Advanced Fiber Sensing Leveraging Coherent Systems Technology for Smart Network Monitoring

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Abstract: We show that coherent technology developed in the past decade for transmission over core optical networks can benefit to Distributed Fiber Sensing technology in various fields as sensitivity, sensing range, and coexistence with data traffic. ©2021 The Author(s)

1. Introduction

Nowadays, optical fiber cables serve as the backbone of the wireline telecommunication network, with millions of kilometers of connections transporting the internet traffic worldwide. Distributed Optical Fiber Sensing (DOFS) was initially introduced for monitoring applications such as oil & gas wells and civil engineering structures [1], exploiting dedicated fibers usually incorporating Fiber Bragg Gratings to enhance the Rayleigh backscattered intensity. Introducing DOFS in standard telecom fibers to address a much wider range of monitoring applications based on the existing deployed telecom infrastructure currently meets a growing interest, mainly driven by network need for deeper automation and telemetry [2]. Also, smart cities applications as car and railway monitoring can rely on deployed terrestrial networks [3] whereas submarine infrastructure may play a role in early detection of seismic events, tsunamis or cable damage induced by ship anchors [4]. However, technological challenges need to be addressed to reach this objective. As DOFS relies on the Rayleigh backscattering effect, the main constraint is the tiny and variable intensity of the backscattered optical field along standard Single Mode Fibers (SMF) used in telecom networks. This restricts both the sensitivity threshold, that is the minimal strain which can be detected, and the length of the optical link to be sensed since the backscattered intensity also vanishes with the distance in the fiberglass. On top of this, when combining DOFS functionality with data traffic in the same fiber, DOFS must guarantee harmlessness for the transmitted data flow. This paper aims to review techniques derived from the coherent transmission world which can be conveniently introduced to design a fully digital DOFS system that circumvent the above-mentioned issues.

2. Enhancing sensitivity through MIMO sensing and OFDM modulation

DOFS is formally a channel estimation problem: it is based on estimating the backscattered impulse response of the Fiber Under Test (FUT). This estimation is repeated periodically, with a period equal at least to the channel round trip delay, to detect potential variations induced by mechanical perturbations affecting the tested channel. In coherent transmission, the optical channel is conveniently modelled under a Jones matrix form to jointly account for intensity, phase, and light polarization state along the SMF. For DOFS, estimating the backscattered optical field response under such a Jones matrix form is appealing to finely characterize perturbations by exploiting the information from all available dimensions. As a matter of fact, most DOFS systems today probe the channel on one polarization axis only with pulses or alternatively with sweep signals optically generated by means of Acousto-Optic Modulators (AOM), leading to incomplete estimation of the backscattered field. In addition, the basic pulse excitation case potentially generates non-linear effects due to instantaneous optical power peaks that alter the channel estimation. To overcome these limitations, we introduced a DOFS approach derived from coherent transmission [5], depicted in Fig.1: the channel is jointly probed on two orthogonal polarization axes by means of two binary codes derived from Golay sequences both of period equal to T_{code} and repeated continuously. These codes use a dual polarization Mach Zehnder

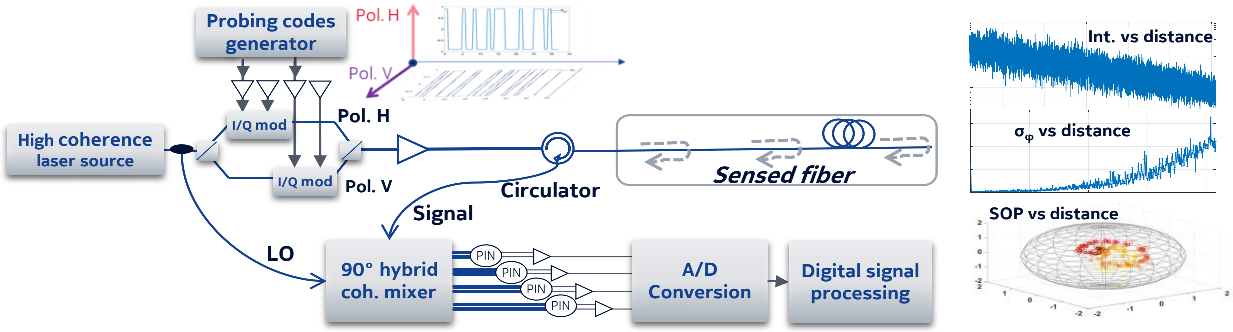

Fig.1: DOFS experimental set-up with polarization diversity both at transmitter and receiver sides (coherent MIMO). Intensity, phase, and polarization information extracted from the Jones matrices estimated along the FUT appears on the right side.

to modulate a highly coherent laser source with a phase modulation format (PDM-BPSK). Also, a coherent mixer with the laser source mounted in a homodyne configuration captures the backscattered optical field over two orthogonal polarization axes. The method yields, after appropriate digital processing, formally perfect Jones matrix estimates $J_{t,d}$ of the FUT [5] distributed in both time and space. In time, the sampling rate $F_{ts}=1/T_{code}$ sets the maximal bandwidth $[0:F_{ts}/2]$ of the mechanical perturbations characterized by the DOFS system ; in space, the FUT is split into virtual segments whose size L_{seg}, or gauge length, is given by the modulator baud rate F_{symb}, as $L_{seg}=c_f/(2.F_{symb})$, where c_f is the light velocity in the fiber core. The cumulated optical phase of the dual-pass response at fiber segment index d and time instant t is estimated as $\varphi_{t,d} = \frac{1}{2}.arg(det(J_{t,d}))$, where $det()$ stands for the determinant and $arg()$ is the associated angle. When differentiating the spatially cumulated phase terms, one gets local phase variations $\delta\varphi_{t,d}$ at each fiber segment index. Since any local strain affecting the fiber linearly transforms into an optical phase change [6], the FUT finally behaves as an array of virtual microphones separated by L_{seg} with a bandwidth of $[0:F_{ts}/2]$. Backscattered intensity, derived as $|det(J_{t,d})|$ to minimize the estimation error [7], and polarization state can also be extracted from the $J_{t,d}$ set to complement the phase information as illustrated in Fig.1.

Therefore, this novel approach to DOFS is largely inspired from coherent transmission systems deployed in long-haul networks: it uses binary codes for channel estimation, polarization diversity both at transmitter and coherent receiver sides, phase modulation format. Hence the name “coherent-MIMO sensing” to highlight the polarization diversity at transmitter and receiver sides. It fully removes both polarization intensity fading, and polarization induced phase noise effects [8]: Fig.2a shows the standard deviation σ_φ in a 1s time window of the estimated phase along a 50km length emulated SMF. This parameter σ_φ highlights the DOFS sensitivity threshold. The simulation encloses the optical noise sources induced by the set-up including the phase noise of a narrow linewidth laser source (75Hz at 1536mn). The figure compares the sensitivity achieved with/without polarization diversity at the transmitter (MI/SI) and at the receiver (MO/SO). The noise floor increase observed along the distance axis is mainly driven by the coherence loss induced by the laser phase noise. The MIMO approach overperforms the two alternative ones, bringing a much lower noise floor, and these results have been fully confirmed experimentally. A simulation performed without polarization rotations has led to an additional curve in Fig.2a that superimposes to the MIMO one, thus demonstrating that coherent-MIMO sensing brings for the first time an ultimate solution to DOFS polarization fading issues.

A major remaining issue in DOFS is the coherent fading, or speckle noise. It affects the intensity level backscattered along the fiber according to the combination of the elementary scatterers present in each fiber segment. OFDM is widely used in telecommunication to mitigate propagation fading effects. It can be suitably included in a digital DOFS to probe the line jointly over N_{sc} synchronized subcarriers rather than over a single carrier, keeping the same electrical bandwidth [9]. This multicarrier approach, fully compatible with the MIMO scheme defined for the single carrier case, reuses dual-polarization binary codes. At the reception, after OFDM demodulation, the N_{sc} channel estimations are combined with a rotated-vector-sum algorithm [10]. Fig.2b shows σ_φ along a 1km simulated SMF with F_{symb}=50MBaud and using N_{sc}=4. The peaks observed at each subcarrier are induced here by the sole coherent fading. This fading is mitigated after combination of the 4 subcarriers by a 10-fold factor here as shown in the red curve, at the cost of a spatial resolution loss by a factor of N_{sc} [9].

Switching to experimental results, Fig.3 shows the acoustic footprint in the time (5s) versus distance (100m) plane of a vehicle driving at a stable speed of 40km/h. The event is captured along a 700m SMF telecom cable located 60cm below the street in a concrete tunnel. Single carrier, OFDM with 2 and then 4 subcarriers cases are tested successively. The vehicle trajectory is highlighted by the blue spot whereas false alarms induced by coherent fading, concentrated in the single carrier case, appear in red. With OFDM measurements, the false alarms vanish while the vehicle trajectory gets more visible when the number of subcarriers increases [11], so enhancing performance of further tracking tool.

The DOFS is now configured to perform detection-localization of a mechanical event along an 82km long SMF [12]. σ_Φ of the backscattered information in Fig.4a shows a peak at 81km. The detected event is a cooling machinery with a noise having a fundamental frequency f_1=24.5Hz inducing a 61dB$_C$ pressure level measured close to the cable place.

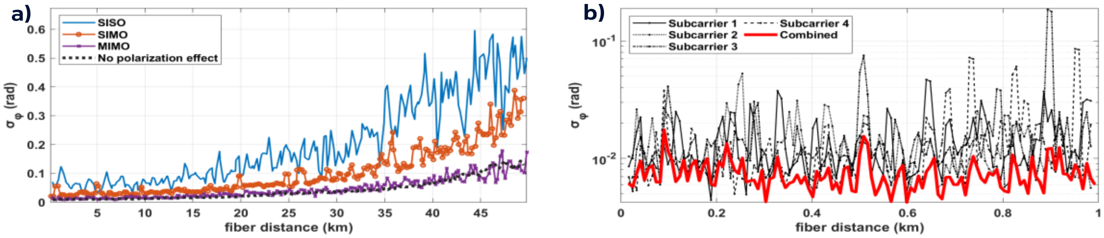

Fig.2: a) MIMO (polarization diversity at Tx & Rx) DOFS along a 50km SMF: cancelation of polarization fading effects, b)Multicarrier probing along a 1km SMF with a 4 subcarriers OFDM scheme & combination of the subcarriers at Rx side: mitigation of coherent fading effects.

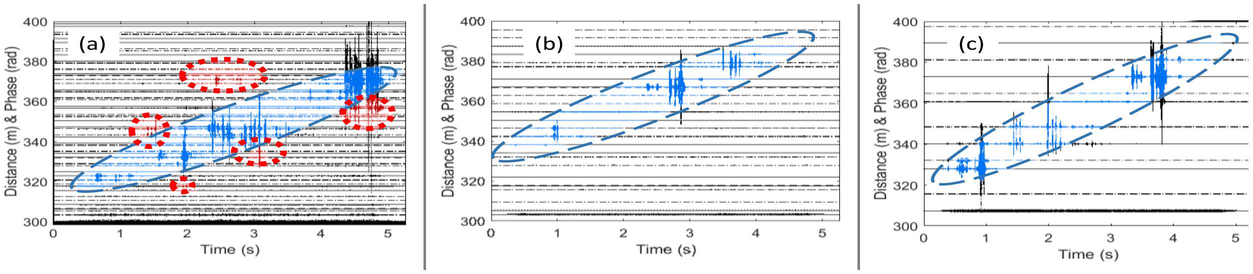

Fig.3: Evolution of phase in the time-distance plane, successive measurements for single-carrier (a) and OFDM2,4 (b,c) interrogations. Blue/dashed: on vehicle trajectory - Red/dotted: unreliable zones or false alarms.

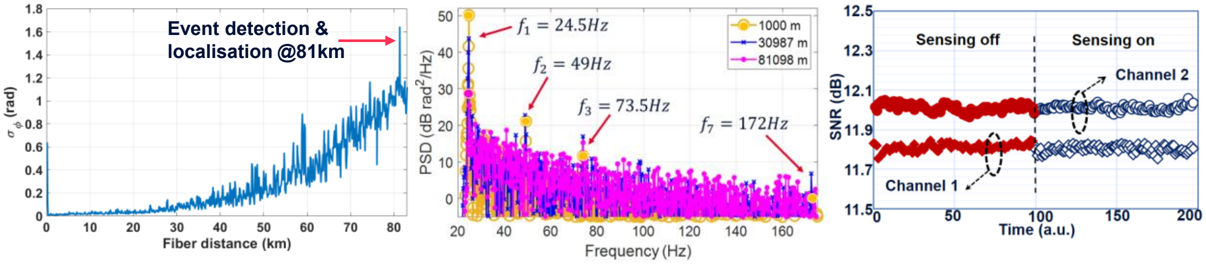

Fig.4: a)Detection-localization of machinery noise near a telecom cable after 81km SSMF, b)Power spectral density of differential phase at σ_ϕ detection peak location: disturbance identification, c)Snr of adjacent WDM channels carrying 600Gb/s data: No impact of sensing.

Fig.4b shows the Power Spectral Density (PSD) of the phase variations at the peak position, highlighting the noise source identification through its spectral signature (f_1 and harmonics up to 7th order – 172Hz). The line was probed at F_{symb}=50MBaud on 1536.6nm WDM channel (ITU51) with PDM-16QAM 600Gb/s data traffic running on adjacent channels. Fig.4c shows performance at ITU50&52 adjacent coherent channels carrying 600Gb/s data on slots, demonstrating that the SNR is left unchanged when switching on the sensing channel. This demonstrates the total innocuity on data traffic when preempting a WDM channel to perform sensing with the DOFS technique detailed here.

3. Conclusion

We highlighted that an advanced DOFS leveraging coherent technology and other techniques derived from telecom transmission enables to tackle major performance bottlenecks as polarization induced fading, speckle noise and non-linear effects. The sensitivity threshold enhancement was firstly demonstrated through modeling and simulation. Secondly, we used experimental results to illustrate performance achieved when detecting, localizing, and identifying various acoustic sources affecting the fiber cable. Thirdly, this DOFS technique can coexist with data traffic on adjacent WDM channel without any performance loss on the traffic flow. These properties make such a DOFS approach very appealing for a future global telemetry system to smartly monitor optical networks.

4. References

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