Capturing Acoustic Speech Signals with Coherent MIMO Phase-OTDR

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Abstract *We demonstrate the identification of an acoustic perturbation made of a 6kHz bandwidth speech signature reaching a 1km long SMF. The fiber is probed with a phase-OTDR over two orthogonal polarization axes and the backscattered signal is received by a polarization-diversity coherent mixer (MIMO sensing) which mitigate fading effects.*

Introduction

Distributed Acoustic Sensing (DAS) was initially introduced to monitor health of pipelines[1] or other specific structures[2] by means of dedicated fiber cables usually including fiber bragg gratings to enhance the backscattered intensity. Though adapting this technology to standard telecom fibers in already deployed infrastructure[3] is appealing for addressing a far wider range of applications linked to IoT and smart cities, DAS technology has to go a step further to enhance bandwidth, sensitivity and dynamic range. We recently introduced a phase OTDR method that captures perfect dual-pass Jones matrix channel estimates from the Rayleigh backscattered field over two orthogonal polarization axes[4]. It is called MIMO (Multiple-Input Multiple-Output) phase sensing since the transmitter uses a dual-polarization phase modulator (PDM-BPSK) and associated codes to probe the line whereas the receiver captures the backscattered information by means of a polarization-diversity coherent mixer. The sensitivity gain of this approach compared with more usual probing techniques has been recently demonstrated and quantified[5].

This paper reports MIMO sensing method performance through a complex practical case by showing that a speech signature impacting acoustically a 1km long standard single mode fibre (SMF) can be captured with a 2m spatial resolution, over a 6kHz bandwidth and with a dynamic range enabling an easy recognition of the voice message by listening test. We also show that the sensitivity (background noise reduction) can be further extended by relaxing the spatial resolution requirement.

Enhanced fibre response sensitivity

The standard fiber probing technique used for DAS systems is based on a light pulse periodically transmitted in single-polarization mode[6]; this approach is subject to polarization fading effects and leads to sub-optimal performance in sensitivity and maximum reach of the mechanical events present along the sensing fiber. To circumvent these limitations, we recently proposed to probe the optical line onto two polarization axes with 2 orthogonal sets of binary codes (derived from the Golay complementary codes). Thanks to a polarization-division-multiplexed (PDM) mapping using binary phase-shift-keying (BPSK), we modulate the light from a narrow linewidth laser source used in a self-homodyne configuration at the receiver side[7]. Such a method allows to recover a perfect estimation of the dual-pass impulse response of the fibre sensor, with a gauge length $d = c_f/(2F_{symb})$ given by the symbol rate F_{symb} of the transmitted probing sequence, c_f standing for the velocity of light in the SSMF core.

The sensor offers a large mechanical bandwidth, defined as $BW = 1/(2T_{code})$ where T_{code} is the duration of the probing sequence $T_{code} = N_{code}/F_{symb}$. N_{code} stands for the number of symbols that compose the code, which is detailed in[4]. The conditions for perfect

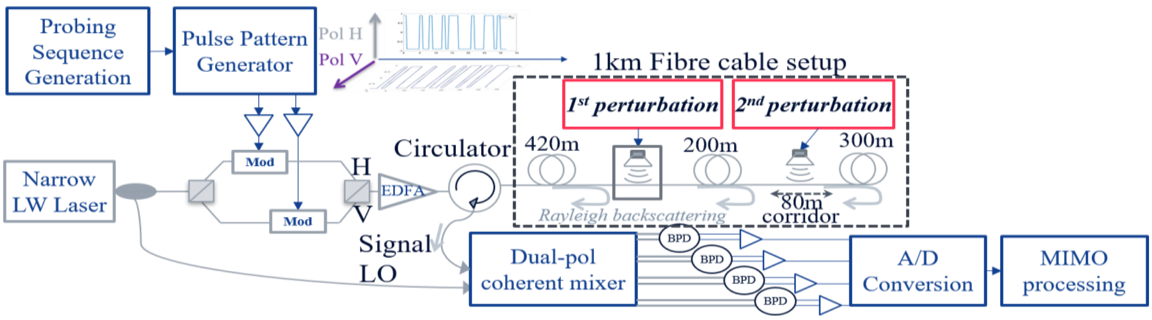

Fig. 1: Experimental setup with 2 acoustic perturbations (Pol: polarization, BPD : balanced photodetectors)

Fig. 2: a)Insulated cabin with loudspeaker (1st source) b)Corridor where 2nd source is captured SMF in crawl space

estimation of the sensor impulse response when the sensing fiber is probed with PDM-BPSK codes is $T_{code}>4.T_{ir}$ where $T_{ir} = 2L/c_f$ stands for the time spreading of the channel response for a fiber of length *L*. Thus, a mechanical bandwidth of 3kHz (similar to the bandwidth of the analog switched telephone network) can be obtained for a fibre sensor length under 4 km, with a symbol rate allowing for spatial resolutions of the order of the meter.

We call "Coherent MIMO" the above described sensor interrogation method. We recently demonstrated its sensitivity gain as compared with more standard single-polarization interrogation[5]: polarization diversity at the transmitter mitigates input polarization phase noise, and polarization diversity at the receiver spares polarization fading. Therefore, all possible polarization related noises are avoided, allowing for precise measurements with high dynamic range and paving the way to the sensing of complex mechanical signals.

Experimental setup

Fig.1 displays the overall experimental setup. The fiber under test is a 1km long SMF made of a 420m long first spool placed inside a mechanically insulated box. Then, the fiber enters into a 0.8mx0.8mx2m insulated cabin that contains a loudspeaker placed at a 0.5m distance from the fiber, see Fig.2a. This 0.8m fiber section is slightly stretched between the two cabin walls. A second 200m long fiber spool, also insulated, extends the tested fiber section in our laboratory up to a total length of 620m. The fiber continues in the crawl space of an 80m long corridor, see Fig.2b, before terminating with a 300m long final insulated spool. The spool sections consist of bare fiber whereas the fiber is covered by a 0.9mm diameter plastic jacket in the insulated cabin and a thicker one (3mm diameter) in the underground section.

The fiber is probed over two orthogonal polarization axes with codes of length T_{code}=82µs that are repeated with a period equal to the code length (continuous probing), leading to an analysis of mechanical perturbations

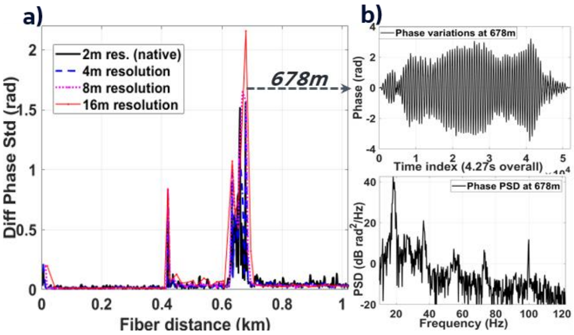

Fig. 3: a)Differential phase std along fiber b)Time slice at second perturbation location (678m) and associated PSD

affecting the fiber over a frequency range from DC up to 6.1kHz. The 82µs time length code is composed of 2^{12} BPSK symbols transmitted at F_{symb}=50MBaud, which yields a gauge length of 2m. Therefore, the 1km fiber is virtually split into 500 segments. Calculating the differential phase between consecutive segments allows to locally monitor the fiber, with a 2m native gauge length here. Hence, we continuously monitor temporal phase changes at different fiber sections.

When sensing with a short gauge length with regard to the fiber length, the number of segments to monitor is large, which requires high processing resources and memory storage. In practice, it can be preferred to relax the spatial resolution to save resources. This sub-resolution process can be emulated keeping the initial baud rate and associated 2m gauge length, by calculating the differential phases from a selected subset of fiber segments instead. We study here the impact of the spatial resolution onto the detection sensitivity by emulating sub-resolutions of 4, 8 and 16m respectively. This is achieved by selecting a segment subset from the native resolution set: for achieving a sub-resolution factor *p*, we choose, among every *p* consecutive segments, the one that provides the highest backscattered intensity on average over the time dimension. The relevancy of this intensity-based selection criterion is justified in[8].

Results

We inject a 5s male voice signal into the loudspeaker placed in the insulated cabin which locally perturbates the fiber at 420m from the start with a Sound Pressure Level (SPL) of 75dB_{SPL}, similar to that of a standard conversation volume[9]. The capture of speech signals over a [150:4000]Hz bandwidth is known to mostly enclose all the relevant information and so to allow for interpreting any voice message. In addition, the 80m fiber section in the corridor crawl space potentially captures acoustic and vibratory perturbations present in this part of the building, such as air conditioning machinery.

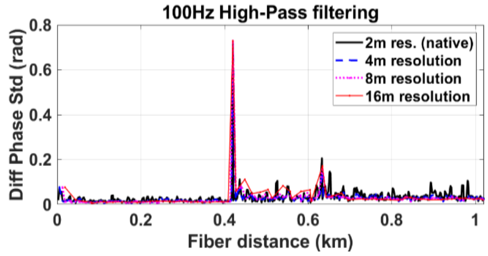

Fig. 4: Diff. phase std after 100Hz High-Pass filtering

Fig.3a displays the standard deviation (std) of the differential phase, measured along the 5s measurement time, as a function of the fiber distance. On top of the 2m native spatial resolution, we superimpose the std estimated every 2, 4 and 8 segments on average following the above described sub-resolution selection procedure. We observe two events at 420m and 660m from the fiber start, which indicates the detection of two mechanical events at the respective locations. The former one is accurately localized whereas the latter one spreads over 50m, between 640 and 680m, meaning that a perturbation is captured by the fiber over a large area in the corridor. Fig.3b displays the differential phase as a function of time along with its associated power spectral density (PSD) captured at 678m from fiber start (native resolution). The second event spectral signature is concentrated in the very low frequencies, with a fundamental component at 18Hz along with its first three harmonics (36, 54, 72Hz) and also a 100Hz component. This detected event is caused by a fan machinery installed 10 meters away from the corridor where the fiber is deployed. Such very low frequencies attenuate slowly with the distance, which explains why it is captured by the fiber over 50m around the actual noise source position. Fig.4 shows the same information as in Fig.3a but including high-pass filtering onto the differential phase time slices to get rid of spectral information below 100Hz. The peak around 650m has vanished, as it could be expected regarding the fan machinery spectral signature. Conversely, the former one at 420m is left unchanged, which complies with a speech signature since human voice does not contain any information below 100Hz.

Fig.5a displays the phase variations measured at the first peak location (420m) for each of the four spatial resolutions. The four signals superimpose with tiny differences only. Fig.5b zooms on a silent zone of the captured speech signal to magnify differences between the various resolutions. The figure shows lesser phase variations at lower resolutions (8 and 16m) than at the native one. Coming back to Fig.3a&4, such a phenomenon is also observed from the phase std in the regions where the fiber is not mechanically excited (insulated spools).

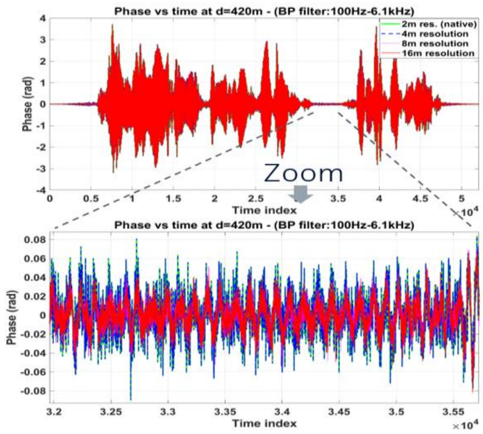

Fig. 5: a)Time slice at the first std peak shows speech signal. b)Zoom on a silent zone

Listening tests (recorded traces are available in .wav format[10]) of the speech signal captured at each spatial resolution bring two observations. Firstly, regardless of the spatial resolution, the voice captured acoustically by the fiber is artefact free, of high audio quality, roughly comparable to that of a mobile phone communication in terms of bandwidth and of dynamic range. These experimental acoustic results complement previous tests where the fiber was mechanically excited by means of piezoelectric actuators[7] which allowed to quantify performance in terms of amplitude and frequency response linearities and quadratic error. They also confirm the capability of the coherent-MIMO phase sensing approach to mitigate Rayleigh backscattering polarization-fading effects[5] and so to accurately capture complex mechanical signals featuring large bandwidth and high dynamic range. Secondly, the audio background noise brought by the system is slightly reduced when relaxing the spatial resolution, in line with the visual observation from Fig.5b. Though the fiber is excited over 0.8m only thanks to the insulated cabin, the differential phase measured over a 16m segment enclosing the cabin offers a higher sensitivity than the one measured over a 2m segment. It highlights the importance to calculate differential phase from highly reflective segments to enhance SNR, at the cost of a potential loss in event localisation accuracy.

Conclusion

We demonstrated the ability of the novel MIMO fiber sensing approach to capture acoustic speech signals from a standard telecom fiber with an outstanding perceptual quality. The speech signature was captured over a 6kHz bandwidth and localized with a 2m resolution over a 1km fibre cable. It was also shown that the dynamic range could be further increased when relaxing the native spatial resolution, with an audible reduction of the background noise, thus further enhancing the sensitivity.

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