bridges, distributed fiber sensing evolved into a broad range of sensing applications, from static detection of cracks to acoustic monitoring and shape sensing with specialty fibers. Now distributed fiber sensing (DFS) has proven its worth to the telecommunications domain and beyond: for network infrastructure protection over bi-directional Raman amplified transmission systems [1], for monitoring submarine cables and exploring the seafloor [2] and using AI for event recognition [3]. However, implementation challenges are yet to come, including big data processing and classification, hardware cost and various noise sources. Also, depending on the deployment conditions of the fiber infrastructure, different processing challenges could arise as the distributed fiber sensing techniques can perform characterization of both the fiber and its environment, be it water, air, or ground. Therefore, subsequent sensitivity and reach restrictions are expected, thus requiring novel technological challenges to be addressed.

We used coherent technologies as well as digital interrogation to develop Coherent-multiple-input-multiple-output (MIMO) digital fiber sensing (DFS), which is a robust interrogation technique that allows harmlessness of the sensing channel over the transmitted data channels in optical networks even when the sensing channel is inserted in the same transmission band [4]. In the following, we discuss technological aspects such as dual-polarization, constant power interrogation, as well as the available metrics to be obtained with the Coherent MIMO-DFS. Mainly, we explore the performance of Coherent-MIMO-DFS on the field, dealing with strong background noise and various types of ground and environments.

2. Digital coherent sensing

With regards to the constantly increasing amount of transported information and the growing impact of a network failure, telecom operators strive for monitoring their network with more and more accuracy [4]. Urban centers are developing into smart cities, where dense human activities are being monitored so to ease interactions and prevent various types of incidents, as depicted in Fig. 1(a). Distributed Fiber Sensing (DFS) is at the interface between smart city applications and network protection: in Fig. 1(b), it is integrated as the finest granularity monitoring within the concept of a global telemetry system where in-depth monitoring is implemented at each network layer.

To avoid fiber break situations such as pictured in Fig. 1(c), the DFS interrogators can be enabled on-demand in conjunction with forward sensing or alarms from the upper network or IP layers, hence enabling accurate event localization and identification when required while generating a reasonable amount of sensing data on the control

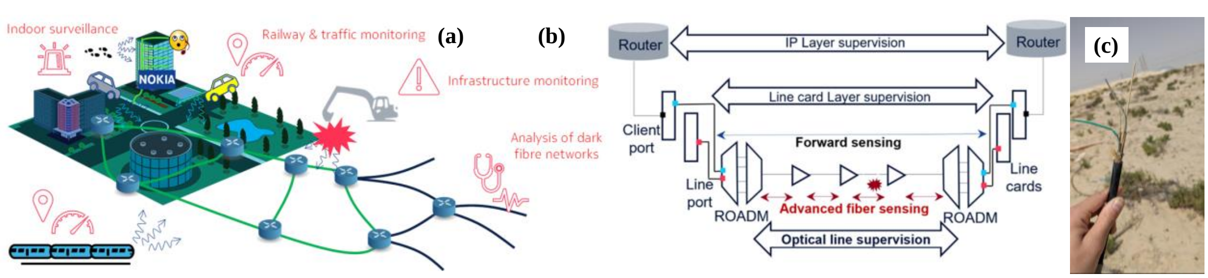

Fig. 1: (a) Smart city overview, (b) global network telemetry system, and (c) fiber cut on the field.

plane. We introduced a spread spectrum interrogation technique inspired by from coherent transmission [5], consisting of phase-modulated polarization-diversity binary codes at the transmission side and of a polarization-diversity coherent mixer at the receiver side, after which a signal processing stage derives the round-trip propagation between the transmitter and the receiver at every fiber position along the sensed link. This technique solves the polarization fading issue and thus lowers the noise floor compared to standard methods that do not fully exploit polarization diversity [6]. Beyond fading issues, the laser source stability is a fundamental requirement to limit the phase noise floor and to enhance the detection threshold and maximum reach in DFS technology [7,8].

Now, the main reason for the use of digital, constant power DFS interrogation is needed for copropagating sensing and communication signals. High power sensing pulses can interfere with data channels if they are co-propagating due to fiber nonlinearity. Coherent MIMO-DFS with constant amplitude and continuous probing sequences exhibits low peak power, which allows for the insertion of the DAS channel within the transmission band without sacrificing bandwidth. In Fig. 2, we show unchanged performance (measured through electrical Signal-to-Noise Ratio (SNR) computed from the equalized constellations, Fig. 2(a) and (c)) of adjacent WDM channels (Channels Under Test, CUT) carrying 600Gb/s net data rate with a co-propagating digital sensing signal as close as 2GHz (Fig. 2(b)), which was demonstrated on an 82-km span transmission including deployed fiber [9].

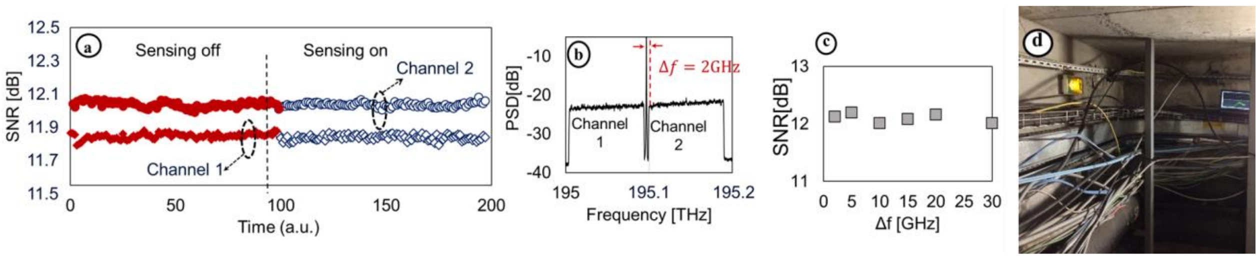

Fig.2: a) Measured SNR of CUTs with and without sensing signal, b) optical spectrum of CUTs spaced 2 GHz apart from the sensing signal, c) measured performance of CUT #2 vs frequency spacing, and (d) the deployed cable conditions [9].

3. Sensing on deployed fiber cables

Performing DFS experiments over deployed infrastructure is the next big step towards networks protection. It is necessary to measure all background noises and other disturbances from the undergrounds and from the surface in urban areas, to be able to differentiate between that background noise and potential threats to the infrastructure.

As we are approaching the limits of single-mode fiber systems, the scaling of future optical systems will require space-division multiplexing (SDM) to cope with the ceaseless increase of data traffic. Sensing for network protection has to prove itself valuable on all types of fiber. The first DFS trial on deployed Multi-Core Fiber (MCF) was conducted in L'Aquila, Italy, with a cable route displayed in Fig. 3(a) [10]. The MIMO-DFS probes two successive cores of a 4-core MCF, resulting in a 12.4km route. Fig.3(c) shows the inside of the underground tunnel where the fiber cables are deployed; the MCF lay on one of the upper shelves. Some noticeable events in the city are indicated on the map in Fig. 3(a) by colored markers. Fig. 3(b) displays the phase variations map output for two consecutive cores interrogation: a coherent combination method was used on the two cores' measurements to effectively reduce coherent fading of the backscattered signal, taking advantage of the multi-core fiber by harnessing spatial diversity [11].

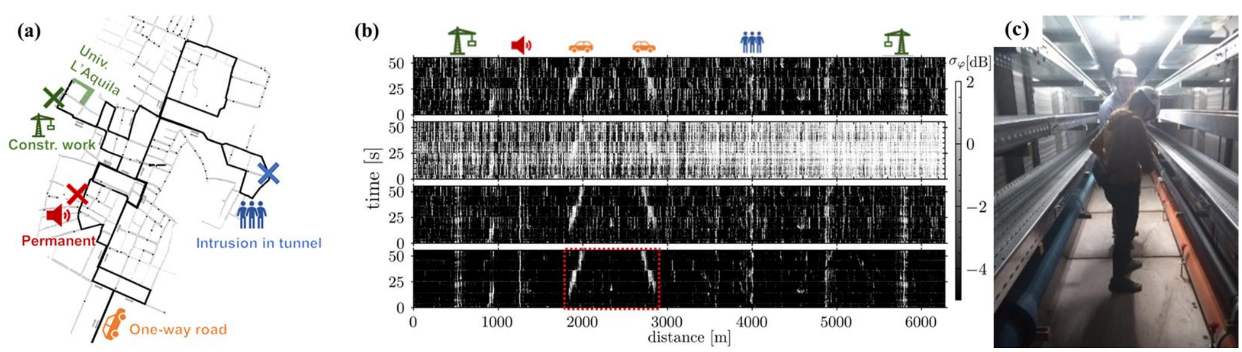

Fig. 3: (a) Deployed MCF map and markers corresponding to a set of selected events (b) Time-distance map of phase variations over a 1-minute-long acquisition for: (from top to bottom) core 1, core 2, and LMS average of the cores (Co.1+Co.2) with respectively 1 and 2 consecutive samples included in the averaging procedure, and (c) the deployed cable conditions [10,11]

The global fiber infrastructure is deployed around the world in different conditions and environments. While some fiber cables are aerial, deployed on poles and subject to wind blowing, the buried cables can be installed in ducts, or in tunnels, several meters under the ground (L'Aquila case) or less than 2 meters deep. In most countries, it is likely that the fiber is deployed along major motorways. Note that although traffic monitoring (demonstrating good detection and localization) was one of the first applications demonstrated with DFS on deployed fiber [12], it is not crucial in case of network safety monitoring since usual traffic is not likely to degrade the optical fiber cable. The bigger threats to the fiber infrastructure are construction works or environmental disasters such as landslides, earthquakes, which must be clearly identified, in addition to detection and localization.

4. Network telemetry

Probing an optical fiber on two orthogonal polarization axes with the designed binary codes formally yields unbiased estimations of the full Jones matrices $H_{i,j}$ (i and j time and distance index respectively) of segments of the sensed fiber with a spatial resolution S_r and refresh rate T_{code}. Indeed, the Jones representation describes an optical system as a succession of retardation plates and partial polarizers that operate on the incoming light [13]. The backscattered intensity, phase, and state of polarization (SOP) are hence retrieved. Now practically, it is important to note that each

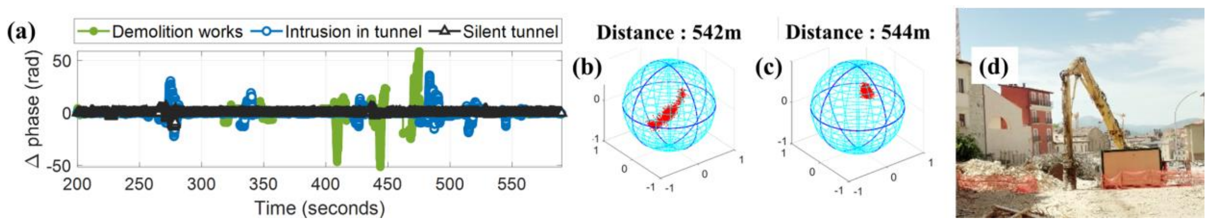

Fig. 4: (a) Backscattered phase measurements using MIMO-DFS in time domain, (b,c) polarization rotation vector respectively at 542 m from fiber start (impact) and 544 m (after impact), 10 seconds measurement on multi-core fiber, and (d) demolition works that occurred above the buried fiber [10].

metric is not used in similar conditions. For example, on a measurement near destruction works, or in presence of intruders directly touching the fiber cables, the phase signal can be strongly disturbed: in Fig. 4(a), up to 35.8 rad and 57.8 rad phase excursions were measured for intrusion and demolition events, respectively [10]. For such strong energy events, the phase metric can locally be affected by slew rate effects, so preventing from a reliable identification of the mechanical stress reaching the fiber. Therefore, we also look at the backscattered polarization states. Fig. 4(b,c) show the polarization rotation vector extracted from the unitary part of the roundtrip propagation. Furthermore, in-depth joint time-frequency analysis of either polarization rotation vectors of phase variations gives precise information on the nature of an event. Event identification can be based on automated pattern recognition using artificial intelligence (AI), but also some events can be directly identified and further classified by means of lookup tables.

5. Conclusions

We highlighted the recent advances of DFS in terms of technology enhancement, namely on polarization diversity and sensing-data co-propagation. We also displayed some of our recent field experiments results, demonstrating a capacity to operate DFS in various environments and fiber types, with clear identification of threats to the fiber infrastructure, thus a capacity to efficiently raise alarms for network protection, paving the way for early warning of costly hazardous events such as fiber cuts on critical infrastructures.

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