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Fibre Sensing: Technologies, Users and Use Cases for NRENs

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Abstract

This document provides a brief overview of fibre-sensing technologies and the possibilities offered by these techniques in both the structural monitoring of National Research and Education Network (NREN) infrastructure and in Earth observation and monitoring. Studying these new technologies by identifying potential NREN use cases, along with wider applications in the national and GÉANT pan-European infrastructures, offers a useful source of data to NRENs, and to the multiple and heterogeneous research communities connected by NRENs whose research stands to benefit. This document is aimed at NRENs but is comprehensible enough that other audiences, such as research communities and industries, will find it useful.

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Executive Summary

This white paper examines fibre sensing, a transformative emerging technology in optical networking. Traditionally, optical networks have been used to transport huge amounts of data. However, optical networks (more precisely, optical fibres) can be used for sensing purposes as well: proactively monitoring the environment around optical cables not only to protect the network itself, but also to offer insights into the environment and provide alerts for all manner of events ranging from unauthorised intrusions to disasters such as fires in tunnels and tsunamis.

This dual functionality is particularly relevant for GÉANT and the NRENs, which have decades of experience in managing extensive terrestrial and submarine fibre infrastructure. This document examines how fibre sensing offers NRENs the opportunity to enhance the monitoring and protection of their networks while simultaneously generating valuable data for scientific research and civil protection.

The operational benefits from integrating fibre-sensing technologies into NREN infrastructure include improved fault detection and localisation, enhanced network resilience, and compliance with regulatory frameworks such as the EU's NIS2 Directive and 5G Security Toolbox. Fibre sensing also supports proactive cable system maintenance and security measures such as intrusion detection.

Beyond network operations, fibre sensing has a broad array of applications across industry. It supports research in fields such as geophysics, oceanography, climatology, and biology. Civil engineering applications include structural monitoring and traffic analysis, while the utility sector benefits from leak detection and infrastructure surveillance, making fibre sensing a valuable asset across the public, academic and industrial sectors.

This wide range of applications positions NRENs as potential key enablers, supporting both advanced network operations and the advancement of their constituents in research and education. After reviewing these fibre-sensing user communities with focus on the NREN perspective, this document presents a mapping of specific application domains to their associated frequency ranges and then outlines the appropriate fibre-sensing technology to use in each case. These technologies cover different but complementary frequency ranges, enabling tailored data collection ranging from high-frequency mechanical vibrations and audio surveillance to low-frequency oceanographic monitoring and long-term structural changes, depending on the events that a given user community seeks to observe.

The paper concludes that owing to the convergence of communication and sensing technologies, fibre sensing is positioned as a critical component of future network and research infrastructure and thus is of critical importance to NRENs.

1 Introduction

Fibre sensing has emerged as a 'hot' topic over the last few years [1][2]. NRENs and GÉANT, both of which own and manage both terrestrial and submarine optical fibre pairs and spectrum, are increasingly studying sensing technologies due to the opportunities they provide: protection and proactive monitoring of the physical network infrastructure, as well as significant gains for NREN users engaged in scientific research, civil protection through environmental monitoring capabilities, and in some cases, national security.

Fibre-sensing technologies can turn optical fibres into sources of data, measuring the variation of a signal in specific optical transmission parameters (amplitude, phase, polarisation, and frequency) as it passes through an optical fibre. It is now possible to detect minimal deformations experienced by a fibre when the surrounding environment undergoes changes. These environmental changes may be caused by natural events such as earthquakes, landslides, tsunamis or by human activities such as roadwork, construction, or intrusion into the area where the fibre is housed. However, this topic has been made increasingly relevant in recent years by the evolution of sensing technology toward solutions that allow its coexistence with data transmission on the same optical fibres [3]. This development permits the use of Distributed Fibre-Optic Sensing (DFOS) on infrastructure resources that in the past were solely dedicated to transmission.

It has become clear that there are multiple uses, by multiple communities, for the vast amounts of data that are generated by fibre-sensing instruments. With the wide adoption of artificial intelligence, the automated selection of datasets from multiple data sources can now be tailored to serve specific research and user communities and generate new perspectives from the amalgamation of different datasets, leading to new scientific discoveries. NRENs, as service providers in an increasingly data-product-driven environment, thus have the opportunity to manage and make this data available to their user communities, as well as benefiting themselves via enhanced monitoring and responding to threats to physical infrastructure.

The remainder of this document is structured as follows: Section 2 offers a brief overview of some of these distributed fibre-sensing technologies. Section 3 discusses the range of possibilities these technologies offer to the different user communities and maps the areas of interest, frequency ranges of events to sense, and the appropriate sensing technology to use in each case. The document ends with a conclusion in Section 4.

2 Overview of Fibre-Sensing Technologies

There are currently two main methods of sensing using cables: point-based sensing and distributed fibre-optic sensing (DFOS) [4].

The concept behind point-based sensing is the addition and integration of physical equipment along the cable that houses optical fibres, primarily either Science Monitoring and Reliable Telecommunications (SMART) sensors [4][5] or a fibre Bragg grating [1]. SMART sensors use the power and telecommunication connectivity provided by the cable system itself and feature on submarine cable systems as opposed to terrestrial systems. However, there are currently no known deployed or active cable systems that utilise SMART technology (although there are plans to deploy some in the near future). The full realisation of this concept depends on cable manufacturers changing their cable designs to introduce as-of-yet unproven technology into the system. It also means that only newly laid cables can benefit from the technology. In comparison, fibre Bragg gratings are passive devices typically used in optical line systems to provide wavelength-selective filtering, reflecting specific wavelengths back to a source. When used in combination with a laser source, quasi-distributed sensing can be achieved [6].

The point-based sensing technology discussed above focuses on generating data from around specific locations along a cable path, rather than providing information on the status of the cable system itself. DFOS, on the other hand, utilises the actual optical fibre within a cable system as the sensing medium itself. This means that existing cable systems (including decommissioned systems, with some specific techniques) can be retrofitted with this technology. DFOS can be deployed on both submarine and terrestrial cable systems. As the optical fibre is used as the medium, the data obtained can be used to understand the status of the optical fibre while telecoms traffic is passing through it. DFOS can also be used to complement point-based sensors, allowing multiple data sources to operate along a single cable system simultaneously.

Within the field of distributed sensing, there are currently two main technical categories: scattering-based sensing and forward-transmission-based sensing. The remainder of this document provides a brief description of the technical approaches of the distributed-sensing technologies with significant potential for successful application in NRENs' network infrastructures for cable protection and scientific observations.

2.1 Scattering-Based Sensing

Scattering-based technologies involve the injection of a laser source into a fibre optic cable, with the returned reflections (backscatter) being recorded and analysed. Backscattering (i.e., the reflection of signals back to the direction from which they came) occurs as a result of tiny changes in the density of the glass core of the optical fibres arising from small imperfections created during its manufacture. Environmental changes in the medium surrounding the fibre, as well as changes to the physical medium of the fibre itself (e.g., stretching, straining, pressure or temperature) can cause changes to (i.e., shifts in the phase of) that backscattered light. Each reflection point becomes a sensing point, meaning that along the length of a fibre, many points can be monitored at varying distances [7]. Taking into account that the speed of light in optical fibre is known, and the time it takes for light to travel along and back through an optical fibre can be measured, this technique allows the detection of the location of those environmental changes along the cable to a precision of around 1 metre [2].

Backscattering occurs mainly in three forms – Rayleigh [8], Raman [9], and Brillouin scattering [10]. Currently, the first two, Raman and Rayleigh scattering, are used to detect changes in cables. For each of these, a particular technical technique is used to extract information. Distributed Acoustic Sensing (DAS), also called Distributed

Dynamic Strain Sensing (DDSS), refers to the Rayleigh-based scattering effect. Despite the word “acoustic” in “DAS” perhaps suggesting the use of sound pressure waves, DAS does not detect pressure directly; it detects strain in the fibre. Raman-based techniques, based on Distributed Temperature Sensing (DTS) [4], are also growing in popularity. In the following sections, only Rayleigh scattering is considered as it is the most widely used. However, the key challenge for any scattering technique is the identification and classification of signals that couple into the infrastructure (e.g. optical cables) as strain and how. This is currently under active investigation by various research communities.

Due to attenuation of the optical signal along the fibre, the maximum sensing range for DAS is typically limited to around 50 km, or up to the location of the first repeater unit in Dense Wavelength Division Multiplexing (DWDM) [11] optical-fibre cable systems, both submarine and terrestrial. While some advanced DAS interrogation techniques can extend the sampling range beyond this, in some cases to as far as 150–170 km, practical sensing often terminates at the first repeater. This is because repeaters, to protect the optical transmission components, commonly contain optical filters and amplifiers that inhibit the backscattered light necessary for DAS operation.

Injecting a DAS signal into a live telecommunications system presents challenges, particularly for transmission equipment. However, research [12] has demonstrated simultaneous telecommunication and DAS operation at different wavelengths within the same fibre, known as optical multiplexing, as an effective solution. In May 2024, a four-day DAS dataset was collected using an L-band interrogator multiplexed onto the submarine cables of the Ocean Observatories Initiative’s Regional Cabled Array, offshore central Oregon [13]. The results showed that multiplexed DAS is neither degraded by network traffic nor impacts communications. Furthermore, the quality of DAS data obtained via multiplexing was comparable to that collected on dark fibre. Using a machine-learning event detection workflow, researchers identified 31 T-waves and the S-wave of one regional earthquake, thereby demonstrating the feasibility of continuous earthquake monitoring with offshore multiplexed DAS.

2.2 Forward Transmission-Based Sensing

Coherent light is used in telecommunications because maintaining fixed phase relationships between light waves allows advanced modulation formats that greatly increase spectral efficiency, while the ability to separate orthogonal polarisations effectively doubles the capacity of each fibre. As such, coherent detection enables digital signal processing to correct for noise such as chromatic dispersion, polarisation mode dispersion and other non-linear effects. These non-linear effects are in part caused by a range of factors along the whole length of the fibre. However, what may be noise to some is signal to others. It is increasingly recognised that coherent detection and digital signal processing (DSP) techniques now allow telecom fibres to serve as programmable sensors [14].

With respect to polarisation, different polarised optical waves propagate with different propagation constants. In optical fibre, this is due to intrinsic fibre birefringence [15]. Both internal and external factors can influence fibre birefringence. The internal fibre birefringence arises from imperfections in fibre manufacturing, such as core ellipticity, bending, twisting, or even material impurities and inhomogeneities. The external factors are changes in environmental conditions (rain, wind gust, snow, heat, lightning, or temperature variations), mechanical stress and pressure. By monitoring the state of polarisation (SOP), we can monitor the changes in fibre birefringence over time.

Polarisation changes are monitored by recording certain parameters, known as Stokes parameters. Stokes parameters are a set of values that describe the polarisation state of electromagnetic radiation [16].

There are two techniques possible for SOP sensing:

- Monitoring of the SOP of the transported data signal at the DWDM transceivers.
- Dedicated SOP polarimeter over a DWDM monitoring channel.

Alongside these traditional SOP techniques, SOP Optical Time Domain Reflectometry (SOP-OTDR) is another technique, first published in March 2022 and piloted by Infinera and Google [1]. SOP-OTDR in subsea optical communication systems combines point-based sensing with forward transmission-based DFOS sensing and allows monitoring of subsea cable health while simultaneously monitoring physical phenomena around the cable at certain points along the cable. This technique uses the periodic transmission of tones generated by a polarimeter, rather than from the telecoms traffic itself, along a cable and utilises built-in high-loss loopbacks (HLLBs) to obtain reflections of these tones at every repeater. As with the traditional SOP techniques, these reflected signals are filtered to eliminate out-of-band noise, then converted to their corresponding Stokes parameters for further analysis. The same technique can be applied to terrestrial cables [3]. It should be noted that SOP and other forward-transmission-based sensing techniques are at a much lower technology readiness level (TRL) than scattering-based sensing techniques.

2.3 Additional Requirements

Alongside the sensing technologies, a consistently precise time source needs to be provided. This could be, for example, via satellite navigation systems, a network time protocol (NTP), a precision time protocol (PTP), or White Rabbit, a technology based on a combination of PTP and Synchronous Ethernet (SyncE) [17]. The time source allows the sensing data generated to be accurately compared with data produced from other locations and using other technologies.

The quantity of sensing data generated can be substantial depending on the configurations used. DAS is the most prolific, potentially generating ~7TB of data per day. Typically, sensing instruments come with a Network Attached Storage (NAS), so disks can be shipped directly to research facilities or a centralised storage location. However, for streaming of data, sufficient connectivity is required. For low-throughput, heavily downsampled data and out-of-band access, 5G dongles are used, while Ethernet connectivity via a fixed network provides access to full raw data files.

Once the data is extracted from the instrument(s), it then needs to be processed and stored. In certain instances, raw data (i.e., unprocessed) is kept in a secure location for retrieval by authorised parties as required for later processing into derived data products for their domain-specific needs. To account for the needs of domain-specific knowledge production from sensing data, the creation of specific ecosystems by the relevant national research institutes and their communities is suggested [18].

To effectively utilise the large amount of generated data (especially in the DAS context), careful design of data management systems, including computational and storage resources, is essential. Machine learning is playing an important role both in improving optical-fibre sensor performance by introducing innovative problem-solving approaches, and in near-real-time analyses [19]. As such, fibre sensing, although facilitated and supported by the network, requires a full-stack approach to support its operations.

2.4 Considerations for Deploying DFOS Technologies

Each fibre-sensing technology sits at a different level of maturity and has its own limitations and trade-offs. As a result, rollout of a given technology and its potential use cases depend on a range of technical and contextual factors. Table 2.1 below summarises the indicative limitations, capabilities, and costs of the most widely used instruments. The figures in the *Equipment costs* column refer only to the sensing units themselves and not the broader expense of deploying an integrated system. For example, adapting a network to host a DAS unit in a cable landing station or amplifier site — facilities that may have previously served only as pass-through or inline amplifier sites without layer 3 breakout capacity — introduces additional, context-specific costs that are difficult to generalise.

	Parameter sensed	Maximum recording distance	Maximum detected frequency (Hz)	Constraints	Cable requirements	Injected power (dBm)	Data produced per day	Equipment costs
DAS (C Band)	Rayleigh backscatter	50-170KM	10,000 Hz	Can't pass first repeater[1]	Dark fibre	0 to 24 dBm	~7 TB	~200 K€
DAS (L Band)	Rayleigh backscatter	50-170KM	10,000 Hz	Can't pass first repeater[1]	Accessible L band	0 to 14 dBm	~7 TB	~200 K€
Transceiver SOP	Stokes variables	Cable length	20 Hz	Low frequency resolution	DWDM system	0 dBm	3 GB	~50 K€
Polarimeter SOP	Stokes variables	Cable length	20 Hz	Low frequency resolution	DWDM channels	0 dBm	6-250 GB	~50 K€

Table 2.1: Comparison of the different fibre-sensing techniques with respect to the type of technique used, range, deployment considerations and indicative unit cost

Despite these constraints, research and development in fibre sensing is progressing rapidly. This acceleration is driven by the breadth of potential applications and by the diverse user communities eager to exploit the data these instruments can provide. A variety of user communities and their potential fibre-sensing use cases are explored in the following section.

[1] DAS operation requires backscattering of light in order to work. The optical repeater / regenerator filters out backscattering for protection, so the laser light isn't reflected back past the repeater, hence DAS signals can't pass the first repeater.

3 Users Communities and Possible Use Cases

Acquiring data through fibre-sensing techniques on the Research and Education (R&E) optical fibre infrastructure may be of interest to an NREN in two different aspects: using the data generated *for* the network to increase the health and security of the infrastructure itself, and generating data *with* the network on behalf of the communities it supports [2][20]. While the raw data and frequency ranges collected can be used by multiple communities, including NRENs, the derived data products for a specific community typically vary and don’t overlap. It is the post-processing of raw data where a community can extract real value for their particular use case.

When considering using fibre sensing *for* the network, the use cases align with a telecom operator’s core priorities: safeguarding service integrity, protecting assets, and minimising user impact – the focus of which (although not the only one) is predominantly operational and with the aim of increasing the speed of reaction to incidents, such as improving fault localisation, and identification of third-party interference in the network. Experiencing delays during outages is costly and raises the overall risk profile on a network through lack of redundancy and resiliency. Thus, an improvement in the time required for fault localisation and restoration of fibre cuts — and even prevention of downtime — are key drivers in the adoption of fibre-sensing technologies and, where appropriate, furnishing the evidential material gathered to support law-enforcement enquiries.

While not limited to NRENs, the ability to monitor, detect, and respond to anomalies is not only sound operational practice; it is increasingly a regulatory requirement. Under the NIS2 Directive, providers of public electronic communications networks and services are designated as essential entities, subject to stronger harmonised cybersecurity obligations across the EU [21]. Similarly, investment agencies are now linking funding for fibre-optic infrastructure to security requirements, including conformance with the EU 5G Security Toolbox. Measure TM03 of the Toolbox explicitly calls for monitoring, detection, and timely response to anomalies [22]. Table 3.1 offers an overview of some of the regulatory drivers and benefits of DFOS for NRENs.

Regulatory drivers and benefits of fibre sensing for NRENs		
Driver / obligation	Requirement	How fibre sensing helps
NIS2 Directive (Art. 21, 23-24)	Essential entities must monitor, detect, and report incidents within 24–72 hrs; implement risk management and continuity measures.	Real-time anomaly detection (vibrations, temperature changes) supports early warning and localisation of incidents, enabling faster reporting and recovery.
EU 5G Security Toolbox (TM03)	Telecom networks must implement monitoring, detection, and timely response to anomalies.	DFOS sensing instruments deliver continuous monitoring of optical infrastructure, supporting compliance with TM03.
Investment & funding conditions	Some infrastructure investment agencies require conformity with NIS2/5G Security Toolbox measures as part of funding eligibility.	Deploying fibre sensing demonstrates proactive security and resilience, strengthening the case for investment approval.
Operational resilience best practice	Reduce mean time to detect (MTTD) and mean time to repair (MTTR); ensure true path diversity; prevent outages.	Trend analysis, redundancy verification, and precise fault localisation reduce downtime and increase service reliability.

Table 3.1: Regulatory drivers and benefits of distributed fibre-optic sensing for NRENs

With respect to generating data for research communities, fibre sensing has started to gain traction for the study of several areas in Earth applied sciences: geophysics, oceanography, climatology and biology are fields currently utilising this technology and are where most of the advancements in the technology are observed. It should also be mentioned that a number of GÉANT NRENs are actively involved in optical fibre-sensing activities via several projects in support of research communities, as well as for their own needs [23][24][25][26]. However, due to the large quantity of use cases within those communities and projects, it is unknown whether there are other research communities that could potentially utilise this data.

Fibre-sensing applications and their corresponding users are summarised in the following Table 3.2. It is by no means definitive.

Fibre sensing applications and potential users		
Area of interest / field	Possible applications	Potential user groups
Research and development, science	Experiments, new principles of fibre sensing, new prototypes of fibre sensing Deployment of existing fibre sensing systems Monitoring of Earth systems and processes	Academic / research institutions, laboratories not limited to 'pure' research, industry, optical cable system developers, optical network service providers, NRENs
Telecommunications	Monitoring of temperature, vibrations, stress, health of fibres and transmission systems, intrusion detection	Internet Service Providers (ISPs), NRENs, optical cable system developers, optical network service providers
Civil engineering, including 'smart cities'	Structural monitoring of bridges, tunnels, buildings, dams / infrastructures etc., intrusion detection Traffic monitoring (vehicles, trains, ships, pedestrians)	Governments, civil sector, security-minded agencies, companies for construction and maintenance of mentioned objects / infrastructures
Water / oil / gas companies	Detection of leaks, temperature changes, intrusion detection	Owners and operators
Energy / power distribution companies	Monitoring power plants, grids etc., intrusion detection	Owners and operators

Table 3.2: Main areas for fibre-sensing deployment together with potential user groups

The use cases for DFOS are expanding rapidly, with publications citing DFOS and related techniques rising sharply over the past five years [20]. While DFOS offers compelling capabilities, it also has constraints that shape its utility for telecom operators and scientific communities – constraints that extend beyond the spatial resolution or geographic representativeness of the sensing data collected. Even so, DFOS can meaningfully complement existing instrumentation, enriching the overall picture available to each community. Because the same raw data can serve multiple users, DFOS can be considered a valuable addition to the monitoring landscape.

The remainder of this section outlines the use of fibre sensing *for* the network (Section 3.1) and *with* the network (Section 3.2), concluding in Section 3.3 by outlining which specific fibre-sensing technologies best support the identified use cases and activities.

3.1 NREN Use Case: Enhancing Infrastructure Health and Security

In the drive to deliver ever greater capacity and bandwidth, telecom networks have largely transitioned from copper line systems to optical fibre. For NRENs, optical fibre (whether leased or owned outright) forms the backbone of metro and wide-area infrastructures. The services provided to R&E communities are therefore critically dependent on this fibre infrastructure. It is in the interest of NRENs to monitor their networks effectively, both to respond promptly to incidents and to prevent outages through early detection and intervention.

Distributed fibre-optic sensing technologies provide a means to address these requirements. By integrating sensing into the network with existing tooling, operators can monitor infrastructure health in real time, enabling targeted interventions that complement and enhance existing network management tools. A comprehensive overview of sensing applications for enhancing fibre network security is presented in Wellbrock et al. (2023) [2].

When combined with accurate time-measurement systems, DFOS can not only detect anomalies but also localise their origin. This greatly reduces the time required to discover and repair faults. With powerful computational capabilities and machine-learning techniques, operators can automatically identify problems and their exact location, improving service continuity [2][19].

Practical examples of issues that can be detected include:

- **Vibrations**: Excavation work near a buried fibre can trigger alarms at the NREN's Network Operations Centre (NOC), which can then alert the fibre owner to intervene before damage escalates.
- **Temperature changes**: Sudden increases in temperature may indicate a nearby fire, prompting rapid maintenance action or evidence collection.
- **Trend analysis**: Long-term monitoring can highlight gradual fibre deterioration, allowing preventive rerouting of traffic and improved network resilience.

Conventional optical time-domain reflectometry (OTDR) has long been used for fibre maintenance, providing distances to events such as breaks. However, OTDR results rarely map precisely to geography due to cable slack and installation conditions, slowing the process of precisely locating a fault. Calibrated distributed fibre sensing can overcome this limitation, for example, by placing vibration generators at known points along the route to get a more accurate picture of a cable path in advance of any incidents, allowing for the timely localisation of the precise point of a fibre break when it occurs.

Another valuable application is verifying fibre path redundancy. NRENs often provision diverse routes to improve resilience. By attaching DAS or SOP instruments to two supposedly diverse fibres, environmental perturbations (traffic, wind, ships) can be used to generate unique "fingerprints". If the fingerprints match over any section, it indicates the fibres are physically co-located and not truly diverse. With high-resolution DAS, the overlap can be pinpointed to within a few metres, albeit up to the first amplifier on a route.

Recent research underscores the viability of these approaches. *Optical Fiber Sensor for Real-Time Monitoring of Industrial Structures and Application to Urban Telecommunication Networks* demonstrates the use of phase-sensitive OTDR (ϕ-OTDR) systems for detecting intrusion events in urban telecom inspection wells [27]. By applying advanced signal processing and machine learning classifiers, the authors achieved identification of a variety of intrusion types with accuracies of up to 98.6%, demonstrating that the data generated from DFOS combined with ML is a powerful tool for monitoring urban networks.

Similarly, *Polarization Sensing over Terrestrial Optical Fiber Networks* (Carver & Zhou) explored the use of SOP sensing as a complementary method to DAS [28]. Laboratory validation and live trials over a 58-km operational fibre in southern California demonstrated SOP's ability to detect physical stressors (bends, connector movement) and anticipate network interface flaps. By normalising the recorded values and applying detection algorithms, SOP sensing produced distinctive signatures for transient perturbations. The authors concluded that coherent transceivers already deployed in metro and long-haul networks provide a low-cost, scalable pathway for SOP-based monitoring, with immediate operational benefits (e.g., pre-emptive flap detection, improved resilience) and future potential for wide-scale seismic sensing.

Finally, while this section focuses on NREN telecommunication applications, it is worth noting that fibre sensing also extends to wider NREN infrastructure monitoring. Use cases include bearing fault analyses in servers and supporting data centre plant machinery [29], data centre acoustic profile monitoring for health and safety purposes [30], remote server buzzer identification [31] and network cabinet intrusion attempts [32], underscoring DFOS' offer of a coherent approach to asset health and security.

3.2 NREN Support for Research Communities

Fibre-optic networks can be viewed as nervous systems, which are affected when stimulated by changes in their surrounding environment, vibrations, strain, pressure or temperature. Alterations in the transmitted light can be analysed to detect unusual events such as earthquakes, floods, lightning strikes, landslides or animal migrations. The potential applications of fibre sensing are extremely diverse, spanning multiple scientific disciplines and operational domains.

The scientific value of fibre sensing lies in its capacity to generate long-term datasets from locations where the deployment of conventional instruments would be difficult, costly, or impractical. This capability enables the observation of phenomena that might otherwise go undetected due to the limited duration of traditional deployments and the transient nature of certain events. In many disciplines, DFOS therefore serves as a complementary data source alongside established instrumentation. Moreover, fibre sensing can be deployed flexibly in temporary configurations; for instance, short sections of above-ground cable can be laid alongside roads to measure traffic flow with high spatial resolution, offering a cost-effective alternative to fixed monitoring infrastructure [33].

Submarine cables provide a particularly attractive environment for sensing. While the ocean depths are relatively quiet, thus providing higher-quality data for scientists, they are also difficult and expensive to monitor by traditional means. Depending on the frequency range of perturbations, submarine fibres are sensitive to events ranging from earthquakes and tectonic movements to ocean currents, ocean-floor temperature, tsunamis, ship traffic, aircraft, and even marine mammal behaviour [1][4][5][13][14][20][34][35][36]. The resulting data is of clear relevance to fields such as oceanography, geophysics, climatology and cetology, and also supports civil protection objectives including early warning and disaster response.

Terrestrial fibre networks present a noisier environment, with perturbations from traffic, construction, and human activity. Nevertheless, distributed fibre optic sensing can extract meaningful signals through correlation across fibres, infrastructures, or sensing points [37][38][39][40][41]. Relevant applications include seismology, volcanology and urban planning, as well as monitoring anthropogenic disturbances and movements. DFOS is even starting to be used in more applied-science use cases such as structural health monitoring of bridges, tunnels and pipelines, as well as transport systems such as airports, ports, railways and highways [42][43][44][45].

Fibre sensing has clear security implications. Vibrations or pressure changes caused by vessels passing over submarine cables can be detected in real time, supporting vessel tracking, border monitoring, evidence gathering, and protection against smuggling or sabotage [46]. DAS systems can also detect underwater explosions and other anomalous acoustic events, with unique signatures that support intrusion detection and enhance the security of pipelines, power interconnectors, and subsea cables [47]. Because such data may have national security implications, NRENs and research operators must coordinate with competent authorities to ensure appropriate data scrubbing and governance before redistribution.

3.3 Overview of Fibre-Sensing Use Cases

As has been shown, the breadth of potential fibre-sensing applications is broad and this is reflected in the diversity of communities that could derive benefits from the use of the data. However, apart from identifying existing use cases as highlighted in Sections 3.1 and 3.2, it is challenging to determine which communities would derive useful information from the raw data gathered from DFOS interrogators. This uncertainty exists due to each discipline having an interest in different physical phenomena ranging from low to high frequency. Therefore, each user group requires different sensing capabilities. DAS and SOP sensing cover overlapping but distinct frequency ranges, making them suitable when combined for most use cases – but not all. NRENs, in collaboration with their research communities, can play an important role by identifying the network segments of greatest interest and matching sensing techniques and geographical regions to the event types required by research communities and operations staff, thus facilitating data acquisition and sharing without impacting service delivery.

The following Table 3.3 provides a mapping of fields of interest, the characteristic frequency ranges of the events relevant to those fields, and the sensing technologies that can be applied. This mapping helps illustrate how research communities, infrastructure operators, and NRENs can identify the right sensing approach for their needs. While not exhaustive, it gives a practical view of how fibre networks can serve both infrastructure health and broader scientific discovery.

Frequency range and technologies	Scientific research, Earth observation						Infrastructure Preservation				
	Civil Alert			Climate Change							
	Geophysical research		Marine research				Network and structural health monitoring			Industrial and security	
	Seismic activity / earthquakes	Volcanic activity	Tsunami	Oceanography	Underwater soundscapes	Cetology	Submarine cable monitoring	Aerial cable monitoring	Buried cable monitoring	Machinery vibrations	Audio / vibration surveillance
Frequency Range	0.01 - 200 Hz	0.05 - 40Hz [1]	4 Hz	0.01 - 0.5 Hz	0.1 Hz - 200 KHz	5 Hz - 100 kHz	16 - 1000 Hz	0.01 - 10 Hz	0.01 - 1000 Hz	5Hz - 100 KHz	19 Hz - 100 KHz
Distributed Acoustic Sensing	P	P	Y	P	P	P	Y	P	P	P	P
State of Polarisation	P	Y	Y	Y	P	P	P	Y	Y	P	P

Table 3.3: Map between the area of interest, frequency range of events and a comparison if the described technology can detect all signals (Y), part of the frequency range (P), or none of the frequency range (N)

The accompanying figure on the following page complements Table 3.3 by showing the frequency bands typically detectable by DAS and SOP alongside the ranges most relevant to the different user groups. Together, Table 3.3 and Figure 3.1 provide both a conceptual and visual framework for aligning fibre-sensing technologies with user community needs.

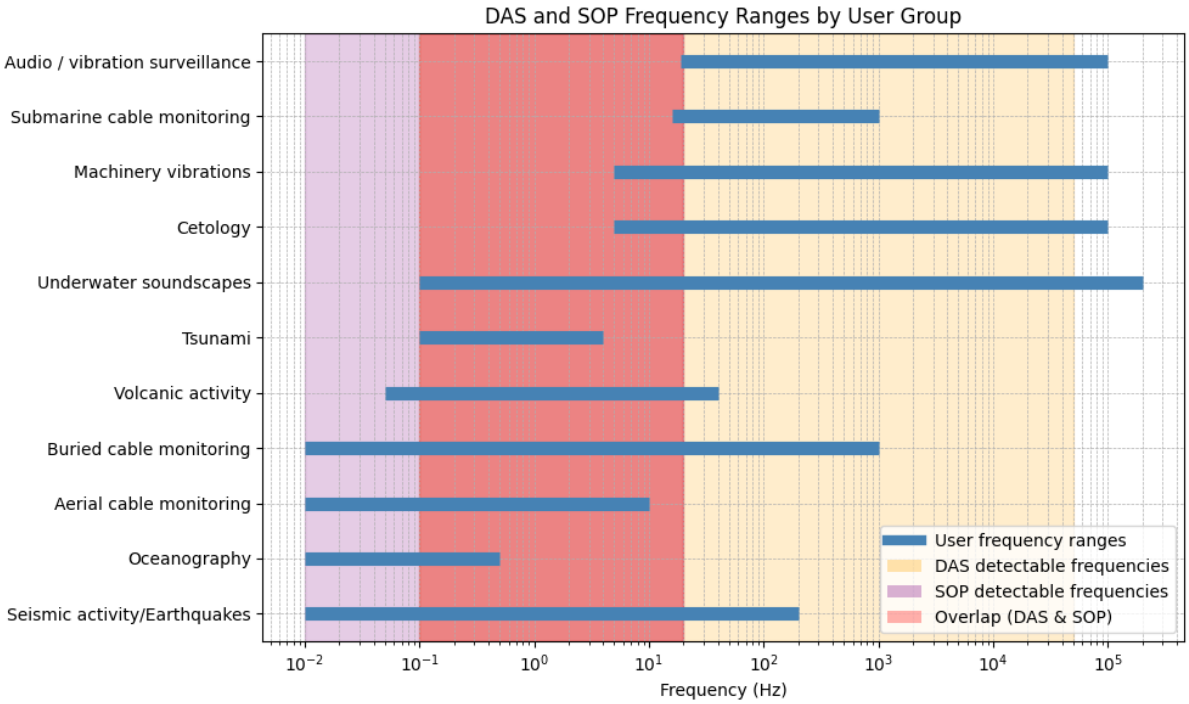

Figure 3.1: Overview of the DAS and SOP frequency ranges in the logarithmic scale. SOP detectable frequency range is shown in purple; DAS detectable frequency range in yellow; red represents the overlap between the two technologies

What emerges clearly from this mapping is that no single technique covers all use cases. DAS offers excellent sensitivity across a wide spectrum, making it ideal for seismic studies, cetology, infrastructure monitoring and intrusion detection, while being limited in sensing range along a cable. SOP sensing, while lower in sensitivity and technology readiness level, leverages coherent transmission equipment already embedded in many networks, providing a low-cost and scalable solution for monitoring network health and detecting lower-frequency perturbations such as oceanographic parameters along the whole length of a network segment.

For NRENs, the implication is twofold. First, selecting the appropriate sensing technology depends on the user community being supported: geophysicists and oceanographers often favour DAS, whereas telecom operators may gain immediate operational benefits from SOP. Second, there are clear opportunities to combine techniques or expand into newer approaches such as interferometric sensing in order to enrich the range of detectable events [26].

Ultimately, these mappings reinforce the idea that fibre sensing is not a niche capability, but a multi-disciplinary enabler. By understanding how event frequencies align with sensing technologies, NRENs and their partners can prioritise deployments, facilitate data sharing with research communities, and position their networks as platforms for both resilient connectivity and scientific discovery.

4 Conclusions

This paper showed that optical fibre sensing is a set of technologies with highly useful applications, not only for NRENs and their intrinsic use case of ensuring the health of their network infrastructures, but also for NRENs as operators and owners of optical telecom fibre in their work of supporting research and education.

Among the main benefits to NRENs from using the fibre network as a passive sensor are:

- Detection of fibre conditions and monitoring the health status of infrastructure.
- Perimeter security, surveillance, and the creation of anti-intrusion systems to protect their Point-of-Presence (PoP) sites.
- Monitoring of data integrity in transit.

NRENs and users utilising fibre sensing for terrestrial applications may benefit from using SOP methods to keep the costs of such solutions low because of competing terrestrial solutions (simple sensors or CCTV analogues). Less expensive variants of DAS, using inferior and therefore less expensive components (e.g., low-cost coherent lasers), may also be an interesting variant for NRENs to collect the data they require. However, this would need to be balanced with the needs of the research communities that wish to utilise high-quality data in their research and the efficacy of the sensitivity results gathered.

The convergence of sensing and communications is becoming increasingly practical. According to the paper *Using Global Existing Fiber Networks for Environmental Sensing* [14], coherent detection and digital signal processing (DSP) techniques now allow telecom fibres to serve as programmable sensors.

This document also mapped the frequency ranges of interest to specific research areas to the appropriate fibre-sensing technologies. Legal and security aspects that require consideration in the context of fibre sensing were briefly discussed; further work in these areas must include the NREN communities and ecosystem.

Glossary

DDSS	Distributed Dynamic Strain Sensing
DFOS	Distributed Fibre-Optic Sensing
DSP	Digital Signal Processing
DTS	Distributed Temperature Sensing
DWDM	Dense Wavelength Division Multiplexing
HLLB	High-Loss Loopback
ISP	Internet Service Provider
MTTD	Mean Time To Detect
MTTR	Mean Time To Repair
NAS	Network Attached Storage
NOC	Network Operations Centre,
NREN	National Research and Education Network
NTP	Network Time Protocol
OTDR	Optical Time-Domain Reflectometry,
PoP	Point of Presence
PTP	Precision Time Protocol
R&E	Research and Education
SMART	Science Monitoring and Reliable Telecommunications
SOP	State of Polarisation
SOP-OTDR	State of Polarisation - Optical Time Domain Reflectometry
SyncE	Synchronous Ethernet
TRL	Technology Readiness Level
ϕ-OTDR	Phase-Sensitive Optical Time-Domain Reflectometry

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