Advances in Optical Fiber Sensing

Transformative Applications for Cable's Next-Gen Resilient Fiber Networks

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1. Introduction

Distributed fiber optic sensing (DFOS) has emerged as a hot topic in major optical communication conferences and is attracting the attention of operators seeking to improve the functionality and resiliency of their fiber networks while gaining valuable intelligence of their surroundings. DFOS provides a natural way to turn an optical fiber into thousands of sensing elements and monitor environmental perturbations in real-time, making it a cost effective and non-intrusive solution that is being adopted by more industries every year. DFOS can be leveraged for many use cases such as proactive monitoring, fiber cut prevention, environmental sensing, and critical infrastructure protection.

The aim of this technical paper is the following:

- Review the latest advances in DFOS technology that unlock new applications of existing fiber infrastructure
- Show the broadband operator community how sensing can coexist seamlessly with traditional data services in live fiber networks
- Discuss the readiness, maturity, and challenges of DFOS systems for large-scale implementation

This paper will focus on various technical and practical aspects of fiber sensing for access and metropolitan networks. In Section 2, we begin with an overview of the fundamentals of forward-based and backscatter-based fiber sensing, highlighting their respective advantages and limitations. In Section 3, we focus on the cable environment and discuss why broadband operators should seriously consider adopting DFOS in their future deployments. We discuss some key opportunities that can give an edge to cable operators by generating significant value using the vast fiber infrastructure already in place. In Section 4, we survey some of the latest technical advances in DFOS signal processing, including the use of machine learning and artificial intelligence to process sensing data, and highlight several recent successful field trials of DFOS technology. Section 5 delves into the current challenges and future opportunities of DFOS, such as the viability of integrating fiber sensing into existing networks, sensing in point-to-multipoint (P2MP) environments, standardization efforts, and a survey of the existing DFOS vendor ecosystem. Finally, Section 6 concludes the paper.

2. Principles of Operation

In this section, we provide an overview of the primary modes of fiber sensing operation, including backscatter-based and forward-based sensing, to highlight their respective advantages, limitations, and relevance to different network architectures.

2.1. Backscatter-Based Sensing

Microscopic fluctuations in the density and composition of the glass in standard single mode fiber (SSMF) cause intrinsic refractive index variations along the fiber propagation path. As shown in Figure 1, these impurities act as distributed scatterers, with each backscatterer generating a small reflection of the incident optical pulse that travels back to the source. External perturbations such as changes in temperature or acoustic pressure modify the local properties of the fiber, and sensing interrogators can analyze the changes in the received backscattered light to deduce changes in the fiber's surrounding environment.
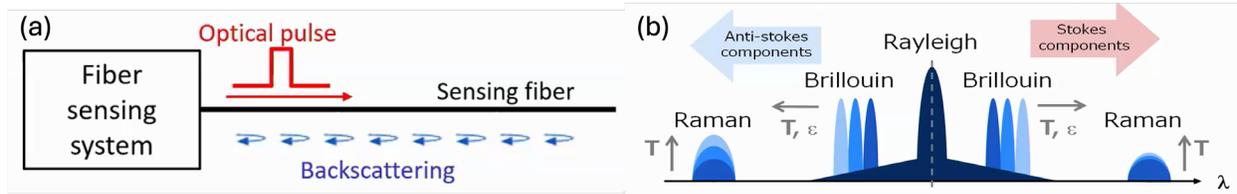
Figure 1: (a) Backscatter-based fiber sensing system. (b) Rayleigh, Brillouin and Raman backscattering in optical fibers [1]

Backscattered light in SSMF can be classified into three broad categories [1, 2, 3]:

1) Rayleigh backscattering – Rayleigh scattering results from the local variations of refractive index due to heterogeneity and density fluctuation of the material in the fiber core. The amplitudes and positions of the Rayleigh-scattered fields are randomly distributed, and environmental perturbations modulate the phase and state-of-polarization (SOP) of the reflected light components. Rayleigh-scattered light is at the same wavelength as the incident light and has the highest intensity among the three scattering types. Distributed acoustic sensing (DAS) refers to systems that analyze the phase changes in received Rayleigh traces to estimate acoustic perturbations using a method known as phase optical time domain reflectometry (Φ-OTDR).

2) Brillouin backscattering – Brillouin scattering is caused by the interaction between an incident light wave and thermally-induced material-density fluctuations (acoustic phonons) travelling along the fiber at the speed of sound. Brillouin scattered light occurs at a frequency shift of approximately 10 GHz from the incident light. The intensity of the generated Brillouin scattering and the exact frequency shift depend on both external strain and temperature, and these effects are exploited to implement distributed temperature and strain sensing.

3) Raman backscattering – Raman scattering in optical fibers is caused by light interacting with the electrons of vibrating molecules (optical phonons). This type of scattering occurs at a frequency shift of approximately 13 THz from the incident wavelength. Although the Raman backscattered power is weak compared to the power of Rayleigh backscattering, its intensity can be used to implement distributed temperature sensors (DTS).

Backscatter-based fiber sensors are usually limited to single-span fiber links with distances of less than 100km. This is because components such as erbium-doped fiber amplifiers (EDFAs), which are used to amplify telecommunication signals to combat fiber propagation loss, usually contain optical isolators at their output which would prevent the generated backscattering from reaching the interrogator. However, recent experiments have extended the reach of DAS to distances exceeding 1000s of km using distributed Raman amplifiers (which do not contain optical isolators) and digital signal processing algorithms [4].

CableLabs' work on fiber sensing is currently focused on DAS sensors, since the primary goal is to detect acoustic vibrations in real-time. Figure 2 shows a demo of a commercial DAS interrogator at CableLabs' Optical Center of Excellence – the acoustic vibrations generated by a person walking next to the fiber is clearly visible in the sensing outputs.
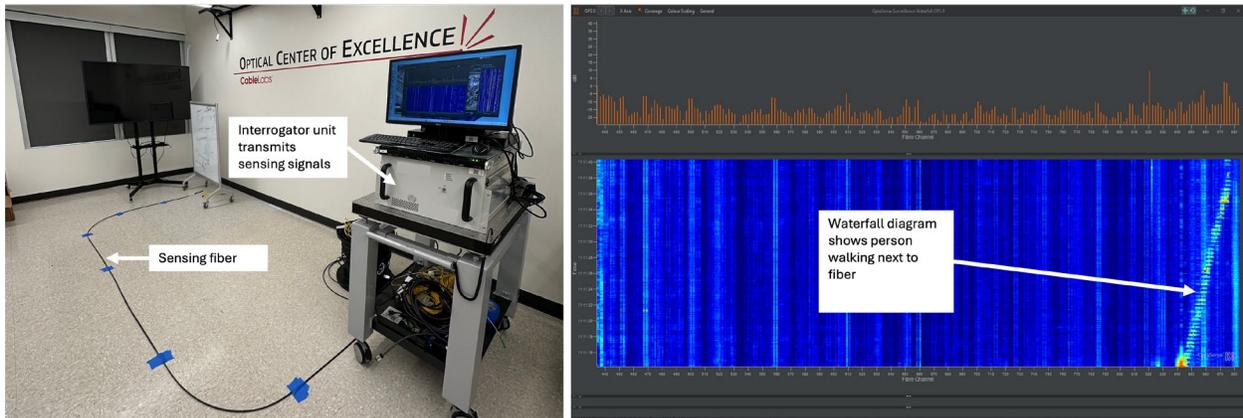
Figure 2: DAS laboratory demonstration showing real-time detection of a person walking next to a fiber

Figure 3 shows a simplified block diagram of a DAS interrogator, which is responsible for generating and transmitting optical probe waveforms into the fiber under test (FUT). Backscattered signals are collected and isolated into a separate port using an optical circulator. A coherent receiver is used to mix the received backscatter with a local oscillator, and the received electric field components are digitized and processed using digital signal processing (DSP).
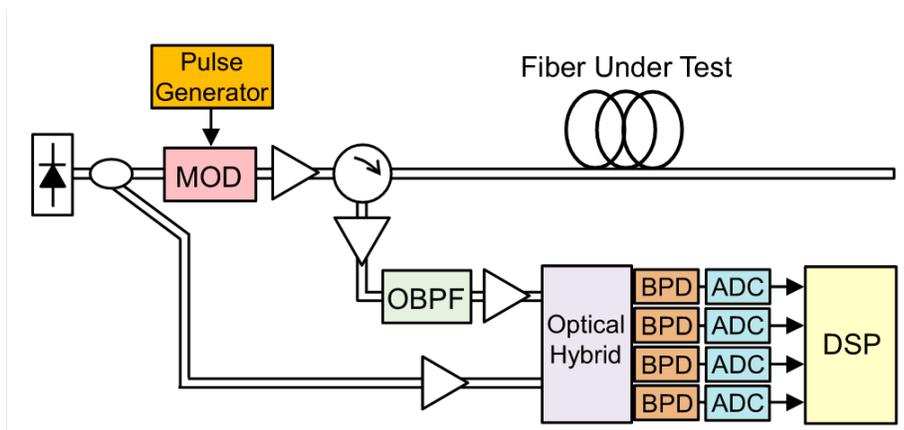
Figure 3: High-level architecture of a DAS interrogator based on coherent detection [4]

DSP algorithms are extensively used to create real-time vibration traces. The signal-to-noise ratio (SNR) and spatial resolution of the detected vibrations are functions of the transmitted pulse shapes. Most DAS systems in existence today launch narrow high peak-power pulses into the FUT and perform Φ-OTDR to sense vibrations. While these systems are relatively simple to implement with low DSP complexity, the SNR is limited by the energy contained each pulse. An alternative approach, covered in greater depth in Section 5, is to use low peak-power continuous probe signals which have higher coding gain resulting in superior detection SNR and vibration sensitivity.

2.2. Forward-Based Sensing

In a forward sensing setup, a light signal is launched into the fiber, and the acoustic disturbances modulate the properties of the forward-propagating light (e.g., phase or intensity). Sensors or detectors placed along the fiber or at the far end capture the modulated light. For example, a forward-sensing

system using two coherent transmitter-receiver pairs is shown in Figure 4. When a vibration event occurs, it modulates the optical phase or polarization of both pairs, and the relative time shift between the received vibration can be used to determine its location [5].
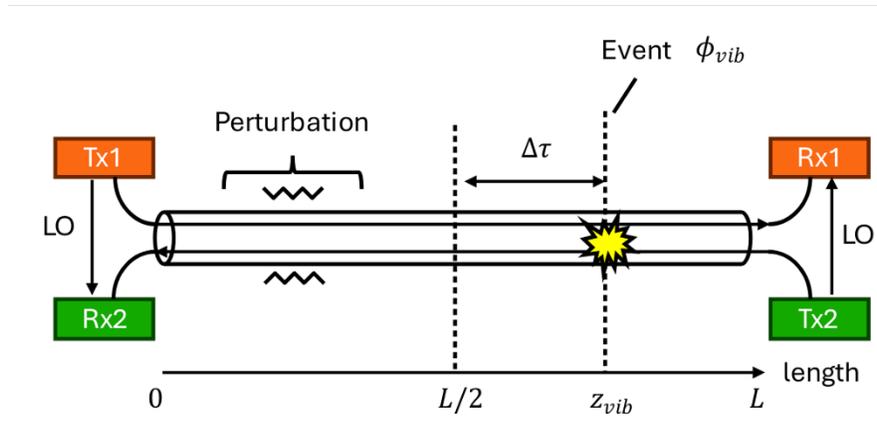
Figure 4: Vibration sensing based on bidirectional forward transmission [5]

Forward-based sensing can be derived from phase estimation algorithms using standard telecommunication data symbols, or with specially designed sensing pilot sequences that are periodically embedded inside the data payload. Therefore, forward-based sensing can be implemented using existing transceivers and coherent integration. For example, Figure 5 illustrates the processing pipeline for extracting forward-scattered phase changes caused by vibrations, which includes standard coherent DSP operations such as resampling, receiver compensation, frequency offset compensation, carrier recovery, IQ demodulation, and frequency correction [5]. These approaches not only enhance sensing capabilities but also highlight an important use case for coherent optics in distributed sensing.
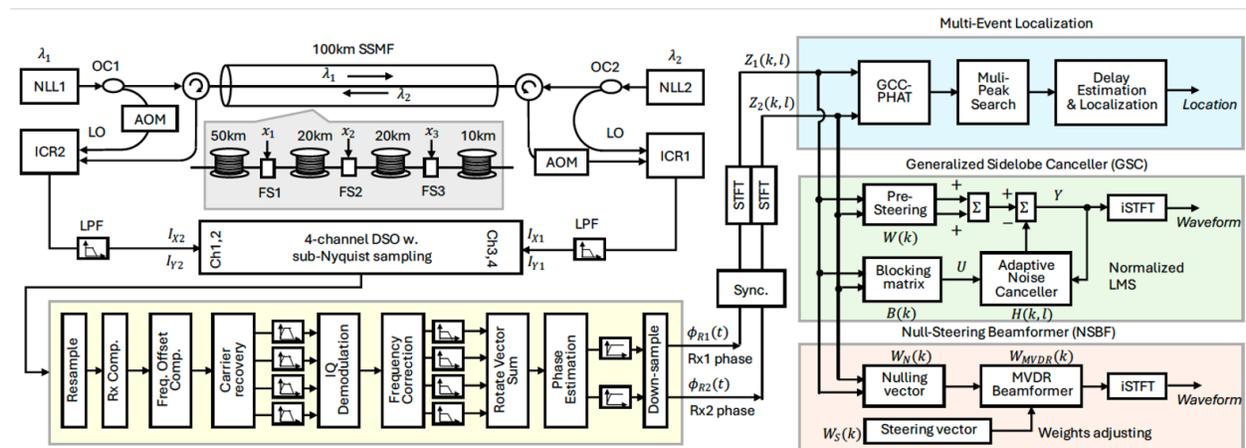
Figure 5: Forward sensing experiment showing coherent DSP processing for vibration phase extraction [5]

Compared to backscatter-based sensing, determining the exact spatial location of vibrations in forward-sensing is difficult since phase and polarization changes are integrated along the entire link distance. Furthermore, the task of disambiguating multiple vibrations happening at the same time is a challenge for feedforward sensing, but it may be possible to mitigate these challenges using various techniques

including multi-end tomography, pilot scheduling, multi-wavelength diversity, and polarization analytics [5].

Forward-based sensing is compatible with long links containing inline amplifiers, such as EDFAs, since optical isolators do not block the forward-scattered light from reaching the transceiver at the far end of the link. For example, in [6], the authors report vibration detection and localization over a 482km bidirectional coherent optical transmission system operating error-free at 200GBd-1.6Tb/s and 200GBd-1.2Tb/s.

The next section summarizes the key differences between forward-based and backscatter-based fiber sensing.

2.3. Comparisons Between Forward-Based and Backscatter-Based Sensing

Forward-based and backscatter-based fiber sensing systems are complementary solutions that each have their own advantages and disadvantages in deployment scenarios. Table 1 summarizes the key characteristics, similarities, and differences between the operational modes. We emphasize that both forward- and backscatter-based sensing systems should be leveraged to enhance the information that can be obtained in an access or metropolitan network.

Table 1: Comparison between forward-based and backscatter-based fiber sensing

	Forward-based sensing	Backscatter-based sensing
Ease of spatially locating vibration events	Spatial resolution is on the order of 10s of meters	Can obtain sub-meter spatial resolution with optimized probe waveforms
Detecting multiple simultaneous vibrations	Difficult	Yes, can measure the fiber state at every location along the link
Compatible with EDFAs	Yes	No
Transmission distance	1000s of km	< 100km, can reach longer distances using distributed Raman amplifiers
Interrogator placement	Requires access to both ends of a fiber link, useful in environments where placing interrogators at multiple points is feasible	Requires access to only a single end of a fiber link, making it easier to deploy in networks
Laser source	Requires low-linewidth light source for phase stability	Requires low-linewidth light source for phase stability
Coexistence with traditional data channels in lit fibers	Yes	Yes, with careful management (see Section 5.1)

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3. Why Fiber Sensing is Exciting for the Cable Environment

One of the aims of this technical paper is to highlight the vast opportunities that DFOS systems provide in the context of a wide-area metropolitan or access network. This is a Network-as-a-Sensor concept—where cable operators leverage their extensive fiber footprint to transform deployed fibers into distributed sensor arrays. Section 3.1 discusses the ubiquitous sensing coverage that can be achieved with DFOS systems deployed over a city-wide network, whereas Section 3.2 discusses opportunities for machine learning and artificial intelligence to revolutionize the design of smart cities.

3.1. Ubiquitous Sensing Coverage
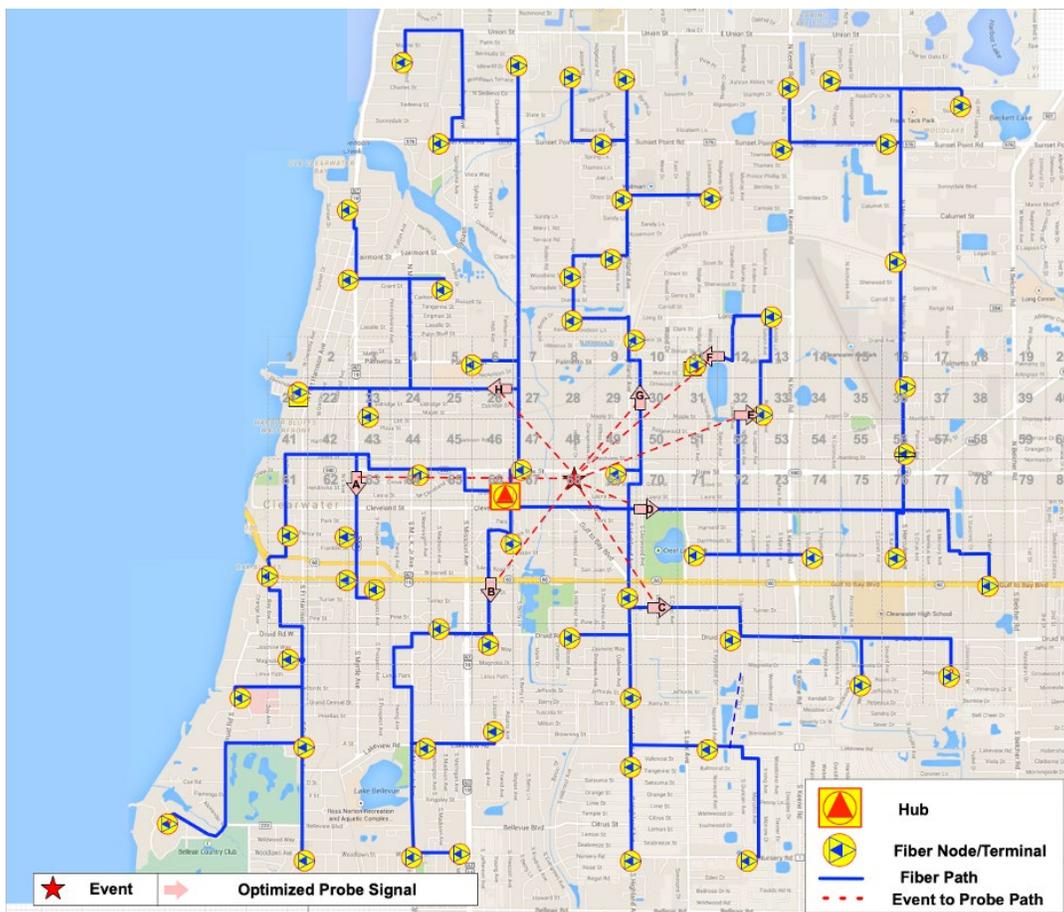
Figure 6: City-wide fiber network serving area for telecommunications and sensing

Consider an example network in a large metropolitan area shown in Figure 6. In an access environment, the hub or the central office is the location from where signals are distributed to endpoints. Bundles of fiber strands, shown in Figure 7, extend in multiple directions. Since fiber network implementations may have hundreds of fiber strands that are bundled together in tubes which are aggregated in sheaths and conduits, there can be telecom or sensing signals that can occupy one or more wavelengths within the transmission wavelength spectrum of fiber. As these fiber bundles traverse a serving area, these fiber paths bifurcate multiple times so that fewer fiber strands remain in a bundle, but the resulting number of bundles increases and so does its coverage. If each fiber strand is simultaneously able to sense the

environment using DFOS interrogators, this fiber topology results in pervasive sensing coverage across the whole city.

Figure 7: Bundling and aggregation of fiber strands

An environmental perturbation of sufficient strength will be seen across multiple fiber links at the same time. Launching many sensing probe signals on fiber strands traversing distinct paths enables the capability of coherently adding the amplitude of an event response at a particular time thereby increasing the sensitivity of the sensing system. For example, by correlating vibration traces across multiple paths, it is easier to pick up weaker acoustic events while simultaneously rejecting false positives.

Probe multicasting is another capability that can be implemented based on the type of devices along the fiber path [32]. A splitter or coupler along the fiber path results in the probe signals traversing two or more branches of the fiber path. In the case of a 2-way splitter or a single port coupler the following reflection-transmission matrices are obtained.

$$\begin{bmatrix} RA & TB1 & TB2 \\ TA1 & RB1 & \sim 0 \\ TA2 & \sim 0 & RB2 \end{bmatrix}$$

In this scenario and as shown also in Figure 8, RA = RA0 + RA1 + RA2, where RA0 are the reflections on the fiber path to the right of the splitter, RA1 are the reflections upper fiber path to the left of the splitter and RA2 are the reflections lower fiber path to the left of the splitter. Since we are assuming good isolation characteristics in the splitter, transmission characteristics from sensing end-device SED1 to SED2 and vice versa, they are approximated to 0 in the above matrix (~0).
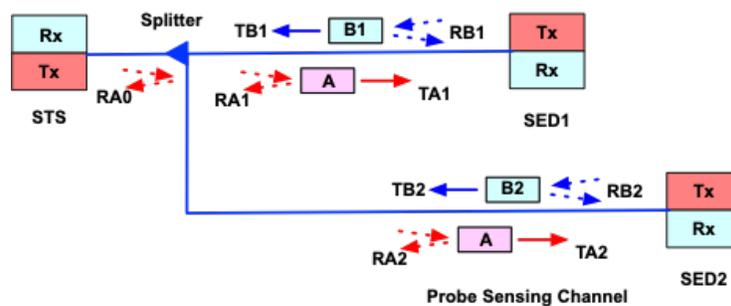
Figure 8: Combining forward- and backscatter-based sensing in a network

Correlation and analysis of this data can help to identify or verify the fiber topology characteristics.

An added benefit of a distributed sensing system is the ability to integrate additional sensing modalities. For example, sensing information from the wireless domain (WiFi/5G/6G) could be fused with DFOS data to create even richer representations of various perturbations.

3.2. Intelligent, Coordinated, and Adaptive Fiber Sensing Solutions

A very interesting, yet relatively unexplored, aspect of wide-area DFOS is the possibility of intelligent, coordinated, and adaptive fiber sensing. A highly responsive DFOS system can be designed with the goal of self-adjusting or optimizing the probe waveforms transmitted from or between interrogators to better sense particular events of interest. For example, in a city environment with multiple dynamic perturbations (traffic accidents, construction, water leaks, etc.), multiple DFOS sensors can coordinate their transmissions to focus on events of interest.

Probe signals particular to an event can be modified in real time to extract further information about the event benefiting from the a posteriori knowledge of what the event was. This also enables the system to train itself and improve for subsequent analysis using machine learning (ML) and artificial intelligence (AI).

CableLabs has recently explored probe waveform optimization using numerical simulations. The premise of the adaptive sensing concept is shown in Figure 9.
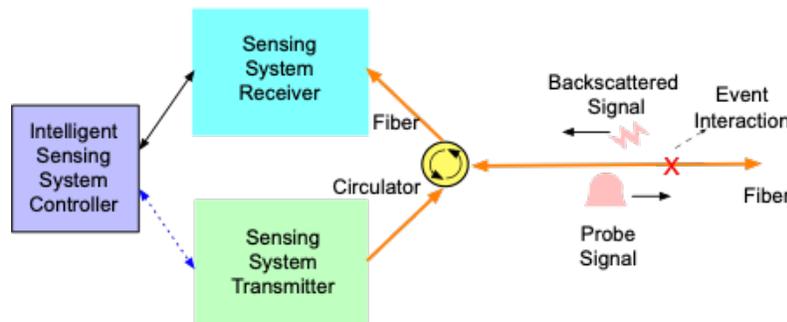
Figure 9: Intelligent fiber sensing system

The intelligent sensing system controller decides what type of probe signals the DFOS system transmits (including wavelength and other parameters describing probe signal), which optical path the probe signals take and when are these probe signals transmitted [32]. A primary goal is to be able to discriminate as accurately as possible the type of event as well as the characteristics and features of the event. A secondary goal is to optimize the use resources and maximize coverage and diversity of types of sensing events to minimize implementation and operational costs.
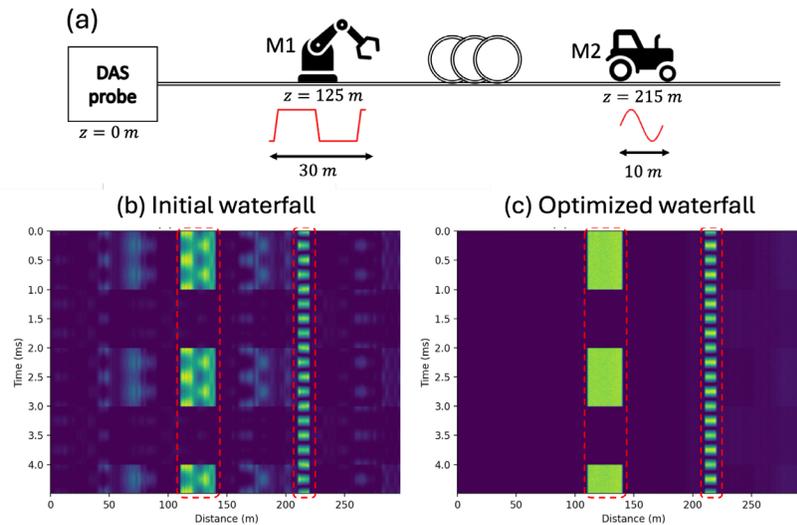
Figure 10: Probe waveform optimization example to focus on two different events of interest along a fiber link

For example, consider a toy scenario shown above in Figure 10(a). A DAS interrogator is transmitting continuous low-power probe waveforms to sense perturbations along a long fiber. Two machines, M1 and M2, are located along a fiber link at distances 125m and 215m from the interrogator, respectively. M1 creates a low frequency 500Hz square wave vibration, whereas M2 creates a higher frequency 2 kHz sinusoidal vibration. The resulting backscatter from the fiber is analyzed to create the initial waterfall diagram shown in Figure 10(b). Significant cross coupling of the two vibration types is observed in the initial waterfall diagram. The sensing system controller runs machine learning algorithms to detect anomalies the waterfall, shown in the red dashed boxes at 125m and 215m. In practice, anomaly detection can be implemented using sophisticated deep-learning algorithms, such as convolutional neural networks or vision transformers, or also with simpler histogram-based methods. It then applies a gradient descent optimization algorithm to fine-tune the probe waveform to increase sensitivity in the areas of interest. Figure 10(c) shows the waterfall diagram obtained using the optimized probe waveforms. It is evident that the optimized waterfall has a higher SNR in the areas of interest and the detected vibrations are no longer cross-coupled.

Although this is a simplistic simulation, it underscores the huge potential of ML/AI in the design of future adaptive distributed sensors. Probe waveform optimization can be used to boost detection of weak events, reject false positives, increase spatial resolution, and make sensing more power efficient.

4. Fiber Sensing Field Trials and Transformative Use Cases

As fiber sensing technology matures, its transition from laboratory research to real-world deployment is accelerating, driven by compelling use cases and successful field trials. This section highlights some work conducted by broadband operators, research labs, and technology vendors, showcasing how distributed acoustic sensing has been applied in live network environments. These real-world implementations demonstrate the transformative potential of fiber sensing for infrastructure monitoring, security, and network optimization.

4.1. Sensing for Network Monitoring and Proactive Maintenance

One of the most natural applications of DFOS technology is detecting anomalous activity near important fiber links in networks to identify dangerous precursors to fiber cuts before they happen so that proactive maintenance can be applied. Here we shed light on experiments conducted by Nokia Bell Labs in 2024 [7].
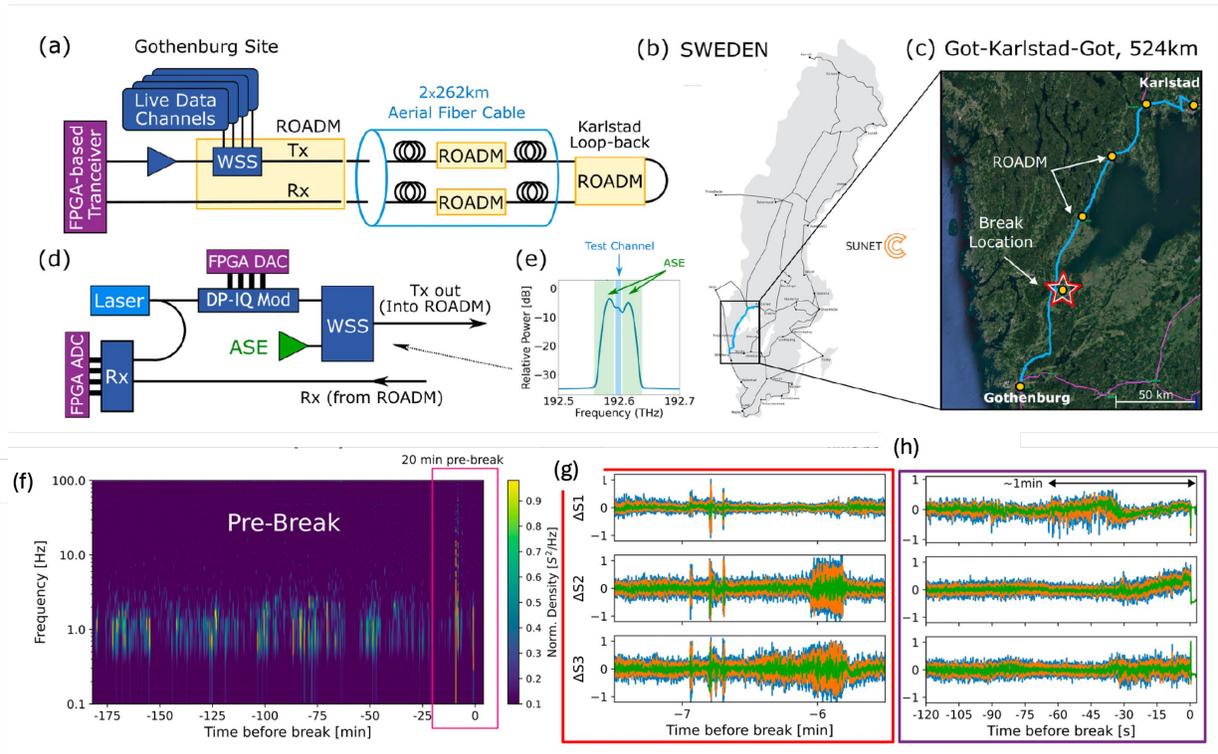
Figure 11: Monitoring a 524-km live network link during a human-caused cable break

As seen in Figure 11(a), the authors in [7] used field-programmable gate array (FPGA)-based transceivers to implement a DFOS monitoring system on a 524-km link spanning Gothenburg to Karlsbad in Sweden. The route consisted of aerial fiber, five ROADM nodes, and multiple sections of buried fiber. One of these buried sections of fiber was accidently exposed by an excavator and subsequently broken. The DFOS system was used to track the SOP fluctuations during this human-caused cable break. As observed in Figure 11 (g), strong polarization changes were observed around 5-7 minutes before the actual break.

SOP monitoring has a potential to identify events that are disruptive in nature, some of which could potentially provide an early-warning alarm. Coherent transceivers with enhanced monitoring capabilities also play vital role in improving the stability of future optical networks by enabling proactive rerouting and potential break avoidance using early-warning signatures extracted from coherent digital signal processing.

4.2. Sensing in Metropolitan Environments

DFOS is particularly well-suited for metropolitan environments, where dense fiber deployments already support broadband and telecommunications infrastructure. By leveraging existing fiber networks, DFOS enables real-time monitoring of urban conditions such as traffic patterns, underground construction, and

infrastructure stress. Its ability to provide continuous, long-range, and high-resolution data makes it ideal for enhancing situational awareness in smart cities. Moreover, DFOS can improve public safety and infrastructure resilience by detecting early signs of disturbances or failures in critical urban systems, allowing for proactive maintenance and rapid response.

Various university research groups have recently studied fiber sensing in dense metropolitan environments. As seen below in Figure 12, the authors in [8, 9] studied wavelet denoising, frequency filtering, and the use of optical frequency combs to increase DFOS performance in urban settings like Hong Kong. In [9], the authors demonstrate an effective method to detect and track the trajectories of vehicles moving on the highway. The authors in [10] were able to record different DAS signatures for buses, trucks, and cars as these vehicles transited near a roadside fiber telecom cable. This is possible because the acoustic waves reverberating from civil structures are impacted by the size and weight distribution of vehicles.

Figure 12: DFOS in a busy area of Hong Kong. AI algorithms can be used to estimate vehicle trajectories on highways [8, 9]

The fusion of sensory outputs from DAS and DTS systems also promises improved DFOS performance. In [11], NEC Laboratories and Verizon conducted a joint field trial using testbeds in Richardson, Texas, Long Beach Island, and Philipsburg, NJ. As shown in Figure 13, they used ambient noise-based automated methods to localize the positions of manholes, their conditions (exposed cables in dry air or submerged in water, frozen in water, etc.), and cable status anomaly detection using integrated real-time DAS/DTS systems. By cross-referencing data from DAS and DTS, they enhanced detection and classification accuracy from 79% to 94.7%. Their results confirm that an integrated fiber sensing architecture is a promising solution for enhancing the operational reliability of telecom networks.
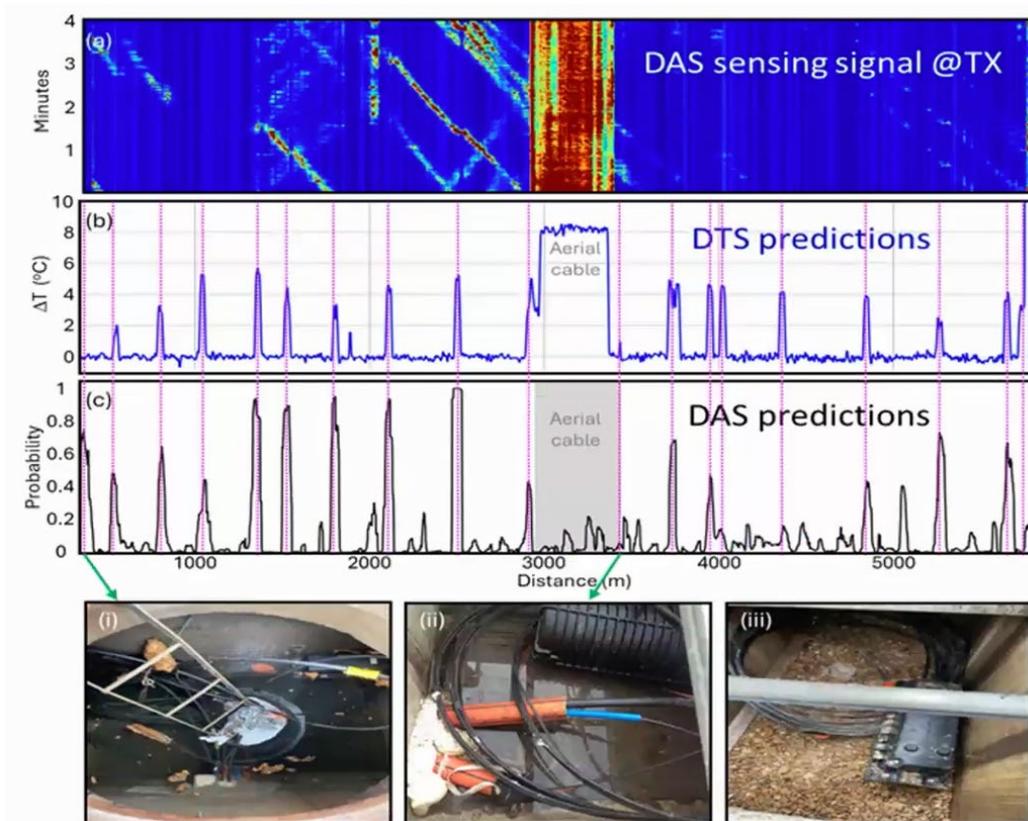
Figure 13: Combining DAS and DTS predictions to increase accuracy of manhole localization

4.3. Sensing for Environmental and Geophysical Monitoring

DFOS offers powerful capabilities for environmental and geophysical monitoring by transforming standard optical fibers into dense, real-time sensor arrays. It can detect and localize ground vibrations, temperature changes, and strain along vast lengths of deployed fiber, making it ideal for monitoring earthquakes, landslides, permafrost thaw, subsea tsunamis and subsurface hydrological processes. DFOS allows researchers to observe dynamic environmental changes over time and across large areas. This enables early warning systems, long-term climate studies, and enhanced understanding of natural hazards in both remote and populated regions.

The authors in [12] propose a smart grid fiber sensing approach based on a deep-learning model with an attention mechanism for earthquake early warnings exploiting terrestrial optical networks. They study the characteristics of a real earthquake near Marradi, Florence, Italy, as seen in Figure 14, and generate synthetic data mimicking the earthquake to train the ML model. When evaluating the model's performance in detecting P waves, they found that they could identify earthquake arrival times at an accuracy of 97%, giving residents of nearby cities nearly 22 seconds to take precautionary measures. Further research by the same group using transfer learning improved the model performance to accuracy of 98% [13]. Researchers at Stanford University also recently designed a system for earthquake detection using deep learning methods which can detect local small-amplitude earthquakes down to magnitudes as low as 0.5, leading to the discovery of previously uncatalogued events [14].
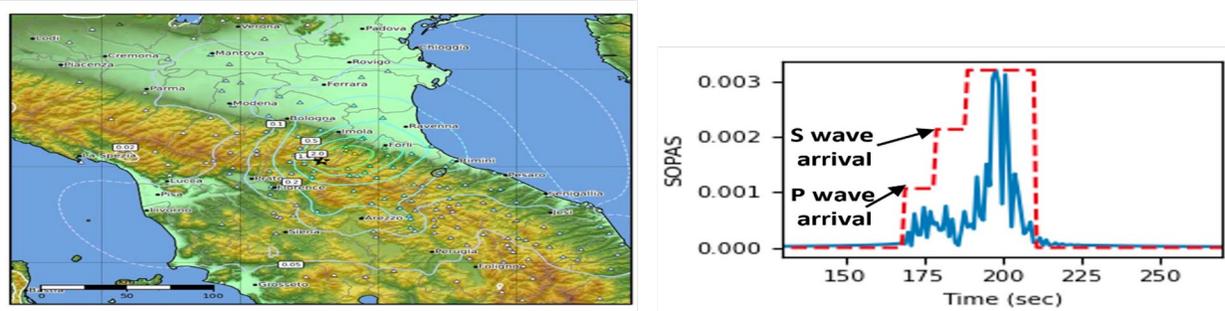
Figure 14: Using ML on SOP data for early earthquake detection

NEC Laboratories and Verizon also recently demonstrated an AI-driven method for detecting road deformations using DAS over existing telecom fibers without the need for additional physical sensors or cameras [15]. In a field test conducted over a 9km Verizon test-bed in Long Beach Island, NJ, the researchers trained a deep learning retrieval-based road deformation model to identify irregular traffic patterns in roads. Shown below in Figure 15, their proposed method uses self-supervised representation learning on small patches of waterfall data to detect potholes over the road. This method works because vehicles will either swerve to avoid potholes or contact potholes generating strong vibrations. This approach significantly reduces operational costs and improves coverage compared to conventional methods, offering a scalable solution for maintaining road quality and preventing vehicle damage.
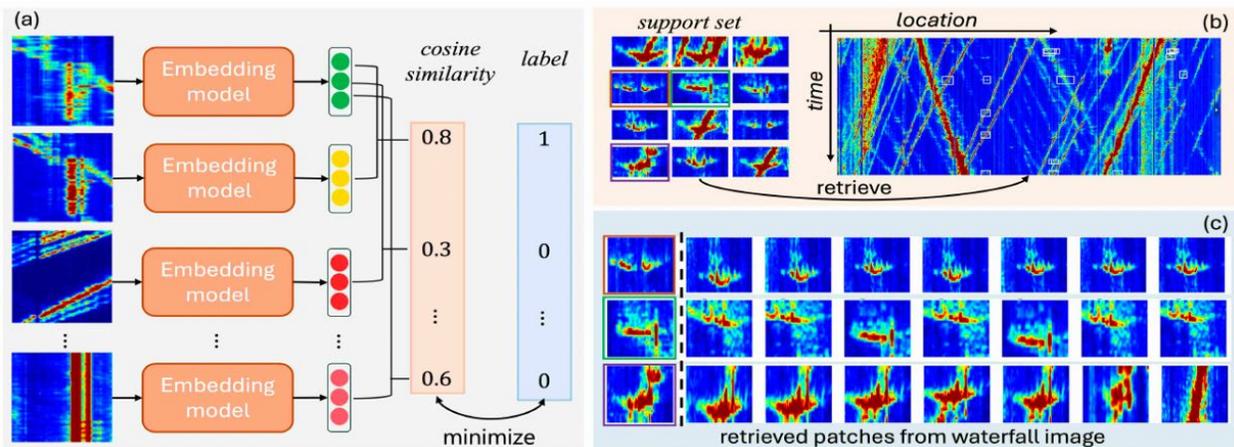
Figure 15: Using DAS data to train ML models for road deformation detection, including potholes

As discussed in [16] and shown below in Figure 15, it is also possible to use DFOS to gain a better understanding of fiber topology by analyzing the impacts of weather on fibers. Figure 16 shows the difference between aerial and buried fiber using both DTS and DAS. Exposed aerial cables exhibit larger variations in temperature over the course of day and night, as well as show strong vibrations due to wind. On the other hand, buried cables exhibit more stable traces in the DAS and DTS waterfall diagram due to their isolation from the environment.
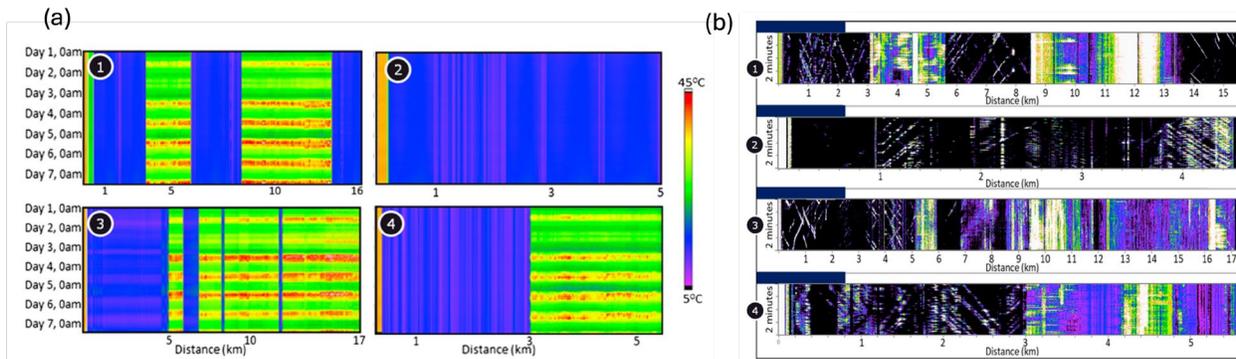
Figure 16: Identifying aerial and buried cables in a fiber network using both DTS and DAS traces

4.4. Sensing for Security and Safety

DFOS technology can also be used to enhance security around critical assets, offering complementary coverage to traditional surveillance methods such as cameras, radars, and lidars. For example, [17] demonstrated mechanical threats classification including jackhammers and excavators, leveraging wavelet transform of DFOS output data across a 57-km operational network link, as illustrated in Figure 17. The authors used a machine learning framework that incorporates transfer learning and shows 93% classification accuracy from field data. Their work demonstrates the effectiveness of training robust classifiers for various mechanical activity using vibration data even though the training dataset may be small and noisy.
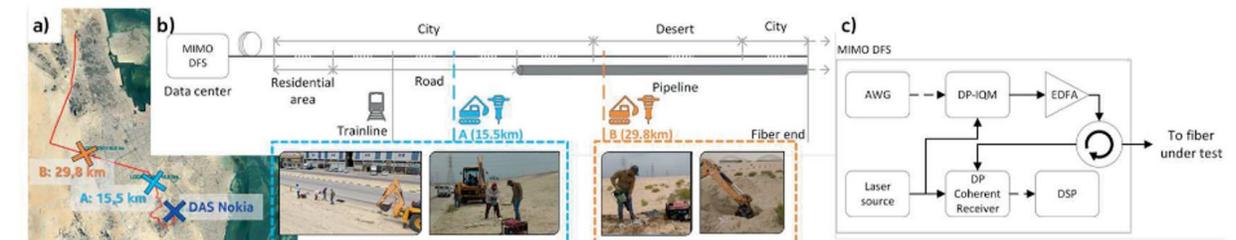
Figure 17: Mechanical threats classification including jackhammers and excavators in a 57km operational fiber link using DFOS and machine learning

5. Current Challenges and Future Opportunities

Given the wide range of use cases for fiber sensing outlined in the previous section—from infrastructure monitoring and environmental awareness to real-time network optimization—DAS holds significant promise for cable operators. However, realizing this potential at scale requires overcoming several technical and operational challenges. In the following section, we will explore these current limitations and barriers to widespread deployment. We will also highlight key opportunities that could drive the future evolution of fiber sensing technology and its integration into intelligent, adaptive network infrastructures.

5.1. Integrated Sensing and Communications

Integrated Sensing and Communications (ISAC) leverages existing optical fiber networks to perform both traditional data transmission and diverse sensing functions simultaneously. Despite all its advantages and promises, most DAS deployments have been limited to dedicated dark fibers, since the integration of sensing signals with live data traffic remains a significant challenge. In early DAS tests, narrow sensing pulses with high peak powers (>10dBm) increased the bit error rate (BER) of neighboring data channels above the forward error correction (FEC) threshold [18]. High peak powers of DAS signals introduce nonlinear crosstalk in neighboring data channels via cross-phase modulation, and the frequency separation between sensing and communication channels must be carefully managed to maintain acceptable bit-error rate performance.

Figure 18: Improving co-existence between sensing and communication channels using low-power coded sequences
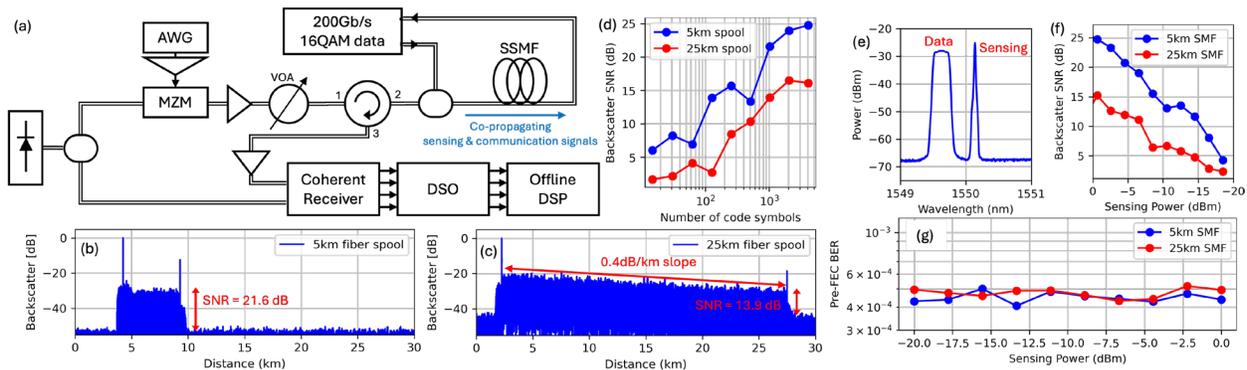
Coding techniques offer potential gains, with the achievable coding gain generally increasing with code length. For example, chirped pulses have been used for sensing in long-distance point-to-point (P2P) links exceeding 1000km aided by distributed Raman amplifiers [4]. Similarly, Golay codes [19], simplex codes [20], CAZAC codes [21], and even random phase-shift-keyed symbols [22] have also been used to spread the sensing energy across multiple time-domain symbols to mitigate cross-phase modulation and integrate with communication systems. In most coded DAS publications to our knowledge, the launched sensing power is close to 0dBm or higher to achieve long distance sensing [4, 23].

In [24], we investigate the applicability of binary maximal-length sequences (also called m-sequences or pseudo-random sequences) for power-efficient DAS, with the aim of reducing sensing power as much as possible for short-to-moderate length links that are commonly found in access and metropolitan networks (e.g. gigabit passive optical networks (GPON) have a maximum physical reach of 20km [25]). Although [24] is a preliminary study that has yet to be published in a peer-reviewed venue, our proof-of-concept DAS system, shown above in Figure 18, is designed to be compatible with lit fibers due to relaxed coexistence conditions for ease of deployment by broadband fiber operators. We show that sensing powers can be reduced as low as −16.5dBm for short-to-medium length link distances to detect fiber backscattering without affecting the pre-FEC BER of an adjacent 200Gb/s coherent data channel. Low-power sensing interrogators would require implementation that is synergistic with the capabilities in coherent transceivers which would further facilitate its introduction along communication systems.

Other research groups have also done extensive work in making sensing channels work alongside high-speed data channels. China Mobile Research Institute, in collaboration with China Yangtze Power Co., Ltd, demonstrated a system integrating 400 Gb/s data transmission with distributed sensing over an ultra-long 527.8 km single fiber span by employing bidirectional sensing, high-order Raman amplifiers, and

remote optical pumping amplifier technology [26]. Politecnico di Torino conducted field trials on a 12 km metropolitan link to validate the coexistence of pulse-based DAS and 400G coherent dense wavelength division multiplexed (DWDM) transmission, demonstrating that DAS could effectively monitor road traffic with negligible impact on communication performance [27]. Non-orthogonal multiple access allows sensing signals to coexist with communication signals without requiring separate channel resources by leveraging power margins.

ISAC is a very important and active research topic for DFOS technology, and progress in this area will be critical to enable widespread adoption of sensing in existing communication networks.

5.2. Fiber Sensing Through Splitters in a Passive Optical Network

It is challenging to integrate traditional DAS techniques into access networks, such as passive optical networks (PONs), which employ passive power splitters to connect multiple homes and businesses to the internet. This is because the backscattered signals from various drop fibers of the splitters superimpose at the trunk fiber before being detected at the optical line terminal (OLT).
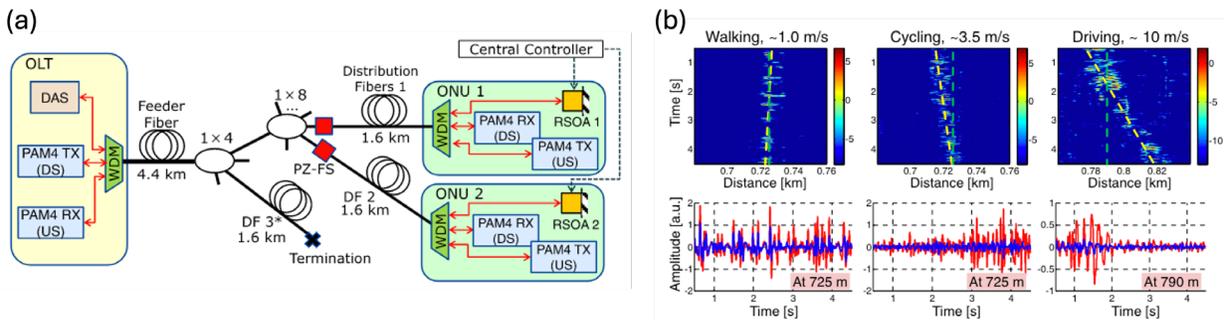

Figure 19: DAS over a passive optical network using reflective semiconductor optical amplifiers

NEC Laboratories recently introduced a potential solution that uses low-cost reflective semiconductor optical amplifiers (RSOAs), which are inserted at each optical network unit (ONU) to make DFOS compatible with time-division multiplexed PONs [16]. When an RSOA at an ONU is turned on, the sensing pulse is amplified and reflected, becoming a backward-propagating sensing pulse that generates its own Rayleigh backscatter. This backscatter initially travels toward the RSOA, which is then amplified and reflected to the OLT by the RSOA. To measure the OTDR trace at a particular drop fiber, a central controller turns on the RSOA at that ONU while leaving the other RSOAs turned off, as shown in Figure 19(a).

While this scheme can technically measure activity at each drop fiber, shown by the walking, cycling, and driving traces in Figure 19(b), this method requires all drop fiber lengths to be roughly equal to avoid interference. Another drawback of this method is operational overhead stemming from the requirement of a central controller to coordinate and synchronize the ONUs and RSOAs, which may complicate deployment and management. Other practical challenges for this method include potential security implications and capital expenditure/operating expense considerations from network operators.

Traditional PON monitoring techniques include placing reference reflectors such as fiber Bragg gratings at each ONU [28]. While this is a simpler implementation than the RSOA approach, it is not as powerful since the Bragg reflectors can only be used as a binary indicator to check if a particular ONU is operational (i.e. they cannot detect distributed vibrations along each drop fiber). Future research in DFOS

for P2MP settings needs to address scalable, cost-effective solutions that can monitor activity across the whole network.

5.3. Training Machine Learning Models for Useful Event Detection

Training ML models to detect meaningful events in DAS data is critical for unlocking the full potential of fiber sensing, particularly for rare but high-impact events such as the early signs of fiber degradation or impending breaks. However, one of the major challenges in this domain is the sheer volume of data generated by DAS systems most of which consists of routine environmental noise or benign activity. For example, a DAS system covering tens of kilometers at a high density of measurements (e.g. 1m spacing at 100s of Hz) could easily produce terabytes of data records per day. This results in highly imbalanced datasets, where the events of interest are vastly outnumbered by irrelevant data, making it difficult for ML models to learn accurate detection patterns. To overcome this, researchers are exploring data augmentation techniques that synthesize realistic examples of rare events, helping to enrich the training dataset and improve model generalization. For example, Nokia Bell Labs recently presented conditional generative adversarial networks and knowledge distillation for addressing field-data scarcity [29]. Evaluating the model trained on augmented data boosted the model accuracy for classifying rare mechanical events, such as jackhammers and excavators, from 83% to 99%.

At the same time, there is a growing need for efficient and scalable software frameworks that can ingest, filter, and process massive streams of DAS data in real time. Commercial DAS hardware providers often provide proprietary software suites with real-time processing, event detection, and visualization tailored to their systems. These tools are essential for enabling practical deployments of intelligent sensing systems that can operate continuously and respond quickly to critical anomalies.

5.4. Survey of Current DFOS Ecosystem and Standardization Efforts

While DFOS is gaining traction in the optical and telecom industries, there is still a gap in low-cost, application-specific commercial solutions that could accelerate broader adoption. Multiple leading vendors have recently announced DFOS solutions such as DAS and DTS interrogators and related software platforms. New products are announced regularly as fiber sensing becomes more popular in various industries.

There is also a growing push to standardize DFOS technology, although the effort is still in its infancy. For example, ITU-T Study Group 15 is examining how distributed sensing can be integrated with optical network infrastructure, particularly in fiber to the home (FTTH) and metro/access networks [30]. SEAFOM (Subsea Fiber Optic Monitoring Consortium) is a consortium that includes major oil & gas and sensing companies, focused on defining best practices and specifications for fiber sensing in subsea applications [31]. Although focused on offshore monitoring, its work influences standardization of DAS more broadly. While IEEE has not yet published formal DAS-specific standards, it is active in defining optical system performance metrics and network telemetry frameworks that intersect with DFOS. Standardization for DFOS is still evolving, with contributions from telecom, energy, sensing, and geospatial sectors.

A key goal for the Cable industry should be to push for an optimal coexistence of sensing signals with communication signals. In case a standardization activity aligns with and supports the above goal, contributions and leadership should be provided to ensure its success. As an industry, it is important to promote the benefits of open source, enabling a broader community to contribute to event discovery algorithms and probe signal design, thereby enhancing the intelligence that can be extracted from fiber sensing systems.

6. Conclusion

DFOS represents a transformative approach to leveraging existing fiber infrastructure for real-time, high-resolution monitoring across a wide range of environments. By enabling continuous sensing over long distances, DFOS provides valuable insights for applications in metropolitan infrastructure, environmental and geophysical monitoring, and broadband network management. As this technology continues to evolve, advances in signal processing, machine learning, and low-power system design are expanding its capabilities and practical deployment potential. Low power coded sensing sequences, such as those demonstrated by CableLabs, can enable flexible coexistence of sensing signals along with any type of optical communication signals to leverage Cable's pervasive fiber coverage. While challenges remain—such as handling large volumes of data and developing standardized interfaces—ongoing research and collaborative industry efforts are paving the way for scalable, intelligent sensing networks. The cable industry is in a great position to gather, analyze and manage significant amount of information that will become more valuable as AI tools are leveraged.

Abbreviations

AI	artificial intelligence
BER	bit error rate
DAS	distributed acoustic sensing
DFOS	distributed fiber optic sensing
DSP	digital signal processing
DTS	distributed temperature sensing
DWDM	dense wavelength division multiplexing
EDFA	erbium-doped fiber amplifier
FEC	forward error correction
FPGA	field programmable gate array
FTTH	fiber-to-the-home
FUT	fiber-under-test
ISAC	integrated sensing and communications
ML	machine learning
OLT	optical line terminal
ONU	optical network unit
OTDR	optical time domain reflectometry
P2P	point-to-point
P2MP	point-to-multipoint
PON	passive optical network
RSOA	reflective semiconductor optical amplifier
SNR	signal-to-noise ratio
SOP	state of polarization
SSMF	standard single-mode fiber

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