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# Protecting Fiber-optic Links from Third Party Intrusion using Distributed Acoustic Sensors

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## ABSTRACT

A major cause of faults in optical communication links is related to unintentional third party intrusions (normally related to civil/agricultural works) causing fiber breaks or cable damage. Distributed acoustic sensors can be used to detect these threats to the fiber-optic infrastructure before they cause damage to the infrastructure and proactively re-route the traffic towards links were no threat is detected. In this talk we will review our recent progress on distributed acoustic sensing and will provide some key considerations for the deployment of these systems in connection with their use in the protection of optical networks.

**Keywords**: Distributed acoustic sensors, fiber optics sensors, phase-sensitive optical time-domain reflectometry, network survivability, scattering Rayleigh, coherent communications.

## 1. INTRODUCTION

Failure in networking systems is a common scenario that must be faced with minimum impact for the user. Amongst the major reasons for network failure, we can find congestion, failed links to provider, equipment failures or operator errors. For network administrators, causes like congestion can be easily managed and prevented by following certain strategies of bandwidth control at crowded places like hotels, public libraries, stadiums, etc. [1,2] As these systems become more and more sophisticated, the failure is more prone to occur at lower layers within the Open System Interconnection (OCI) model (e.g., fiber cut or duct cut), for which prevention schemes with remote control are not available yet. Nowadays, failed links due to construction work, weather conditions, or power outages are much more likely than internal equipment failures, and usually those problems lead to more serious consequences, including severe service loss [1].

Once the cut has occurred, its exact location is typically found using, e.g., an optical time-domain reflectometer (OTDR). However, this strategy does not prevent a huge data loss and a lot of traffic being blocked, especially in optical networks with throughputs on the order of gigabits and terabits per second. Extensive research has been done to address these problems via the development of survivable networks, i.e., networks capable of protecting itself against the failure [2,3]. Indeed, survivability is one of the most important requirements of optical networks nowadays. One of the key functions of survivable networks is the early detection of potential hazards aimed at proactive re-routing of data traffic towards links with no detected threats. Besides, the early detection of threats in optical networks could potentially minimize the need for restoration methods, extending the lifetime and consequently the efficiency of the deployed infrastructure [3].

In this communication, we will briefly introduce the fundamentals of distributed acoustic sensing (DAS) and review our recent progress on this topic. DAS based on phase-sensitive (φ)OTDR have been actively used in pipeline security and structure health and operation monitoring in railway industry [4]. Similarly, this DAS technology can arise as a powerful tool to implement survivability strategies against link failures (usually due to cable cuts) in optical telecommunication networks. In particular, φOTDR-based sensors have the capability for early detection of potential wiring disruption due to third party intrusions (e.g., civil or agricultural works) or natural phenomena (e.g., earthquakes or floods) by monitoring the dynamic vibration and/or strain recorded along the cable. In this regard, potential approaches for optical network survivability systems based on φOTDR are also presented and discussed.

## 2. PRINCIPLE OF OPERATION OF DAS BASED ON φOTDR

Distributed optical sensing based of φOTDR is gaining a great deal of interest in a wide number of distinct areas, e.g., for structure health monitoring, aerospace or material processing [4]-[8]. φOTDR-based sensors are routinely employed for the monitoring of vibrations and displacements over large perimeters. Additionally, recent advances have unveiled the capability of φOTDR sensors for measuring temperature and strain in a simple and elegant fashion [5], reducing the measurement time in two orders of magnitude with respect to that of previous Brillouin scattering-based sensors, which have been traditionally used for that means. This fact, together with their potential for higher spatial resolution and bandwidth than other available distributed sensors make φOTDR an interesting technology solution for a wide number of applications [4].

φOTDR-based sensing schemes operate similarly to OTDR technology, but using a highly coherent optical pulse instead of an incoherent one. The received power trace is then produced by coherent interference of the light reflected via Rayleigh scattering in the inhomogeneities of the fiber. In φOTDR operation, dynamic range, resolution, and signal-to-noise ratio (SNR) are closely related parameters. Thus, the probe pulse should have high energy for long-range capabilities with enough SNR. This can be achieved by either increasing the pulse width or the pulse peak power. However, the first solution leads to a reduction of the system spatial resolution (defined as the minimum spatial separation of two resolvable events) while the second one is limited by the onset of nonlinear effects, such as modulation instability, in its propagation along the sensing fiber [4]-[6].

Figure 1(a) shows the typical setup used to implement a φOTDR-based sensor. The top arm of the setup generates the coherent optical probe pulse via the modulation of the light emitted by an external cavity laser (ECL). The modulation process is preferably carried out by a semiconductor optical amplifier (SOA) in order to generate high extinction ratio pulses [5]-[8], which is critical to obtain backscattered traces with high SNR. The generated pulses are subsequently amplified and filtered (to eliminate amplified noise emission) prior to be launched into the optical fiber under test (FUT). The propagation of the pulse along the FUT induces a Rayleigh backscatter that is amplified and detected for its analysis (bottom arm of the scheme). The resulting traces show a static, noise-like interference pattern (see an example in Fig. 1(b)), which is only altered by variations in the state of the fiber, such as vibrations or strain changes (Fig. 1(c)). Hence, those variations can be continuously detected from the analysis of the backscattered trace.

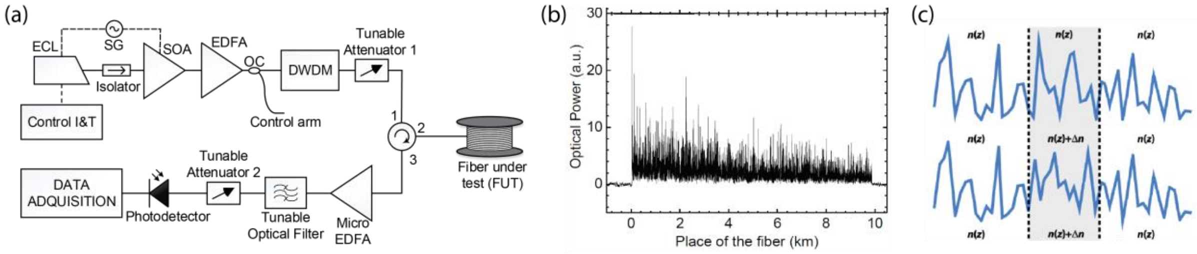

*Figure 1. (a) Setup of a typical φOTDR scheme. ECL: External cavity laser; SG: Signal generator; SOA: Semiconductor optical amplifier; EDFA: Erbium-doped fiber amplifier; OC: Optical coupler; DWDM: Dense wavelength division multiplexer. (b) Example of received backscattered trace from a φOTDR sensor. (c) Example of a trace variation due to a localized perturbation in the FUT refractive index.*

Conventional φOTDR-based sensors can reach sensing ranges of a few tens of kilometers, with spatial resolutions in the meter range and have proven capable of providing enough sensitivity to allow the detection of people walking over a buried fiber [7]. As for the detection bandwidth, this is limited by the fiber length, which imposes the maximum repetition rate ($R_R$) for the train of probe pulses ($R_R \leq c/(2n_g \cdot L)$, where c is the speed of light, $n_g$ is the effective refractive index of the mode propagating along the fiber and L is the fiber length). Detection of vibrations up to 40 kHz has been reported for fiber lengths of less than 1 km (see references in [5]). Also, current technology has enabled the direct sensing of temperature and strain variations with resolutions of 1 mK and 4 nε, respectively [6]. All these measurements are performed remotely and using a single interrogation unit, where the fiber is not only the sensor but also the transmission means. Hence, this solution represents a cost-effective, highly reliable methodology for optical fiber link integrity operation over relatively long ranges.

## 3. RECENT ADVANCES ON φOTDR SENSOR SYSTEMS

In this section, we review our recent progress in DAS-based systems for prevention of integrity threats along optical fibers. The section is divided into four main blocks, each of them describing a key development in φOTDR-based DAS that has been carried out in our group, greatly contributing to the current state of maturity of this technology. The two first blocks present innovative advances related to the fundamentals of the technology, while other two blocks are focused on applications that could inspire novel procedures or readily be employed for the prevention of failures in telecommunication networks.

### 3.1 Long range φOTDR systems using distributed Raman amplification

As introduced in section 2, for a given resolution of the φOTDR system the increase of the input pump peak power will increase the dynamic range and SNR, this approach being limited by the onset of nonlinear effects. Several solutions have been proposed to improve the performance of φOTDR such as the use of signal post-processing algorithms. Still, a significant increase of the sensing range can only be achieved using optical amplification. In particular, we have demonstrated vibration detection of up to 380 Hz over a distance of 125 km with a spatial resolution of 10 m using distributed Raman amplification along the FUT [5]. The achievable range is then comparable with the typical distance between nodes of a fiber link (~100 km). As shown in Fig. 2, Raman amplification can be engineered to keep the power of the optical pulse almost constant along the whole fiber length, generating a trace with sufficiently high visibility at all locations. The main concern of using Raman amplification is the relative intensity noise (RIN) transferred from the Raman pump to the signal. This problem can be easily solved by using balanced photodetection, which can completely eliminate the RIN.

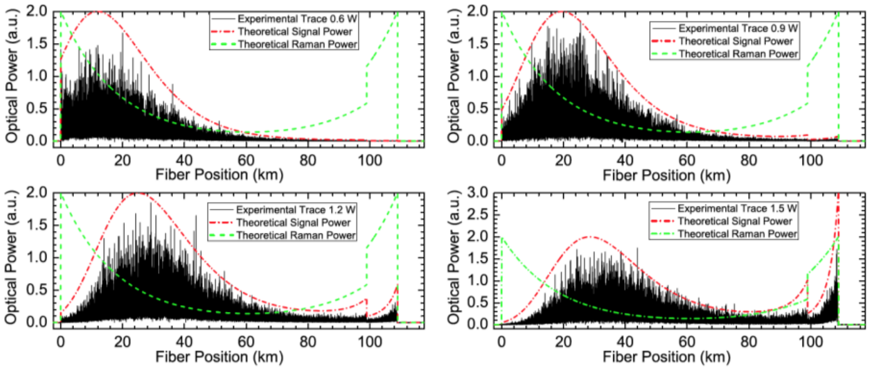

*Figure 2. Experimental and theoretical evolution of the trace profile for different Raman pump powers (from [6]).*

### 3.2 Chirped pulse φOTDR

Traditionally, φOTDR has been used for the detection of mechanical variations such as vibration or displacement. Other perturbations on the fiber like temperature or strain variations could be also detected, but the photodetected power trace does not show a linear relationship with the applied perturbation. The trace optical phase does however show a linear variation with this perturbation. Therefore, the measurement of these kinds of perturbations requires the use of polarization diversity, coherent detection schemes. To avoid the need for coherent detection, alternative methods such as frequency sweeping of the pulses have been proposed (references in [6]). Although this method provides very sensitive static measurement of refractive index variations, the requirements of a frequency scan significantly increases the measurement time and complexity of the system.

We have recently proposed a novel method that allows for the measurement of distributed strain and temperature changes in a single shot and without the requirement of a frequency scan [6]. This method involves the use of a linearly chirped optical probe pulse, i.e., a pulse with a linear instantaneous frequency along its width. In this case, a perturbation of the refractive index ( $\Delta n$ ) translates into a linear temporal shift of the trace ( $\Delta t$ ). The relationship between $\Delta n$ and $\Delta t$ is given by

$$\left(\frac{\Delta n}{n}\right) = -\left(\frac{1}{\upsilon_0}\right)\cdot\left(\frac{\delta\upsilon}{\tau_p}\right)\Delta t, \tag{1}$$

where $\upsilon_0$ and $\tau_p$ are the central frequency of the probe pulse and its width, respectively. Figure 3 shows an example of longitudinal shift of the photodetected power trace when the temperature changes approximately $8\cdot10^{-3}$ ºC at a specific position of the FUT. Hence, temperature and strain perturbations can be readily measured by simple correlations from trace to trace, greatly simplifying the required schemes to date.

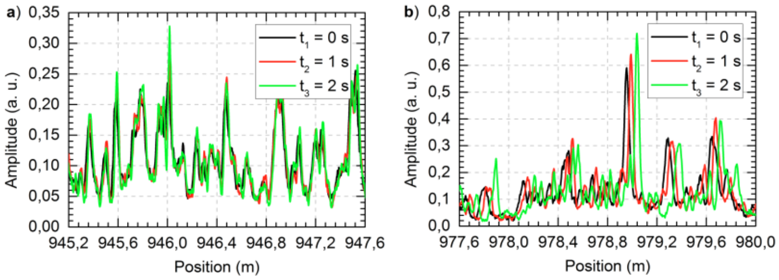

*Figure 3. Longitudinal shift of the chirped pulse φOTDR trace when temperature changes are applied to the FUT. a) Non heated region; b) heated region (from [5]).*

### 3.3 Applications of φOTDR for early detection of threats

φOTDR based sensors have already been proposed and tested for critical safety applications in areas as energy source transmission via pipelines. A system for detection and classification of threats in the vicinity of a long gas pipeline has been proposed and successfully demonstrated based on φOTDR technology [7]. The system relies on the deployment of a standard telecommunication optical fiber in parallel with the pipeline. This vibration-based sensor monitors potentially dangerous activities near the pipeline in a remote, cost-effective and highly reliable fashion. Moreover, the classification of a complete set of relevant activities based on the sensed vibration have been performed by means of pattern recognition strategies. This approach can further increase the cost-effectiveness of the system as the number of false alarms can be significantly reduced.

This proposed operation procedure could inspire a similar strategy for detecting integrity threats in communication networks due to construction works analogous to those affecting pipelines. In this case, the optical fiber used for sensing could be the same fiber transporting the data traffic or even a dark fiber of the network. The former approach has been recently investigated and some preliminary results are described in section 3.4.

### 3.4 φOTDR using telecommunication data stream as probe signal

A pioneering work aimed at the implementation of real time distributed strain sensing in parallel with an operation optical communication channel has been recently reported. The technique relies on monitoring the Rayleigh backscattered light from optical communication data transmitted using standard modulation formats. In particular, a non-return-to-zero (NRZ) phase-shift keying (PSK) pulse coding has been employed as proof-of-concept [8]. The backscattered trace resulting from the propagation of this signal is detected using polarization diversity I/Q detection, enabling a successful decoding of the trace. Using this method, the distributed sensing of dynamic strain with a sampling of 125 kHz and a spatial resolution of 2.5 cm (set by the bit size) over 500 m is demonstrated for applied sinusoidal strain signals of 500 Hz. This technique has been already proposed for monitoring of intrusion or threats to integrity of the physical fiber link. The sensing is performed at the same wavelength of the modulated data, which could be used in networks employing wavelength division multiplexing (WDM). This work could settle the base for future survivable optical networks in which potential link failure due to fiber cut is remotely and early detected using the proposed technology.

## 4. CONCLUSIONS

Distributed acoustic sensing is a continuously growing technology with strong potential to become a critical tool in future network survivability strategies. In this talk, we review of our recent progress on DAS based on φOTDR, paying special attention to those properties that could be of high interest for the prevention of threats in optical fiber links. Some of the more significant developments achieved by our group are briefly described; namely, the use of distributed Raman amplification to increase the range of operation of φOTDR sensors in at least one order of magnitude, and the employment of chirped pulse φOTDR to allow for the linear and efficient detection of strain variations with high spatial resolution and with no need for phase detection schemes. Additionally, a practical, cost-effective approach proposed for integrity threat detection of pipelines is described, which is based on φOTDR together with pattern recognition strategies. This approach has a strong potential for serving as baseline in future survivable optical telecommunication networks. Finally, a pioneering work including codification of the probe pulse using telecommunication data streams is also presented. This scheme could be readily used for the early detection of cable integrity threats. The combination of φOTDR technology for fiber link failure prevention and current strategies for node congestion control and traffic re-routing could rise as a promising arrangement to significantly reduce the network disruption rate and associated data loss.

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