Novel Concepts and Recent Progress in Distributed Optical Fiber Sensing

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Abstract: Recent techniques open new perspectives for distributed fiber sensing. Pulse coding and multi-dimensional denoising methods result in a > 10 dB noise reduction with minor modifications of the experimental layout.
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1. Introduction

Distributed fiber sensing has experienced a tremendous development during the past decade and has gained a substantial success, offering commercial growth rate currently unmatched by other fiber optics systems. The most promising techniques are those based on stimulated Brillouin scattering and on coherent Rayleigh scattering, which can today commonly reach a distance range of 50 km with a spatial resolution of 1 m and an acquisition time below 1 minute, for a typical temperature accuracy of 1 K. In addition, Brillouin-based distributed sensors can be implemented in sophisticated configurations to obtain a very sharp spatial resolution down to the centimeter range [1-4] or to realize efficient signal enhancement by combining gain and loss Brillouin processes [5-7].

It has been clearly demonstrated that the signal-to-noise ratio (SNR) on the sensor response actually scales any sensor performance [8]: the *maximum distance range*, since the response decays exponentially with distance; the *spatial resolution*, since the signal is proportional to the interaction length; the *acquisition time*, because a higher SNR requires less averaging, and finally, the *uncertainty* on the measured quantity [4]. So it can be easy concluded that any action resulting in an improved SNR will automatically lead to a better performing sensor.

We present in this paper a couple of smart techniques dedicated to substantially increase the SNR at the expense of a very minor hardware overhead. The first technique – coding the activating pulses in sequences – is an efficient way to raise the sensor response while keeping the peak pulse power strictly limited, avoiding detrimental nonlinear effects like modulation instability [9]. The second technique smartly uses the high redundancies found in typical distributed sensing data to provide a drastic noise reduction by a pure layer of software post-processing.

2. Enhanced response using pulse coding sequences

The great majority of distributed fiber sensors uses time-domain reflectometry to obtain the map of the local

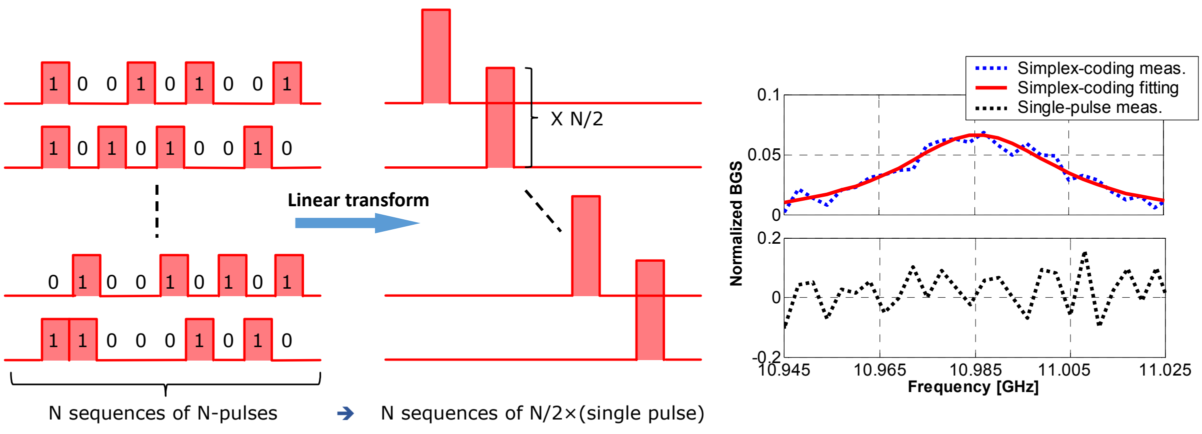

Fig.1 Left : In a linear system, the equivalent response of an isolated pulse of *N*/2 times larger power can be retrieved from the response of a set of *N* pulse sequences containing *N* bits, through a simple linear algebraic transform. This makes possible to increase the equivalent interacting energy without raising the pulse peak power, thus avoiding limiting nonlinear effects such as modulation instability [9]. Right: Comparison of the Brillouin gain spectrum obtained at 50 km distance with and without pulse coding, using an equivalent number of launched sequences (*N* coded sequences vs *N*-averaged single pulse sequence), i.e. under equivalent acquisition time conditions [12].

response along the fiber. The interaction is activated by an intense light pulse that causes a continuous back reflected response, which can be either a simple recapture of spontaneously scattered light in the back direction, or a resonant Bragg-type reflection (stimulated Brillouin scattering and faint long optical gratings [10]). The amplitude of the response is proportional to the pulse energy in a first order approximation (weak signal), which is given by the product of the peak pulse power and the pulse duration. Since this activating pulse undergoes attenuation during its propagation, the pulse energy decays exponentially with distance and so does the sensor response. The distance range therefore corresponds to the ultimate position where the sensor response reaches the noise floor.

The pulse energy cannot be increased indefinitely and turns out to be strictly bounded in most implementations: the pulse duration is fixed by the spatial resolution and cannot be extended without losing spatial granularity and skipping local details. In the best performing configurations based on stimulated Brillouin scattering or coherent Rayleigh reflectometry, the pulse must be perfectly coherent and this strictly limits its peak power before detrimental nonlinear effects jam its spectrum and deplete the original pulse waveform [11]. Modulation instability and forward Raman scattering are the practically limiting effects and the peak pulse power cannot be raised above a strict given value. For instance in the case of a standard single-mode sensing fiber, the peak pump power is restricted by modulation instability to about 100 mW [9].

So practically, it is impossible to raise the energy of a single pulse to obtain a stronger sensor response. The solution to increase the activating energy is to spread the energy over several pulses by forming a sequence which can be identified to a binary word: a "1" corresponds to the pulse "on" and a "0" to the pulse "off", as shown in Fig.1. Instead of averaging N temporal traces obtained by an isolated pulse, N non-averaged traces are acquired, each with a different bit sequence arrangement [4, 12]. Then by a linear combination of all traces a trace equivalent to a N-times averaged single-pulse trace is obtained, but with an equivalent pulse energy $N/2$ times larger, since the sequences nominally contain the same number of 0 and 1. This way the activating signal energy can be very substantially raised, without exceeding the limiting peak pulse power. Sequences up to 512 bits are practically implemented, which result in a 12 dB SNR improvement. This corresponds to a distance range extension of ~30 km (considering the loss on the return propagation) at equivalent measuring time and spatial resolution.

Different types of code sequences can be implemented, the simplest being the *Simplex code* [12,13], while higher SNR can be obtained using more sophisticated codes, such as the *bipolar Golay code* – where "-1" and "+1" elements can be practically realized by pulses inducing Brillouin loss and gain processes, respectively [14] – or the *colored codes*, in which each pulse has a different optical frequency [15].

3. Denoising using image processing

Distributed fiber sensors based on Brillouin or coherent Rayleigh scatterings show a response shaped like a resonance in the spectral domain. The spectral position of this resonance informs about the value of the quantity to be measured – essentially temperature and strain – and the local spectral positioning of the resonance is obtained by performing an optical frequency scan, so that a time trace is obtained for each frequency step, corresponding to the distribution of the response along the fiber at that particular frequency. The amplitude response of the temporal traces as a function of frequency can be graphed in a 3-D plot, as shown in Fig. 2a for a Brillouin time-domain analyzer (a color grade is here used to map the intensity). The peak response frequency can then be determined for each fiber position by fitting procedures [8], since the visible presence of noise requires a statistical estimation.

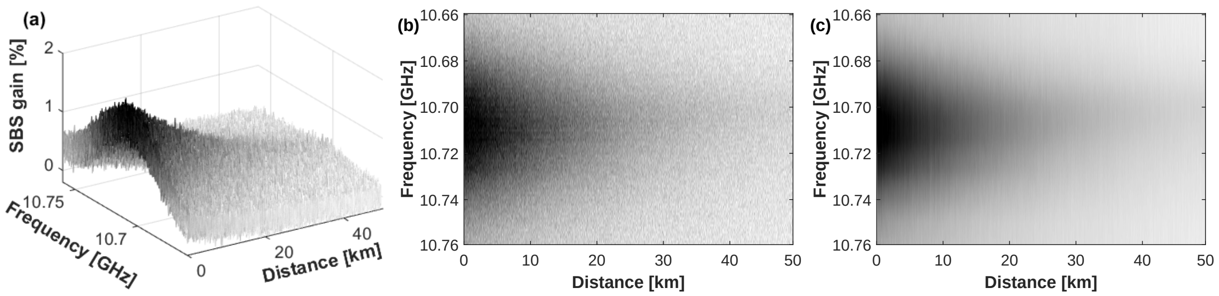

Fig.2 (a) 3D map of the measured Brillouin gain response as a function of distance (x-axis), obtained by stepwise scanning the pump-probe frequency difference (y-axis). Measurements are obtained along a 50 km-long sensing fibre using a spatial resolution of 2 m and 4 temporal averages. (b) Top-view of the same measured Brillouin gain response, where pixels with darker black tones represent frequency-position pairs with higher Brillouin gain. This image provides a visual representation of the noisy measured data. (c) 3D map of the measured Brillouin gain response obtained after denoising the raw data with a 2D denoising method based on discrete cosine transform (DCT), showing the selective removal of noise granularity.

By taking some distance from the physical background of Fig. 2a, it can be merely seen as an image riddled by noise (Fig. 2b), each pixel of this image being associated to an ordered pair (position-frequency) with its intensity given by the normalized sensor response. In a pure transdisciplinary approach, powerful algorithms employed to improve the quality of an image can be applied on the data represented in Fig. 2b, in particular *image denoising* procedures [16]. These advanced algorithms analyze the image by defining 2D windows on which sophisticated nonlinear averaging procedures are applied, thus relying on redundancies and similarities in the image. This is exactly the situation prevailing in the 3D representation of the distributed measurements: the resonance pattern is smooth in its distribution and similar at all positions, while the finite spatial resolution, the temporal oversampling and the limited detector bandwidth make the transitions gradual in the time domain.

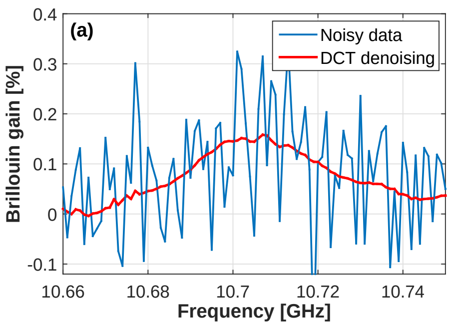

Fig.3 Comparison of the Brillouin gain spectral distribution obtained at one position (50 km) from the 4-times averaged raw data in Fig. 2b (blue line) and after the 2D DCT denoising shown in Fig. 2c (red line).

Fig. 2c shows the result obtained after using image denoising. By quantitatively evaluating the resulting distributions, as shown in Fig. 3 at the far end of the fiber, a 13 dB noise reduction is achieved from the raw data. This is even better than what is obtained by a 512-bit coding described in Section 2. After subtracting the denoised data from the raw data a white noise distribution is obtained with no visible pattern, proving that the denoising purely extracts noise without eliminating essential information. It has been confirmed by measuring a local event ("hot spot") showing no perceptible loss of spatial resolution. The technique can be employed for any distributed sensing system and turns out to be drastically more powerful in noise reduction than successive processing on individual traces or spectral distributions.

4. Conclusions

Without modifying the optical layout of distributed sensors, we have shown that 2 signal processing techniques – one enhancing the response, one reducing the noise – can lead to a significant increase of the SNR and thus of the sensor performance. These 2 techniques are not mutually exclusive and can therefore be associated, cumulating gains in SNR and leading to a potential 60 km extension of the sensing range. This should undoubtedly make the distributed fiber sensors more attractive since these techniques can be readily implemented on existing instruments.

[1] X. Bao and L. Chen, "Recent Progress in Brillouin Scattering Based Fiber Sensors," Sensors **11**, 4152-4187 (2011).
[2] L. Thévenaz, "Brillouin distributed time-domain sensing in optical fibers: state of the art and perspectives," Frontiers of Optoelectronics in China **3**, 13-21 (2010).
[3] K. Hotate, "Fiber optic nerve systems for secure life and society," in *15th OptoeElectronics and Communications Conference (OECC)*, (IEEE, 2010), 792-793.
[4] M. A. Soto and L. Thevenaz, "Going beyond limits in Brillouin distributed fibre sensors: Challenges and possible approaches," in *IEEE 5th International Conference on Photonics (ICP)*, (IEEE, 2014), 47-52.
[5] A. Dominguez-Lopez, A. Lopez-Gil, S. Martin-Lopez, and M. Gonzalez-Herraez, "Signal-to-Noise Ratio Improvement in BOTDA Using Balanced Detection," Photonics Technology Letters, IEEE **26**, 338-341 (2014).
[6] M. Dossou, D. Bacquet, and P. Szriftgiser, "Vector Brillouin optical time-domain analyzer for high-order acoustic modes," Opt. Lett. **35**, 3850-3852 (2010).
[7] X. Lu, M. A. Soto, M. Gonzalez Herraez, and L. Thévenaz, "Brillouin distributed fibre sensing using phase modulated probe," in *Fifth European Workshop on Optical Fibre Sensors*, (SPIE, 2013), Proc. SPIE 8794, Paper 87943P.
[8] M. A. Soto and L. Thévenaz, "Modeling and evaluating the performance of Brillouin distributed optical fiber sensors," Optics Express **21**, 31347-31366 (2013).
[9] M. Alem, M. A. Soto, and L. Thévenaz, "Analytical model and experimental verification of the critical power for modulation instability in optical fibers," Opt. Express **23**, 29514-29532 (2015)
[10] L. Thévenaz, S. Chin, J. Sancho, and S. Sales, "Novel technique for distributed fibre sensing based on faint long gratings (FLOGs)," in *23rd International Conference on Optical Fibre Sensors*, (SPIE, 2014), Proc. SPIE 9157, Paper 91576W.
[11] S. M. Foaleng and L. Thévenaz, "Impact of Raman scattering and modulation instability on the performances of Brillouin sensors," Proc. SPIE **7753**, 77539V (2011).
[12] M. A. Soto, G. Bolognini, F. Di Pasquale, and L. Thévenaz, "Long-range Brillouin optical time-domain analysis sensor employing pulse coding techniques," Measurement Science and Technology **21**, 094024 (2010).
[13] M. A. Soto, G. Bolognini, F. Di Pasquale, and L. Thévenaz, "Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range," Opt. Lett. **35**, 259-261 (2010).
[14] M. A. Soto, S. Le Floch, and L. Thévenaz, "Bipolar optical pulse coding for performance enhancement in BOTDA sensors," Opt. Express **21**, 16390-16397 (2013).
[15] S. Le Floch, F. Sauser, M. Llera, M. A. Soto, and L. Thévenaz, "Colour simplex coding for Brillouin distributed sensors," in *Fifth European Workshop on Optical Fibre Sensors*, (SPIE, 2013), Proc. SPIE 8794, 879437.
[16] M. A. Soto, J. A. Ramírez, and L. Thévenaz, "Intensifying Brillouin distributed fibre sensors using image processing," in *24th International Conference on Optical Fibre Sensors*, (SPIE, 2015), Proc. SPIE 9634, 96342D.