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Detection and Localization of Metropolitan Anthropic Activities by SOP Monitoring of IM-DD Optical Data Channels

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***Abstract*—We propose an optical network architecture exposing environmental sensing functionalities using the network elements streaming telemetry. We experimentally show the detection and localization (with 100-meter accuracy) of anthropic activities by state-of-polarization monitoring of two IM-DD channels copropagating with 94 coherent channels.**

***Index Terms*—optical fiber sensing, state of polarization, monitoring, im-dd, anthropic activities**

I. Introduction

Optical fiber communication networks based on wavelength-division multiplexing (WDM) have become a pervasive infrastructure in order to cope with the ever increasing demand for high-bandwidth connectivity. Recently, we have also witnessed an increasing interest in exploring the use of the already deployed optical fiber networks as a wide distributed network of sensors [4]. This finds application in many fields: from earthquake detection [5] to anthropic activities monitoring [10]. Optical fibers have been shown to be excellent mechanical stresses sensors as these affect the propagating signals' phase and state of polarization (SOP) [3]. Distributed acoustic sensing (DAS) or optical time domain reflectometer (OTDR) -based systems are effective but have a short reach and require dedicated hardware and channels or the use of dark fibers, preventing their wide diffusion. [6], [7]. In [11], [12], the authors propose to use coherent DSP data for sensing, since it already tracks the external strain affected phase and SOP evolution to recover the transmitted data, although access to this data is not easy due to vendor lock in. On the other hand, in the access and metro segments, the much simpler intensity modulated direct detected (IM-DD) transceivers are still widespread, both as 10 Gbps WDM data channels or lower rate optical supervisory channels (OSC). Thanks to the polarized nature of IM-DD signals, SOP variations induced by mechanical stresses can be observed by tapping some power to feed a polarimeter or even a simpler polarization beam splitter (PBS) followed by a pair of photodetectors and low-speed ADCs and electronics for signal processing [8], [9]. In particular, OSC channels, usually transmitting at 1.25 Gbps with small form-factor pluggables (SFP) modules, are commonly available at every amplification site, thus providing several sensing sources [1], [2]. In this paper, we first propose an optical data network architecture exposing sensing functionalities by exploiting the already deployed pervasive telecommunication infrastructure. The idea is to get the information content from the physical quantities already monitored for network control and management purposes or integrated by other sensors. Secondly, we experimentally provide a proof of concept of the sensing technique envisioned to be employed in the proposed terrestrial network architecture. In this experiment we prosecute the activity of [8], [9] adding the localization capability of external perturbations using the SOP monitoring of commercial IM-DD channels carrying data in the presence of other co-propagating data channels.

II. Network Architecture for Sensing

Differently from submarine applications, in terrestrial scenario optical networks are usually arranged in meshed topologies densely covering large geographical areas. As depicted in Fig.1, to fulfill modern traffic requirements and business

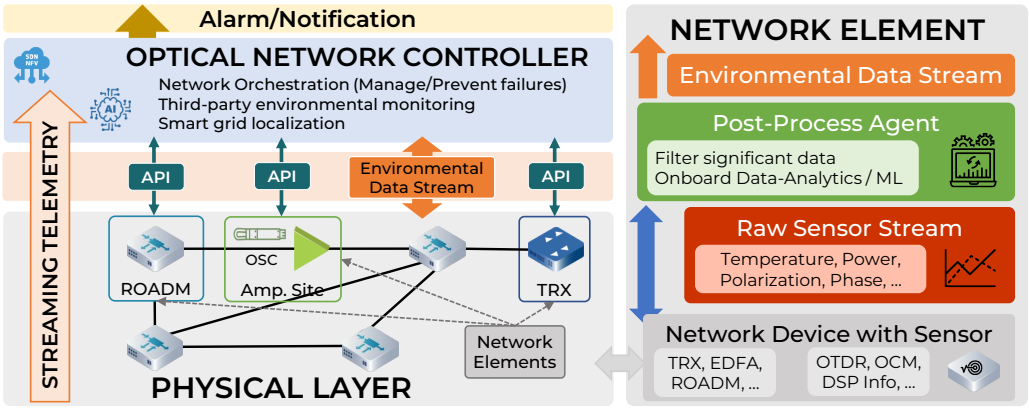

Fig. 1. (Left) Sensing network architecture; (Right) Generic network element with embedded post processing.

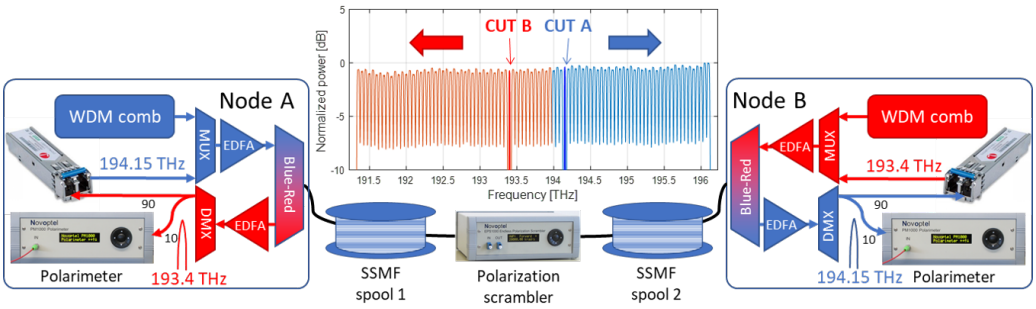

Fig. 2. Experimental setup. On both ends an IMDD TRX and a polarimeter are present, being the opposite flows separated with blue/red filters. SSMF: standard single-mode fiber; DMX: demultiplexer; EDFA: erbium-doped fiber amplifier; Blue-Red: multiplexer/demultiplexer.

models, optical networks are evolving towards multi-service autonomous, flexible, software defined entities based on a centralized optical network controller (ONC) orchestrating the networking functions and communicating with the network elements using standardized interfaces. The evolution of some physical quantities (such as phase or Stokes parameters) calculated on the data signals already contain information related to the environmental condition. In addition, devices as ROADMs or optical amplifiers typically have several other sensors already embedded (power monitors, temperature sensors) or they can be equipped with some others (GPS modules for exact site localization, for example) which can provide additional useful environmental data. Hence, as in Fig.1, network elements as IM-DD TRX/OSC channels, amplifiers and ROADMs can continuously provide environmental data streams. To ensure network reliability, streaming telemetry services have been proposed and demonstrated to provide on-demand, real-time streaming of monitoring parameters [13], [14] to the ONC. In our vision, the ONC can implement a dedicated software sub-module whose aim is to exploit the streaming telemetry data to extract environmental information. Furthermore, as shown in Fig.1, to reduce the amount of data sent to the sensing-ONC, a post-processing agent may be implemented exploiting the computational capabilities available. By cross-processing the data coming from all the network elements, the sensing-ONC is able to detect and localize events acting as a smart grid continuously monitoring large areas and reacting with early disaster-warning signals or prepare to traffic re-routing. Indeed, a couple of IM-DD transceivers, polarimeters or PBSs and acquisition devices connected by a bidirectional fiber pair is the minimum setup to perform not only detection but also localization. The experimental detection and localization were carried out at the LINKS laboratories with such setup.

III. Detection and Localization Experiment

The bidirectional setup implemented for the experimental validation of the environmental activity localization is depicted in Fig. 2. Each node is composed by a commercial DWDM card and a ROADM. The card is equipped with an IM-DD SFP+ TRX module generating an intensity modulated optical signal at 10 Gbps carrying data. The ROADM is composed by two DWDM filters (MUX and DMX, used as add/drop node) and two embedded EDFAs (used as booster and pre-amplifier, respectively). A blue/red filter is placed in front of each node to separate the two bidirectional DWDM combs in frequency. The 10 Gbps signal generated at the Node A, centered at 194.15 THz, is multiplexed with 42 DWDM interfering channels (32 GBaud, 50 GHz spaced) in the frequency range 194-196.1 THz. Similarly, the 10 Gbps signal generated at the Node B, centered at 193.4 THz, is multiplexed with 52 DWDM interfering channels (32 GBaud, 50 GHz spaced) in the frequency range 191.35-193.95 THz. At the receiver side of each node, after dropping the 10 Gbps signal from the DWDM comb, a small portion of the received optical power (-20 dBm) is tapped by means of a 10/90 optical splitter and collected by a commercial polarimeter (Novoptel

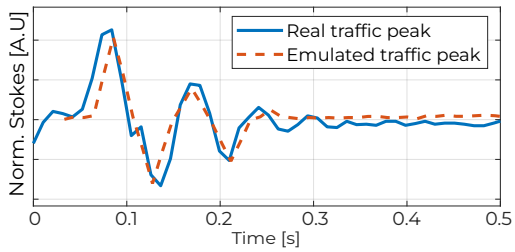

Fig. 3. Comparison between Stokes parameters variation over time generated by the real traffic and the laboratory polarization scrambler.

PM1000) to monitor the Stokes parameters variations. An alternative low-cost, low-energy solution (already demonstrated in [8]) could be obtained replacing the polarimeter with a detection system composed by a PBS and two commercial photodiodes followed by a trans-impedance amplifier stage and a 14-bit differential Analog-to-Digital Converter for signal acquisition. The bidirectional link is composed by two standard single mode fiber (SMF) spools with a polarization scrambler (Novoptel EPS1000) between them. This scrambler is programmed to emulate fast Stokes parameters variations, similar to the one caused by the local birefringence modulation induced by vibration/pressure that can be produced by the passage of the front and rear car's axle across high sensitivity points like the mini/micro trenches for fiber cable installation on the roadway (Fig. 3), which have been observed in [9]. The birefringence change induces variations of the Stokes parameters of the IM-DD signals, which can be identified as a peak. The emulated peak propagates towards both nodes, therefore the two polarimeters shall be synchronized in time, in order to share the same time reference during peak detection. The difference between the two polarimeters timestamps corresponding to the peak detection is then evaluated and translated in spatial difference. The polarimeters sampling rate is set as a trade-off between the maximum number of samples that can be stored and the time resolution that can be achieved; for this experiment, 3.1 MSample/s is used, resulting in a time resolution of about 320 ns, corresponding to a spatial resolution of about 64 m. In order to validate the peak localization method, we used different fiber spools. While the first fiber spool length was kept constant, we varied the second spool length to emulate a mechanical stress happening at seven different positions in the overall fiber length. The results are summarized in Table I, where the real fiber lengths are precisely measured by means of an OTDR and reported in the second and third columns. The estimated values using the SOP technique are reported in the fourth and fifth columns. In this way, the localization problem reduces to a correct estimation of the spool lengths. This result suggests that acceptable estimation errors can be obtained with reasonably low cost/complexity ADC circuits. Moreover, as previously stated, further cost reduction may be gained using a simpler PBS-based system to estimate the SOP variation, which will be verified also in terms of accuracy in future works. In our experiment, the polarimeters were synchronized by connecting themselves with a BNC cable, which is not feasible scaling

TABLE I
EXPERIMENTAL RESULTS

Test	Measured with OTDR [km]		SOP Method [km]		
	Spool 1	Spool 2	Spool 1	Spool 2	Error
1	20.006	0.957	19.972	0.991	0.034
2	20.006	6.045	19.981	6.070	0.025
3	20.006	7.002	19.945	7.063	0.061
4	20.006	9.515	20.037	9.484	0.031
5	20.006	10.437	19.899	10.580	0.107
6	20.006	15.560	19.976	15.590	0.030
7	20.006	16.518	19.907	16.617	0.099

the technique outside the laboratory. From our experiment we found out that the required synchronization accuracy needed is in the order of tens of microseconds, which is not satisfied by the Network Time Protocol (NTP) [15]. Better timing protocols such as the Precision Time Protocol (PTP) [16] can be used, whose accuracy scales down to the sub-microsecond regime. Alternatively, it could be possible to equip the network elements with GPS-based timing systems with accuracy in the range of nanoseconds [17]. This could also provide accurate positioning information for precise localization of the node and facilitate the localization of the detected event.

IV. CONCLUSIONS

We have briefly proposed an optical network architecture based on the streaming telemetry and integrated with additional sensors for environmental sensing. In particular, we have demonstrated detection and localization of mechanical stresses by means of a SOP monitoring technique generated by a pair of commercial IM-DD transceivers.

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