Vibration Detection and Localization in Buried Fiber Cable after 80km of SSMF using Digital Coherent Sensing System with Co-Propagating 600Gb/s WDM Channels

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Abstract: We report detection-localization-identification of true mechanical events on a buried fiber cable up to 82km SSMF using a digital sensing system copropagating with adjacent 600Gb/s WDM channels. Non-intrusive coexistence with WDM channels is demonstrated. ©2021 The Author(s)

1. Introduction

Fiber optic sensing has recently attracted much attention in the field of optical communications addressing various applications like smart cities [1,2] or environmental monitoring [3, 4]. Several approaches are being investigated providing different flavors in terms of bandwidth, distance, sensitivity, and localization. The extraction of State of Polarization (SOP) [5] from digital coherent transponders was demonstrated in a deployed subsea cable with the potential to detect high magnitude events such as earthquakes [4]. Recently, extraction of optical phase recovered from coherent transponders has also been demonstrated [6], providing higher sensitivity than SOP extraction. However, those techniques require bi-directional configuration with time synchronization to achieve localization of detected vibration events, which may prove to be unpractical for optical networks. One approach providing accurate localization and high sensitivity is Distributed Acoustic Sensing (DAS), based on Rayleigh backscattered light. While initially relying on fiber sensors, several approaches have been proposed based on coherent receivers to allow DAS on the optical fiber infrastructure. DAS over telecom fibers allows fine detection, localization, and identification of events along fiber spans (flap detection…), paving the way to a multi-layer telemetry vision for future network monitoring and automation [7]. In [1], a first demonstration of fiber sensing based on 40ns optical pulses has been reported with 1-meter resolution for localization. However, since signal pulses in the DAS system exhibit high peak powers, they interfere with data channels if they are co-propagating due to fiber nonlinearity. the DWDM signals and sensing signals were thus counter-propagated and three 50GHz slots were left empty to ensure non-intrusive coexistence between both signals [8].

In this paper, we report on a highly sensitive digital DAS system based on coherent receiver and low peak power digital interrogation sequences, that continuously modulate an optical carrier. We demonstrate non-intrusive co-propagation with WDM channels on an 82km link made of Standard Single Mode Fiber (SSMF). We show the accurate localization of true vibration events within a 600Hz bandwidth in a buried fiber cable located at 100m, 30km and 80km distance from the digital DAS system. Moreover, we demonstrate the non-intrusive coexistence of the sensing signal by measuring the unchanged performance of the adjacent WDM channels carrying 600Gb/s net data rate with a co-propagating digital sensing signal as close as 2GHz.

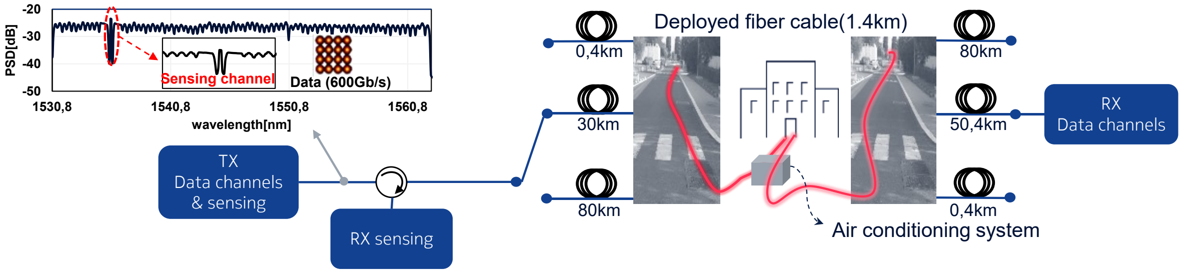

Fig.1: Experimental demonstration of co-propagating digital sensing signal and WDM channels over an 82km-long span

2. Experimental set-up

An 82km span of SSMF consisting of fiber spools and a 1.4km long deployed fiber cable alternatively placed at different distances from the transmitter is used for the transmission of full C-band data, except for ITU-C51 WDM slot enclosing the sensing signal, as displayed in the full set-up in Fig.1. The fiber in use is part of a coated cable deployed between two buildings. It exits the first building after crossing a datacenter, then it is buried 0.6m under an asphalt road, where various vibration sources are met. The main perturbation is an air conditioning system 10m distant from the cable and located near the second building. Acoustic measurements (sonometer and spectrum analyzer) showed a stable low acoustic pressure of 63dBC/45dBA SPL at the cable with a spectral signature made of a 24.5Hz fundamental component and harmonics up to the seventh rank (172Hz).

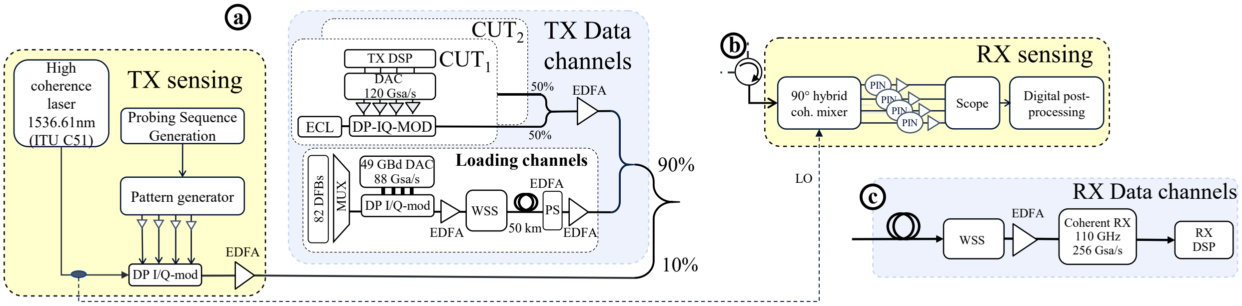

Fig.2: (a) Transmission setup (b) sensing receiver and (c) data channels receiver

As shown in Fig.2(a), the sensing signal is coupled to the transmitted C-band channels through a 10/90 optical coupler to set the power of the sensing signal in ITU-C51 slot similar to other WDM slots used for transmission. The WDM testbed is composed of 82 loading DFB lasers spaced by 50GHz, plus two Channels Under Test (CUT). The loading channels are modulated at 49GBd with Dual Polarization (DP) 16QAM modulation and Nyquist pulse shaping using 0.01 roll-off. The CUTs for data transmission each occupy two consecutive 50GHz slots and are modulated at 90GBd with DP-16QAM, carrying 600Gb/s net bit rate in 100GHz spacing. The CUTs are located on adjacent slots to the one occupied by the sensing signal to assess the impact of the sensing channel on data transmission performance. The digital sensing interrogator probes the full span at a rate F_s using single polarization digitally generated linear frequency sweep signals. Though formally less efficient than MIMO codes, single polarization sweep probing requires a laser source coherence restricted to the sole fiber round-trip time [9], so enhancing here the distance to sense. The sweep covers a $[0{:}\, F_s\,/2]$ bandwidth over a period $T_{sweep} \geq T_{ir}$, where T_{ir} is the round-trip time of light in the fiber. A high coherence OEwaves^{TM} laser source at 1536.6nm is modulated continuously and periodically at the period T_{sweep}. The use of continuous probing reduces the Peak-to-Average Power Ratio (PAPR) with respect to pulsed probing, thus mitigating non-linear induced distortions on surrounding WDM channels [10].

The generated full C-band comb is launched into the fiber span at 18dBm, yielding an average channel power of -1dBm per 50GHz slot. At the receiver side, after 82km of SSMF, the CUTs are selected using a WSS before being sent to the coherent receiver as depicted in Fig 2(c). A high-speed sampling scope operating at 256GS/s is used to store waveforms and digital signal processing [11] is performed offline to measure the output SNR of each 600Gb/s channel. The backscattered light is captured at the launching end of the fiber span by another coherent receiver. As illustrated in Fig. 2(b), self-homodyne configuration of the coherent receiver captures the signal backscattered from the sole sensing slot. After correlation with the transmitted signals, the coherent sensing system recovers the backscattered optical field and extracts a segmented representation of the probed fiber where the differential phase is characterized at each segment along the fiber path. The spatial resolution is derived from the modulation frequency as $SR = c_f/(2.F_s)$, c_f standing for the light velocity in the fiber.

3. Experimental sensing results

The fiber span is interrogated continuously with F_s=50MHz, covering a 600Hz sensing bandwidth. The standard deviation of the backscattered phase denoted σ_ϕ is given in Fig.3 for the three different scenarios depicted in Fig.1.

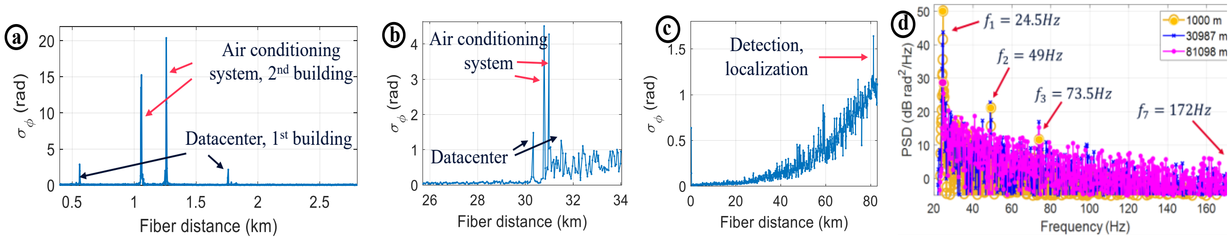

Fig.3: Detection and localization of machinery noise near a telecom cable after (a) 400m (b) 31km (c) 81km SSMF (d) Power spectral density of differential phase at σ_ϕ detection peak location: identification of the disturbance

First, the deployed fiber cable is placed at the start of the span, and its phase variations signature is captured in Fig.3(a). After such short distance, the σ_ϕ along distance is given at the native resolution of the system (SR=2.05m), therefore the phase variations due to both the crossing of a datacenter at the beginning of the fiber cable and the presence of an air conditioning system halfway-through the cable path are detected as different peaks. Moreover, as described in Fig.1, the deployed fiber cable experiences the external vibrations twice as it performs a round trip between two buildings, leading to the 4 distinct peaks in Fig.3(a). Then, a 30km fiber span is inserted between the TX and the cable (Fig.3(b)). The datacenter and air conditioning systems are still correctly localized and identified with a precise spatial resolution, allowing to differentiate between the different detection peaks. Finally, the fiber cable is connected after 80km SSMF and the full evolution of σ_ϕ along the fiber span is given in Fig.3(c). Due to the increased phase noise at the coherence length limit of the laser source, further averaging was needed, thus decreasing the spatial resolution to SR=100m. Therefore, the peaks are not differentiated anymore and appear as one single event, yielding a single σ_ϕ detection peak at 81km. Nevertheless, successful identification of the disturbance is observed at such distance as shown by the power spectral density of the phase in Fig.3(d). The spectrum of phase at the σ_ϕ peaks locations gives the spectral signature of the machinery, in line with the acoustic measurement performed near the cable (harmonic spectrum with 24.5Hz fundamental frequency). After 81km, the fundamental and third order harmonic are visible on the spectrum, exceeding the noise level by nearly 10dB. Consequently, such raw data could be used as input for a pattern classifier based on advanced AI algorithm.

Finally, as shown in Fig.4, we analyze the performance of the adjacent coherent channels carrying 600Gb/s data. The measured SNR after 82km transmission is left unchanged while switching on and off the sensing signal (Fig.4(a)). Moreover, we measure the impact of setting the CUTs closer and closer to the sensing signal. As shown in Fig.4(b) and Fig.4(c), the SNR performance of the channel 2 under test remains stable as we approach the sensing signal down to 2GHz. This result demonstrates the non-intrusive coexistence of our digital sensing system with high speed transmission data.

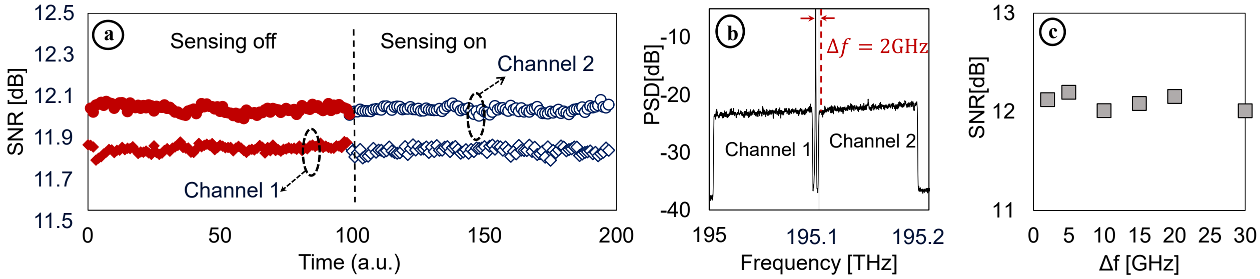

Fig.4: a) Measured SNR of CUTs with and without sensing signal, b) optical spectrum of CUTs spaced 2 GHz apart from the sensing signal, and c) measured performance of CUT #2 vs frequency spacing

Conclusions

Detection, localization, and identification of a true vibration event was performed over a deployed fiber cable after 82km fiber distance, together with co-propagating 600Gb/s WDM data transmission. We observed no impact of the digital coherent sensing system over the transmitted data down to 2GHz band spacing, paving the way for a per span high sensitivity-high bandwidth vibration monitoring of telecom networks seamless to the transmitted data traffic.

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