



ICON

HORIZON-HADEA

**WP2 Use cases, physical requirements
and data format for sensing systems**

**Deliverable 2.1 Final report on use cases and
physical sensing solution specifications**

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Executive Summary

This report presents the principles of intent and context-aware networking (ICON) as well as a description of its various use cases.

ICON transforms the optical network into an intent-driven and context-aware integrated communication and sensing (ICAS) system, which exploits the capabilities of the deployed optical fibre network to sense the environment. This is achieved by combining various flexible physical layer sensing technologies (e.g., distributed acoustic sensing (DAS), state of polarisation (SoP), optical time domain reflectometry (OTDR), telemetry, optical probing, etc.) with a context creation (through the digital signal processing and digital twin) and the intelligent intent-based controller. The result is a system allowing for (1) the critical infrastructure protection and resilience (through a real-time situational awareness), (2) improved optical network operation (thanks to availability of detailed information on health, failure rates, failure causes of different network links), and (3) creation of new revenue streams to network infrastructure owners and operators (by enabling new sensing applications over the networks infrastructure such as seismic and earthquake detection, traffic monitoring for smart cities, landslide and ground instability monitoring etc.).

An important aspect of ICON exploitation is mapping the different sensing technologies to concrete operational use cases. Infrastructure owners and telecom operators require precise, actionable sensing capabilities to maintain high network availability and prevent service-impacting incidents, spanning real-time detection, timely notification and long-term reliability analysis.

Proactive protection requires real-time, high-sensitivity instrumentation capable of detecting fast-developing threats, such as trawling and anchor drag on subsea segments, digging or lightning-induced disturbances on land routes, conductor galloping, and node-room intrusion. This demand sensing technologies that operate directly on the live fibre, such as DAS, SoP, OTDR and transceiver telemetry, each contributing complementary strengths.

In contrast, building network availability maps and planning infrastructure upgrades requires comprehensive, long-term telemetry and sensing data to quantify link-level and network-wide reliability, feeding models that compute failures-in-time (FIT), mean time between failures (MTBF), mean time to repair (MTTR), attenuation trends and environmental stress patterns.

These differing requirements have a direct impact on data handling, including storage strategies, alarm and warning logic and data presentation. While the handling of experimental data is described in ICON Deliverable D1.1 Data Management Plan, Task 2.3 will investigate how sensing data should be presented and shared so that it can be effectively used in both telecommunication and non-telecommunication use cases.

Introduction

Deliverable 2.1 “Final Report on use cases and physical sensing solution specifications” is an outcome of the Task 2.1 Specifications of sensing use cases and Task 2.2 Physical sensing technology and demo specifications.

The main objective of this deliverable is to provide a comprehensive picture of the use cases that can be served by the ICON system, with a special focus on the use cases that will be demonstrated by the end of the project. These include the network infrastructure protection and the availability assistant/availability maps.

The deliverable is structured in the following way:

- Section 1 provides a detailed description of the ICON principle and the various enabling ICON components, such as the physical layer sensing technologies, the digital signal processing and the intelligent ICON controller.
- Section 2 describes the various use cases enabled by the ISAC concept, with a special focus on the use cases that will be demonstrated by the project partners.
- Section 3 provides the description of the physical layer sensing technologies, exploiting both forward and backward propagating signals, investigated/developed/optimised within ICON, and the sensing performance achievable by each of the methods. This section also provides guidelines for mapping the sensing technologies to the sensing use cases.
- Section 4 briefly outlines aspects related to telemetry and sensing data management flow.
- Section 5 contains the conclusions.

1. Principles of Intent and Context Aware Networking

1.1. Background

Optical fibre networks are increasingly expected to provide not only high-capacity digital connectivity, but also meaningful information about the physical state of the underlying infrastructure and its environment. This dual role has become more important as network availability requirements grow across telecom, energy, and other critical infrastructure sectors, and as new applications (5G/6G, distributed industrial automation, remote monitoring) rely on stable optical transport with stringent latency, jitter and reliability constraints. Existing network telemetry provides only a partial view: conventional monitors report link-level parameters, while sensing devices are typically deployed and analysed independently, with limited correlation across domains or time.

The ICON concept responds to this gap by transforming the optical network into an intent-driven and context-aware integrated communication and sensing (ICAS) system. Rather than treating sensing as an add-on function, ICON integrates it as a core operational capability of the network, enabling the infrastructure to observe itself, understand the significance of these observations, and adapt accordingly. As described in the ICON proposal, this is achieved by combining flexible physical-layer sensing, advanced data processing, a digital-twin-enabled contextualisation layer, and an intelligent control platform able to interpret application intent and respond to the information derived from the sensing system.

The intent-based paradigm enables sensing functions to be configured dynamically based on the information that is actually required — for example, increased vigilance during seabed operations, enhanced strain monitoring during storms, or rerouting during fibre intrusion events. In parallel, context awareness correlates heterogeneous data sources (distributed acoustic sensing (DAS), state of polarisation (SoP), telemetry, environmental feeds such as automatic identification system (AIS) or weather data) to create a unified operational picture, supporting both real-time control and long-term availability analysis.

Together, these principles allow optical networks to progress from passive transport systems to adaptive infrastructures capable of situational awareness, enhanced resilience, and improved spectral and operational efficiency.

Figure 1 explains the concept by presenting the physical infrastructure, telemetry- and sensing-enabled devices, and required processing layers in one figure.

The physical infrastructure component in the figure is composed of fibre optical cables, terrestrial housing facilities with power supplies, containers, and cabinets, subsea power supplies or (passive) amplification facilities, etc. The device layer consists of all the active telecommunication equipment - transceivers, terminal nodes and amplification nodes together with dedicated active probes for the telecommunication systems, and sensing equipment together with necessary splitters and combiners for the sensing devices. Typically, each of the active telemetry and sensing devices has a proprietary, vendor-specific software, but uses a standardised interface to extract telemetry and sensing data from the devices. Through these interfaces, software-defined networking (SDN) controller of the ICON network can send provisioning and configuration commands to the network elements and sensing devices and extract monitoring and sensing data from the devices.

On top of the SDN controller sits the ICON intelligent platform, consisting of intent translation, data processing and correlation, and quality of transport (QoT) aware probe routing function blocks. The data processing and correlation block includes four internal components – machine learning based analytics, context creation, data lake storage, and an information compression block. The ICON intelligent platform is responsible for sending probe activation and routing requests to the SDN controller, but also receiving inputs from sensing probes. Correlations between various internal monitoring and sensing data and external databases (weather, AIS, etc) enable extraction of valuable information, which can be used in various sensing-enabled applications, such as a notification app for proactive network operations, an availability assistant for long-term network availability and reliability estimations, etc.

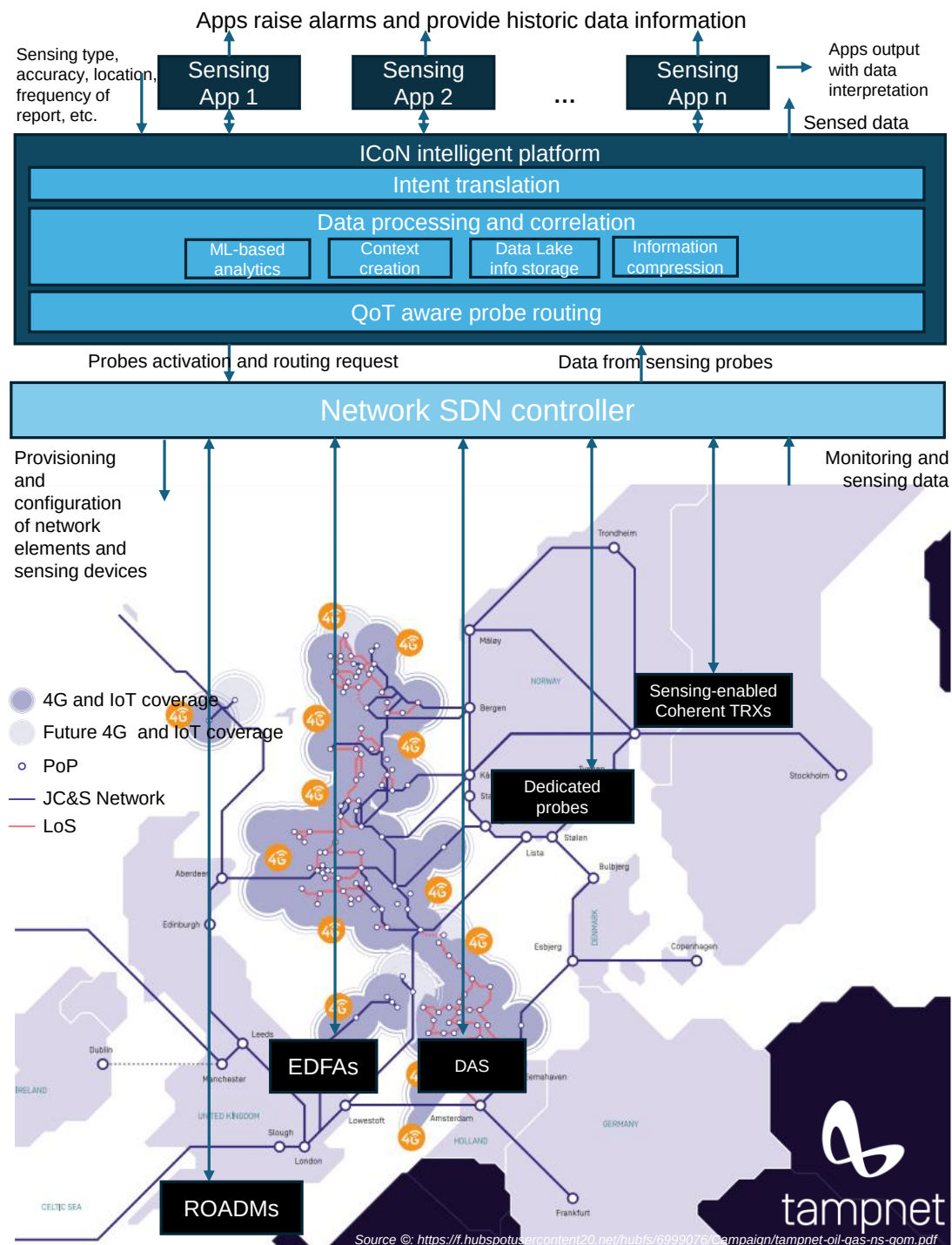


Figure 1: Underlying physical network infrastructure with telemetry and sensing-enabled devices and intent- and context-aware processing layers

1.2. Enabling components for ICON

The ICON architecture realises intent and context awareness through a coordinated set of components spanning the physical layer, digital processing, and control plane. The following paragraphs explain the enabling components in more detail.

1.2.1. Flexible physical-layer sensing technologies

ICON builds on a portfolio of adaptable sensing methods that can be configured dynamically to match the requirements of individual applications. Instead of relying on static sensing deployments, the network can activate, route, or combine sensing probes according to the operator's intent. This flexibility

is essential, given the highly varied conditions across subsea, terrestrial, aerial, and in-facility fibre infrastructures. The physical sensing options include advanced reflectometry, such as correlation-aided optical time domain reflectometry (OTDR), which distributes probe energy across coded sequences to improve range and resolution; time-expanded OTDR, which uses dual optical-frequency combs to achieve fine spatial resolution with relaxed electronic constraints; and coherent-receiver-based sensing, which extracts environmental information from built-in digital signal processing (DSP) and SoP tracking functions of communication transceivers. Optical probing and optical network tomography (ONT) extend these capabilities by sensing spectral properties, noise, polarisation behaviour, and dispersion across multi-span networks. As described in the proposal, these technologies allow ICON to observe both localised and large-scale disturbances while maintaining coexistence with high-capacity dense wavelength-division multiplexed (DWDM) channels.

1.2.2. Context creation through data processing and digital-twin modelling

To translate raw sensing outputs into actionable insight, ICON incorporates an extensive processing layer that reduces data volume, extracts salient features, and correlates heterogeneous information sources. Local pre-processing significantly decreases the data rate from the interrogators — from terabytes per week to gigabytes — enabling their transmission and long-term storage without overwhelming communication channels or cloud resources. At the network level, ICON fuses information from DAS, SoP, OTDR, ONT, coherent telemetry, and external feeds such as AIS vessel locations or weather data, creating a unified representation of the infrastructure's operational environment. Machine-learning models are developed to identify and classify events with high accuracy, while the digital twin models fibre behaviour, environmental coupling, and sensing-system performance under varying conditions. This contextual layer underpins real-time anomaly detection, availability estimation, and long-term reliability analysis across diverse network segments.

1.2.3. Intelligent intent-based control and orchestration of sensing probes

At the control and management layer, ICON introduces an intelligent platform capable of translating high-level requirements into optimised sensing configurations. Applications express intents, such as increased monitoring during critical operations, verification of suspected link degradation, or enhanced scrutiny of specific fibre spans. The controller interprets these intents and determines the most suitable sensing technologies, measurement parameters, and routing options. By leveraging reconfigurable optical add-drop multiplexers (ROADM) based wavelength switching, the platform can dynamically steer probes across the network, reuse sensing resources for multiple applications, and ensure that sensing operations coexist with data traffic without violating QoT constraints. Interfaces to SDN controllers and network management systems allow sensing insights to trigger operational actions, such as modulation adjustments, protective rerouting, or deployment of additional sensing probes on demand. This control layer is key to making sensing information directly usable for service provisioning, fault mitigation, and resilience enhancement.

1.2.4. Integration with existing optical infrastructures and operational environments

ICON is designed for seamless adoption within current telecom, energy, and subsea infrastructures, ensuring that sensing and communication functions can be combined over the same fibre assets without requiring disruptive changes. The architecture accommodates long subsea cables, aerial optical ground wire (OPGW) and all-dielectric self-supporting (ADSS) installations, metro-access networks, buried terrestrial routes, and node-room environments. In each case, the sensing capabilities are adapted to the physical conditions and operational risks — for example, detecting anchor drags and seismic activity in subsea systems, identifying wind-induced strain or lightning effects on aerial cables, or monitoring digging, construction, and in-facility activity in terrestrial networks. Because ICON supports both reflective and transmissive sensing approaches, and because the intelligent platform manages coexistence with DWDM traffic, the system can be incrementally deployed as operators expand their monitoring and availability-assessment capabilities. The integration approach ensures compatibility with ROADM-based architectures, coherent transmission systems, and existing operational control frameworks.

2. Integrated Communication and Sensing Environments and Use-cases

Fibre-optical cables form the backbone of global communications. In particular, subsea fibre-optic cables carry more than 97 % of transcontinental (intercontinental over oceans) Internet and data traffic¹. Because of their ubiquity and criticality, damage or interruptions to these cables can have widespread consequences, ranging from loss of connectivity, energy outages, financial transactions, cloud services, to national security risks.

In addition to communication applications, the energy sector relies heavily on these fibre networks. For instance, offshore oil and gas facilities require secure, high-capacity fibre links for monitoring, control, and data gathering; electrical grids and power plants (both onshore and offshore) use fibre for telemetry, as well as for protection and control. In many power infrastructures (overhead lines, subsea power cables, underground transmission), components such as OPGW² or ADSS³ cables integrate fibre-optics for communication and/or sensing purposes. Due to these dependencies, fibre communications infrastructure is classified as critical infrastructure in many jurisdictions.

A major cause of network failures and cable cuts is due to human activity⁴. Ensuring high availability implies protecting this infrastructure physically against impacts, whether human (trawling, anchoring, digging, vandalism) or environmental (storms, ice, earthquakes, seabed shifts).

2.1. Telecom Infrastructure availability and protection introduction

To ensure the availability of fibre networks that underpin modern communication and energy systems, telecom operators and infrastructure owners increasingly require capabilities that go beyond traditional fault detection. Conventional monitoring methods typically detect problems only after a failure has occurred, when a cable has already been cut, strained, flooded, or otherwise damaged. Fibre-sensing introduces a fundamentally more proactive approach by enabling continuous, real-time awareness of physical conditions acting on the cable itself. By using the fibre as a distributed sensor, operators can observe changes in the environment surrounding terrestrial and subsea cables, identifying early indicators of risk such as external mechanical impacts, ground movement, marine activity, or construction machinery operating near buried routes.

For subsea infrastructure, such real-time situational awareness can provide early warning of activities like anchoring or trawling that frequently lead to cable faults, allowing operators to initiate protective measures or issue alerts before damage occurs. On land, fibre-sensing enables monitoring of excavation, drilling, or heavy vehicle movement near ducts and rights-of-way, offering the opportunity to intervene while the threat is still developing. In both cases, the objective is not merely to detect failures faster but to prevent them altogether by identifying and responding to hazardous conditions, while the network is still fully operational.

This proactive monitoring capability directly contributes to higher network availability. By reducing the number of severe incidents and shortening response times, fibre-sensing supports more resilient service delivery across critical communication and energy systems. As network operators face increasing performance expectations and dependency from sectors, such as finance, cloud computing, and offshore energy production, the ability to safeguard fibre infrastructure before failures occur becomes essential. Real-time fibre-sensing thus strengthens the robustness of both terrestrial and subsea networks, helping operators maintain the continuity of services that societies and industries rely on every day.

¹ M. P. M. D. E. Georgia Bafoutsou, "Subsea cables - what is at stake?", ENISA, Luxembourg, 2023.

² Fibconet, "Full Guide of Optical Ground Wire," 22 11 2024. [Online]. Available: <https://fibconet.com/full-guide-of-optical-ground-wire/>. [Accessed 5 12 2025].

³ AFL, "All-Dielectric Self-Supporting (ADSS) Fibre Optic Cable," AFL, www.aflglobal.com/en/Products/Fibre-Optic-Cable/Aerial/ADSS.

⁴ M. P. M. D. E. Georgia Bafoutsou, "Subsea cables - what is at stake?", ENISA, Luxembourg, 2023.

The seamless integration of fibre sensing in data-carrying fibre networks is of high interest to enable simultaneous data transmission and sensing in the same fibre. This allows to use of the existing large-scale fibre network with more than 8 Terameters⁽⁰⁶⁾ being deployed worldwide as a sensor for various applications. The integration can be achieved by using a separate wavelength for sensing. It needs to be ensured that the sensing signal does not impair the quality of transmission, and in turn that the sensing quality is not impacted by the data signals. In particular, non-linear signal interactions between the sensing and data signal need to be considered. Factors like the nature of the sensing signal (bursty or constant power signal), the used wavelength channel and the power characteristics and transients need to be considered.

Fibre sensing enables telecommunications network owners/operators to detect anomalies that pose a risk to their network infrastructure. In contrast to fibre monitoring, which enables the detection of damage (e.g. fibre cut) only after it occurs, fibre sensing enables the identification of critical events beforehand and gives a certain time window to take action before damage occurs. In addition, not only the fibre network itself but also other critical infrastructure that is often deployed next to fibre cables, such as power cables, water, gas, and oil pipes, can additionally be monitored.

2.2. Non-telecom critical infrastructure availability and protection introduction

Utility companies responsible for power transmission, water distribution, and oil and gas pipelines depend on extensive physical networks that must operate reliably under constantly changing environmental and mechanical conditions. Ensuring the availability of these critical systems traditionally relies on fault detection methods that react only once an outage, leak, break, or hazardous condition has already occurred. However, as infrastructures expand, face more extreme weather, and operate under tighter safety and regulatory constraints, this reactive approach is no longer sufficient. Fibre-sensing provides a transformative alternative by enabling continuous, real-time insight into the physical state of utility assets and their surroundings.

By integrating fibre-optic cables into power lines, buried ducts, subsea connections, or co-routed pipeline communication channels, utilities can monitor external impacts, environmental loads, and structural changes before they escalate into failures. For electrical transmission networks, this includes early recognition of conditions such as conductor galloping during storms, icing loads on aerial lines, lightning-induced disturbances, or mechanical shocks from short circuits and switching events. For water and wastewater infrastructure, fibre-sensing can reveal ground movement, flooding, or heavy machinery operating near buried conduits, signals that may precede pipe deformation, washouts, or service interruptions. In oil and gas networks, real-time awareness of external activity, pressure-induced strain, or third-party interference helps operators identify risks such as excavation near pipelines, mechanical impacts, or environmental changes affecting pipeline stability.

Across both terrestrial and subsea segments, this continuous monitoring enhances situational awareness during events that are traditionally hard to detect: storms affecting power lines, underwater disturbances near subsea cables or pipes, shifting soil threatening underground assets, or abnormal vibrations preceding faults. Instead of discovering damage only after an outage or leak, operators gain the ability to intervene when the first signs of hazardous conditions appear.

The result is a significant increase in infrastructure availability and resilience. By enabling early warning, reducing the severity of failures, and improving response times, fibre-sensing helps utilities maintain safe and reliable operation of energy and water networks that societies depend on. As climate change intensifies weather events and as regulatory and operational pressures grow, proactive fibre-based monitoring becomes a critical capability, supporting not only the continuity of essential services but also the protection of people, environments, and high-value assets.

2.3. Fibre sensing use-case examples

This section describes various applications of the ISAC concept within the subsea, terrestrial and aerial fibre deployment.

2.3.1. Subsea Fibre Deployments

Eavesdropping and Tampering Detection

Physical interference with subsea cables, such as bending, tapping attempts, or external handling, creates localised disturbances that can be detected and located along the cable route, enabling rapid identification of intrusion attempts.

Trawl and Anchor Drag Detection

Fishing trawls and vessel anchors impart strong mechanical forces when dragged across seabed cable routes. These impacts generate characteristic strain signatures, allowing early warning and intervention before faults occur.

Subsea Landslides and Seabed Instability

Slope failures and submarine landslides produce measurable strain waves along the fibre. Continuous observation supports early detection of hazardous seabed movement and improves understanding of geohazard processes.

Ocean Currents, Tides, and Large-Scale Ocean Dynamics

Slow, low-frequency loading of cables caused by tides, currents, and other oceanographic processes can be observed over long distances. Continuous sensing provides valuable environmental insight complementary to traditional ocean monitoring systems.

Marine Mammal Activity and Biological Monitoring

Acoustic and mechanical signals associated with marine life, such as whale vocalisations, can be detected along the length of subsea fibres, enabling large-scale passive monitoring without deploying additional sensors.

General Cable Movement and Environmental Forcing

External forces from storms, gravity waves, or shifting sediments produce distributed strain or vibration patterns that reflect cable motion, supporting both operational awareness and environmental monitoring.

2.3.2. Terrestrial Fibre Deployments

Detection of Digging and Construction Activity

Excavation, drilling, and heavy machinery near buried cables produce distinctive mechanical signatures. These disturbances can be detected early, helping operators prevent accidental cuts.

Node-Room and Manhole Activity Monitoring

Handling of fibres and equipment inside node rooms, handholes, and manholes leads to identifiable disturbances, enabling operators to differentiate between authorised maintenance and potential unauthorised access or vandalism.

Seismic and Earthquake Detection

Ground motion from earthquakes generates strain variations along terrestrial fibres. These signals can supplement traditional seismic networks and provide dense coverage in urban or infrastructure-rich areas.

Landslide and Ground Instability Monitoring

Slope movement produces transient or sustained strain along cables. Detecting these patterns supports early-warning efforts in landslide-prone regions.

Traffic and Transportation Monitoring

Vehicle and train movements induce characteristic vibration signatures. These can be used for continuous monitoring of traffic flow, rail operations, axle loads, speeds, and infrastructure condition.

Road Work and Heavy Vehicle Detection

Construction near roads or cable routes creates strong, localised mechanical activity. Early detection helps protect buried fibre infrastructure from accidental damage.

2.3.3. Aerial Fibre Deployments – Use-Case Examples

Wind-Induced Conductor and Cable Motion

Aerial fibres, including those integrated into power-line ground wires, undergo strain fluctuations from wind-driven sway. Monitoring these variations supports assessment of line stability and mechanical loading.

Lightning and Electrical Disturbances

Lightning strikes and fault currents create impulsive mechanical and electromechanical effects that travel along aerial cables, enabling rapid disturbance and fault localisation.

Short-Circuit and Power System Events

Electrical faults induce thermo-mechanical responses in cables. Detecting these responses provides immediate awareness of power-system events affecting overhead fibre installations.

Icing and Weather-Related Loading

Ice accumulation changes the mechanical loading of aerial cables, producing detectable patterns of strain. Continuous monitoring helps identify icing hazards and supports operational decision-making during severe weather.

Storms and Environmental Stressors

Windstorms, conductor galloping, and other meteorological forces impart dynamic loads on aerial fibre deployments. Monitoring these effects improves situational awareness and supports maintenance planning.

2.4. Main use-cases

Fibre-optical networks underpin critical communication and utility infrastructures, serving both telecom network operators/Internet service providers (ISPs) and infrastructure owners. Ensuring the resilience and availability of these networks requires moving beyond reactive fault detection to proactive, context-aware monitoring and management. Three primary use cases have been identified, each addressing distinct operational needs and leveraging advanced fibre sensing technologies.

1. Proactive Protection of Physical Infrastructure (Real-time)

This use case focuses on the early detection and prevention of fibre issues, such as potential harmful impacts, degradation and impending faults, through continuous, real-time monitoring. By integrating, e.g. DAS and SoP monitoring, operators can detect and localise events like trawling, digging, anchor drags, and environmental loads (e.g., currents, ice, earthquakes) before they escalate into service-impacting incidents. Key user requirements include:

Rapid response: The system must specify and meet acceptable response times, ensuring detection occurs sufficiently ahead of potential damage to enable intervention.

Comprehensive sensing: Monitoring may cover multiple parameters: signal performance, OTDR/attenuation indicators, back-reflected signal's phase changes, SoP changes, and other relevant parameters.

Event classification and risk evaluation: Automated algorithms should distinguish between benign and hazardous events, assess their seriousness, and quantify uncertainties in location and severity.

Actionable outputs: The system should trigger immediate alerts, support preventive maintenance scheduling, and integrate with Network Operation Centres (NOCs) for coordinated response and trend analysis

This proactive approach is essential for minimising downtime, reducing repair costs, and safeguarding critical services across both terrestrial and subsea infrastructures.

2. Availability Map (Non-real-time, Long-term Analysis)

The availability map use case supports network operators in identifying stable versus risk-prone routes, planning maintenance, and reacting to emerging risks. Unlike real-time protection, this use case emphasises long-term data collection and analysis, combining sensing data, telemetry, and data-lake resources with visual interfaces. Key aspects include:

Comprehensive parameter mapping: The map may incorporate frequency, type, intensity, and position of detected events (e.g., digging, trawling, node-room work), as well as environmental threats (earthquakes, landslides, storms, ice).

Risk modelling: Historical and real-time data are used to assign failure probabilities to cable sections, enabling probabilistic risk assessment and supporting redundancy planning and investment decisions.

User requirements: The system defines which parameters are sensed and visualised and supports the development of an “availability assistant” application for operational decision-making.

Operational impact: Availability maps inform where to inspect, reinforce, or reroute infrastructure, aid regulatory reporting, and underpin cost-benefit analyses of protection measures.

3. Environmental Sensing & Infrastructure Monitoring

This use case extends fibre sensing to the detection of environmental factors and infrastructure health, serving utilities and infrastructure owners as distinct users from telecom operators. The system can detect and report:

Environmental events: Icing, power failures, lightning strikes, vibrations, and external interference affecting aerial, terrestrial, and subsea assets.

Infrastructure status: Continuous monitoring supports early warning of hazardous conditions, such as conductor galloping, short circuits, ground movement, and unauthorised access.

User requirements: The sensing solution may be adaptable to diverse environments, provide actionable insights for maintenance and emergency response, and ensure data security and privacy.

By integrating these capabilities, infrastructure owners can enhance resilience, reduce the severity of failures, and maintain reliable operation of essential services.

2.5. Use-cases to be demonstrated

Within ICON, two use cases will be demonstrated: optical network infrastructure protection and the availability map.

A key use case to be demonstrated involves the integration of fibre-based environmental sensing into optical networks to proactively detect and mitigate potential physical layer failures. In this scenario, a lab emulated environment simulates various forms of external mechanical and environmental stresses, such as ground vibration and movement, aerial vibrations, or temperature anomalies, along the optical fibre path. These signals are acquired using distributed sensing technologies (e.g., Brillouin or Rayleigh-based methods, as well as measurements based on SoP) and processed to extract meaningful indicators of risk, such as increasing strain trends or sudden vibration anomalies that may signify early stages of degradation or an imminent fault.

The demonstration will highlight how this contextual physical insight can be used to feed intent-based control systems that reconfigure the network in anticipation of events that could impact ongoing services. Specifically, the system will evaluate the sensing data to classify the severity and temporal characteristics of the anomaly (slow degradation vs. sudden impact), estimate the risk of optical link failure, and determine the appropriate mitigation action. One such action is the proactive rerouting of wavelength channels over alternative paths, ensuring service continuity while reducing the likelihood of transmission disruption due to fibre failure. Another key aspect of such advanced warning is that the system can carry out QoT measurements and estimation before activating the channel reroute.

This use case covers both real-time and non-real-time scenarios. Real-time responsiveness enables intervention during fast-evolving risks (e.g., excavation near buried fibres), while historical data analysis supports long-term asset health modelling and failure probability estimation. The integration of sensing with intelligent orchestration showcases the potential of context-aware networks to enhance resilience, minimise downtime, and optimise spectral efficiency.

The ICON project will also demonstrate an Availability Assistant (AA) application, extracting data from the central data lake and presenting analysed information as link- and network-level reliability indicators. The demonstration will focus on extended test cases, notably the Elering trial in Estonia (Nov 2025–Feb 2026) and trials over the complete project period using several links in Tampnet's network, showcasing how sensing-driven insights translate into actionable availability metrics. The AA will provide operators with intuitive dashboards, enabling proactive maintenance and rapid response to emerging risks.

A detailed description of the use cases to be demonstrated within ICON will be included in deliverable D6.1 due in M15.

3. Description of Physical Sensing Technologies

3.1. Overview of sensing technologies

ICON builds upon a diverse set of physical-layer sensing technologies that enable the monitoring of environmental conditions, structural integrity, and fibre health across subsea, aerial, metro, and in-facility infrastructures. These sensing methods represent both mature technologies used today in operational networks and novel platforms developed within ICON and in earlier projects such as ECO-enET⁵. To support the multi-environment use cases and the data-driven availability insights targeted in WP2, each sensing device offers distinct capabilities in terms of spatial resolution, measurement range, sensitivity, power requirements, and coexistence with DWDM traffic.

Available sensing devices are grouped into two primary categories, the backreflection and forward type of sensing and their characteristics and capabilities are described in the following sections.

The meaning of the keywords in the tables below is as follows:

Principle: General overview of the principle of the technology, e.g. does it sense polarisation or phase, or indirectly phase, what physical effect is detected, e.g., mechanical vibration, electromagnetic fields.

Application: the type of application this technology can be used for. This is dependent on the detected effects as well as the range of frequencies that can be sensed (various events such as passing trawlers, gravity waves, wind, earthquakes, and electric discharges are characterised by their own frequencies).

Integration: How can this be embedded in the telecom networks/integration/standards / bidirectional (e.g. forward/backward sensing, bidirectional (loop), unidirectional dark fibre, wavelength, live wavelength with data, wavelength band).

Range: in km of fibre, what length of fibre can be covered/sensed, does the technology work through repeaters/ optical amplifiers

Spatial resolution: is the received sensing signal integrated over the whole length of the fibre (as in the case of SoP) or can the effects of different fibre segments be separated/devised from the detected signal (e.g. gauge length and the channels in DAS).

Sensitivity: defined with respect to use case, e.g. distance to an object that can be detected, like e.g. surface vessel.

Equipment type: dedicated equipment or probes vs. extracting data from telecom equipment (e.g. coherent receiver for SoP)

Storage needs: Used capacity/generated data (amount of data generated per day).

Data format: including the metadata (e.g. FLAC, Hierarchical Data Format version 5 (HDF5))

Processing type: local processing/centralised processing (e.g. the raw data is directly transferred to a central location, vs. local storage and transfer of processed data (similar to transfer of DAS waterfall diagrams).

Use-cases in ICON: which use-cases or part of use-case from our selected final use-cases are served by the technology (e.g. SoP sensing detects movements of fibres, but not approaching trawlers, hence partly supporting both real-time proactive sensing and the availability map).

3.2. Forward-type of Sensing Specifications and Capabilities

Forward-type sensing is an advanced distributed fibre-optic sensing technique that analyses light properties (like polarisation, phase) travelling *forward* through a fibre.

3.2.1. Transceiver and Open Line System telemetry data

Topic	Description
Principle	Changes in the network traffic, configurations, external environment, etc., can impact network performance. This is reflected in the telemetry data. The data can present hop-by-hop changes when collected from Open Line System (OLS) devices, or end-to-end changes when collected from the transceivers.
Application	End-to-end network performance monitoring
Integration	Wavelength, traffic wavelength
Range	Up to thousands of kilometres

⁵ <https://www.eco-enet.eu/>

Spatial res.	Hop length for OLS devices, integrated measurement along the complete measured service for transceivers.
Sensitivity	Poor for environmental changes, high for configurational changes inside the networks
Equipment	Standard telecom equipment
Storage	External databases required for collection with a minimum collection interval
Data format	.csv
Processing	Centralized
Use-cases	Availability Assistant, proactive protection

3.2.2. SoP

3.2.2.1 Dedicated SoP systems

Topic	Description
Principle	Detects changes in SoP at the receiver side due to changes in fibre birefringence. Caused by e.g. strain changes in the fibre.
Application	Detection of fibre movements, lightning strokes, temperature, gravity waves, wind
Integration	Dark fibre, wavelength, traffic wavelength
Range	Limited by channel optical SNR
Spatial res.	Integrated measurement along the complete measured fibre.
Sensitivity	Low sensitivity to local perturbations on the fibre, vibrations accumulated along the fibre can be sensed, moderate sensitivity to e.g. gravity waves and earthquakes.
Equipment	Dedicated probes or extraction from telecom equipment coherent receivers.
Storage	Depends on resolution, sampling rate and parameters monitored. Typical example: 7 GB/day for lossless compression of 16-bit/44.1 kHz. Data for S0 and S1 parameters.
Data format	FLAC, HDF5.
Processing	Local and/or centralised
Use-cases	Detection of fibre movement in real-time sensing. For the availability map: detection of and statistics of installation instabilities, as well as work in manholes and node-rooms.

3.2.2.2 SoP measurements using telecom transceivers

Topic	Description
Principle	Changes in birefringence, e.g. due to fibre bending, lead to changes in SoP. They can be extracted from the receiver DSP in coherent transmission systems. Stokes parameters can be extracted from the butterfly equaliser coefficients.
Application	Detection of fibre movements, lightning strokes, temperature, gravity waves, wind
Integration	SoP monitoring can be added to coherent receivers of live links
Range	In principle, thousands of kilometres in long-haul multi-span links. Usability for very long links limited since SoP changes accumulate over fibre distance.
Spatial res.	Measurement of accumulated changes over the complete link
Sensitivity	Low sensitivity to local perturbations on the fibre, vibrations accumulated along the fibre can be sensed, moderate sensitivity to e.g. gravity waves and earthquakes.
Equipment	Coherent telecom transceivers
Storage	Depends on sampling rate, quantisation and number of stored parameters: Example: 1 kSps, 2 Byte per Stokes parameter, normalised S1, S2 and S3 monitored, ~5 GB/month

Data format	HDF5, csv.
Processing	Local
Use-cases	Detection of fibre movement in real-time sensing. For the availability map: Detection of and statistics of installation instabilities, as well as work in manholes and node-rooms.

3.2.3. Non-disruptive tomography

Topic	Description
Principle	Typical approaches to evaluate the wavelength-dependent performance of DWDM optical components consist of using transceivers or OTDRs that interrogate the open spectrum in line systems. However, these approaches — unless they are applied out of band and bypass amplifiers and other components — disrupt the current network state by introducing probing signals that interfere with data-bearing channels. On the other hand, nondisruptive probing methods enable online probing of the spectrum, including wavelength-dependent gain and ASE noise, without interfering with other signals ⁶ .
	Power excursions provoked by automatic gain control (AGC) algorithms in Erbium-doped fibre amplifiers (EDFAs) are one of the most critical causes of disruptions. Namely, a change in input wavelength configuration into an EDFA can affect the channel gains through wavelength-dependent gain and hole-burning effects ⁷ . The proposed nondisruptive tomograph is a probing subsystem that monitors the channel power, OSNR and end-to-end link gain as well as the passband of inactive channels during network operation without affecting active channels. Note that the <i>non-disruptive</i> measurements can be performed by using a pulsed probe, with a duration much shorter than an EDFA AGC's response time (on the order of tens of microseconds), ensuring that the probing does not cause power excursions. Additionally, depending on the application, single-source input (tunable laser) and multisource (optical frequency comb) inputs can be employed. The device is tunable over the whole C band and potentially may be easily extended to the C+L bands.
Application	Monitor the channel power, the optical SNR and end-to-end lightpath gain of inactive channels during network operation without affecting active channels. Other applications are to be determined.
Integration	Dark fibre, wavelength, bidirectional
Range	To be determined
Spatial res.	N/A
Sensitivity	To be determined
Equipment	Dedicated low-cost low-complexity probing subsystem (equipped with transmitter and receiver blocks).
Storage	To be determined (depends on the telemetry sampling rate and parameters monitored).
Data format	.csv, .json
Processing	Local and/or centralised
Use-cases	Real-time telemetry for QoT monitoring. For the availability map: detecting variations of the received power, optical SNR and end-to-end lightpath gain on the inactive channels in an optical link. QoT estimation for lightpath provisioning.
Comments	The research and development on this device is currently in progress, and the actual applications and capabilities will be determined during the next year of the project.

⁶ W. Mo, et al, " Proactive and Nondisruptive Channel Probing for Wavelength Switching in Optical Transmission," in IEEE Photonics Journal, Vol. 9, No. 6, pp. 1943-0655, (2017).

⁷ A.S. Ahsan, et al., "Excursion-Free Dynamic Wavelength Switching in Amplified Optical Networks," J. Opt. Commun. Netw. 7, 898-905, (2015).

3.2.4. Dual Comb sensing

Topic	Description
Principle	Dual electro-optic frequency combs generate two broadband, evenly spaced optical spectra with a slight difference in repetition rate. When dual comb interrogates the fibre, changes in the fibre, such as strain, vibration, temperature, or faults, modify the phase and intensity of each comb line through dispersion and propagation effects. Beating the two combs on a simple photodetector maps the optical changes into a low-frequency radiofrequency (RF) spectrum, enabling single-shot measurement of the fibre's spectral phase response. From this, disturbances and faults can be precisely localised without requiring complex receiver circuitry.
Application	Detection of events like environmental vibrations, cable disturbances, and fault detection. Real time monitoring of critical network infrastructure, fibre Bragg grating (FBG) based interrogation for temperature, stress and strain measurements. Lightpath passband characterisation.
Integration	Operates on standard telecom single-mode fibres, compatible with dark fibre, C/L-band wavelength. Supports forward/backward sensing.
Range	Typically, short ranges, limited by the power of the optical signal, especially in the case of a backward type of sensing, but can be operated over longer distances with inline optical amplifiers.
Spatial res.	Very high resolution is possible, depending on the comb spacing and is tunable.
Sensitivity	To be determined
Equipment	Standard telecom equipment and low low-bandwidth receiver
Storage	To be determined (depends on sampling rate and parameters monitored).
Data format	To be determined
Processing	Predominantly local due to low-bandwidth signals to be processed.
Use-cases	Telemetry for QoT monitoring, QoT estimation for lightpath provisioning, fault detection and real-time network monitoring, temperature, stress and strain measurements.
Comments	The work is in progress, and actual capabilities will be determined during the next year of the project.

3.3. Backward-type Sensing Specifications and Capabilities

Backward-type sensing technology is the most commonly used technique, which transforms an entire standard optical fibre into a continuous sensor. It works by sending a light signal down the fibre and analysing the small amount of light that is scattered back to the source (backscatter).

3.3.1. Direct Detect OTDR

Topic	Description
Principle	A series of pulses is sent into a fibre, and based on the time of flight of the Rayleigh backscattering, the returned power versus fibre length is measured
Application	Fibre link integrity monitoring. Localisation of defects to reduce downtime when repairs are required.
Integration	Integration using wavelength multiplexing. Standard OTDR use 1650 nm
Range	160 km unidirectional, 320 km bidirectional
Spatial res.	Depends on sensing range (pulse duration)
Sensitivity	39 dB dynamic range of the module
Equipment	Commercial OTDR product (Adtran ALM) or others
Storage	Local storage
Data format	CSV file
Processing	On-device processing
Use-cases	Fibre integrity monitoring, fibre cut localisation, fibre tap detection and localisation, loss anomaly detection, PON branch fibre cut detection

3.3.2. C-OTDR/DAS

Topic	Description
Principle	Senses changes in phase and intensity caused by changes in temperature or strain.
Application	Temperature measurement, detection of people and vehicle movement, eavesdropping, detection of earthquakes, wind, and rain. Frequencies up to 25 kHz can be detected.
Integration	Integration into telecommunications networks can be achieved using dark fibres or unused wavelengths (e.g., DWDM).
Range	~100 km without repeaters, thousands (PD ECOC) of km in experiment with repeaters using HLLB.
Spatial res.	The fibre is split into segments. The spatial resolution is from 1.3 m to 38.9 m. The gauge length is from 4.1 m to 34.7 m.
Sensitivity	Typical sensitivity is $-60 \text{ dB rad}/\sqrt{\text{Hz}}$. The distance to an object that can be detected depends on the magnitude of vibrations caused by this object.
Equipment	Dedicated equipment.
Storage	The amount of data generated per day depends on the repetition frequency and the number of channels captured. For example, when capturing phase data from 15 channels at a repetition frequency of 10 kHz, the system can generate approximately 18.5 GB of data per day.
Data format	Data can be stored in HDF5 or CBT format.
Processing	Local storage and transfer of raw or processed data.
Use-cases	Temperature measurement and detection of people and vehicle movement in real-time.

3.3.3. Raman-IOFDR

Topic	Description
Principle	Senses changes in intensity of Raman scattering caused by changes in temperature.
Application	Temperature measurement
Integration	Integration into telecommunications networks can be achieved using dark fibres
Range	The range is up to 5km
Spatial res.	In theory, a spatial resolution of 0.05m can be chosen; in normal use, it is set to 0.5-3m, depending on the modulation parameters
Sensitivity	Highly dependent on fibre type and length, usually 1K - 4K
Equipment	Dedicated equipment, lab demonstrator
Storage	100MB/day
Data format	HDF5
Processing	Raw data is transferred to a central location and processed offline
Use-cases	Not applicable to selected final use-cases

3.3.4. Brillouin-OTDR

Topic	Description
Principle	Measuring Brillouin frequency shift along the fibre link using the OTDR principle. Brillouin frequency shift depends on fibre properties: temperature and strain
Application	Strain and temperature measurement on a long timescale in the order of minutes

Integration	Integration on a separate wavelength in counter-directional propagation with respect to the data signal in a live link, compare ITU-T G.681
Range	60 km @ 0.25 dB/km
Spatial res.	Depends on the probing pulse width
Sensitivity	Highly sensitive to strain and temperature, strain: ~500 MHz/% and temperature: ~1.1 MHz/K
Equipment	B-OTDR interrogator, wavelength add-drop multiplexer
Storage	External network storage required
Data format	Custom data format
Processing	Local preprocessing and visualisation
Use-cases	Distributed strain and temperature measurements, Strain measurement of different cable sections

3.4. Mapping the sensing technologies to the sensing-use cases

3.4.1. Infrastructure owner/operator requirements

Infrastructure owners and telecom operators require precise, actionable sensing capabilities to maintain high network availability and prevent service-impacting incidents. These requirements span real-time detection, timely notification, and long-term reliability analysis.

Detection Timelines and Notification Needs

Different threats demand different response windows. For high-risk events such as trawling or anchor dragging near subsea cables, the system must detect and notify operators with sufficient lead time—typically 10 minutes before the vessel reaches the cable—to allow intervention or alerting maritime authorities. Similar urgency applies to excavation near terrestrial routes, where early detection enables preventive measures before fibre damage occurs.

Conversely, slower-developing conditions such as icing on aerial cables or wind-induced conductor galloping require continuous monitoring but allow longer response intervals (hours, days). Here, notifications focus on trend analysis and maintenance scheduling rather than immediate action. Node-room or manhole activity, while less time-critical, still requires timely alerts within minutes to distinguish authorised work from potential intrusion or vandalism. These differentiated timelines underscore the need for adaptive sensing strategies that align detection speed with event severity.

Availability Map Inputs and Reliability Metrics

Beyond real-time protection, operators need tools for long-term risk assessment. Availability maps must integrate data on activities that could degrade fibre integrity or increase attenuation, including:

- Frequency and intensity of trawling events, anchor drags, and excavation signals.
- Environmental stressors such as wind, icing, and seismic activity.
- Operational disturbances like node-room handling or heavy vehicle movement.

This aggregated data feeds into reliability models that compute Failures in Time (FIT), Mean Time Between Failures (MTBF), and Mean Time to Repair (MTTR) for individual links and network segments. These metrics enable informed decisions on redundancy planning, maintenance prioritisation, and investment in protective measures. Availability maps also support regulatory reporting and cost-benefit analysis, ensuring compliance and operational transparency.

These requirements collectively ensure that infrastructure owners and operators can safeguard critical fibre assets, maintain service continuity, and optimise operational resilience in increasingly complex and risk-prone environments.

3.4.2. Proactive Protection instrumentation needs

Proactive protection requires **real-time, high-sensitivity instrumentation** capable of detecting fast-developing threats such as trawling, anchor drag, digging, lightning-induced disturbances, conductor galloping, and node-room intrusion. This demand sensing technologies that operate directly on the live fibre, **DAS, SoP, OTDR, and transceiver telemetry**—each contributing with complementary strengths. DAS provides high spatial resolution and segment-level vibration awareness needed for early warning

of approaching machinery or marine activity, while SoP offers continuous whole-link monitoring of strain, lightning strokes, and environmental changes with minimal hardware overhead. OTDR (direct-detect) enables immediate localisation of integrity anomalies such as bends, taps, or sudden attenuation increases, and is especially valuable when actionable precision within metres is required. Telemetry from transceivers and OLS equipment supplies hop-level performance deviations that support early detection of impairments even when environmental sensitivity is low. To support real-time response windows—from seconds to minutes—the instrumentation must allow **coexistence with DWDM traffic**, operate over ranges from short metro spans to thousand-kilometre subsea links, and provide local edge processing with short-term storage (e.g., two-week rolling buffers). The combined instrumentation ensures operators can detect, classify, and act on threats *before* they evolve into service-impacting incidents. The sensing technologies and properties are summarised in the table below.

Topic	Description
Principle	Using the existing fibre-cable without modifications as the sensing element.
Application	Proactive Real-time detection of potential cable damage
Integration	Priority: 1) Combined with the data signal. 2) Separate wavelength, 3) L-band, 4) Dark-fibre.
Range	Zero to Thousands of km.
Spatial res.	Approx. ~10 m.
Sensitivity	Detection of trawl 2 km from cable, cable movement and added attenuation
Equipment	SoP, DAS, OTDR
Storage	Two weeks rollover? Critical events: 5 years, Maximum two rack units local on-site.
Data format	Non-proprietary standardised format
Processing	Maximum two rack units local on-site.
Sensing technologies	SoP, DAS, OTDR

3.4.3. Availability Assistant/Availability Map instrumentation needs

The Availability Assistant requires **comprehensive**, long-term telemetry and sensing data to quantify link-level and network-wide reliability, feeding models that compute FIT, MTBF, MTTR, attenuation trends, and environmental stress patterns. Unlike real-time protection, the focus here is on aggregation from diverse data sources. The technologies OLS and transceiver telemetry, SoP, OTDR (direct-detect, C-OTDR, B-OTDR), DAS, non-disruptive probing, and dual-comb interrogators will be combined for revealing slow-evolving risks such as recurring trawling activity, seasonal icing, cumulative strain, installation instability, or repeated node-room handling. Because each technology differs in spatial resolution, measurement range, and sensitivity, their combined dataset enables a multi-layered view: SoP gives link-integrated environmental variability; OTDR and B-OTDR provide precise attenuation, strain, and temperature evolution; DAS adds statistics on vibrational patterns and external activity frequency; telemetry exposes performance drift and configuration-induced impairments; and dual-comb or non-disruptive probing offers spectral integrity insights over time. These heterogeneous data streams are collected into centralised storage in standardised or technology-specific formats (HDF5, FLAC, CSV), processed centrally, and visualised in the Availability Assistant as availability maps and recommended protection paths. The instrumentation, therefore, prioritises coverage, continuity, and long-term data integrity over immediacy, enabling utilities and telecom operators to understand structural risks, optimise maintenance, and plan resilient network architectures based on empirical, sensor-driven reliability metrics. The sensing technologies and properties are summarised in the table below.

Topic	Description
Principle	Centralised analyses of collected telemetry and sensing data enable the creation of an overview of the network-wide availability and reliability, distinguishing links with lower availability and giving suggestions for protection path implementations.
Application	Long-term availability and reliability calculations. Presentation of the data.

Integration	
Range	All telemetry- and sensing-enabled links across the network
Spatial res.	Depending on the used sensing technology installed on the link
Sensitivity	Depending on the used sensing technology installed on the link
Equipment	
Storage	Central storage
Data format	Depending on the used sensing technology installed on the link
Processing	Central processing
Sensing technologies	All sensing technologies explored in ICON: OLS and transceiver telemetry, SoP, OTDR, DAS, B-OTDR

4. Handling of the Collected Telemetry and Sensing Data

The handling of the experimental data gathered from lab tests and testbeds owned by academic institutions, as well as from field trials, is described in ICON Deliverable D1.1 Data Management Plan. As a result, the sharing and dissemination of the data can vary significantly depending on its origin.

The method of presenting and sharing the sensing data for use in telecommunication and non-telecommunication related use-cases will be investigated in Task 2.3. This includes the collection, transportation, storage, and sharing/representation of the collected data. The preliminary workflow showing the blocks of data collection, transmission, storage, and sharing is presented on Figure . This workflow can change during the project timeframe, to reflect the changes in the sensing technologies, changing legal restrictions or requirements, or to reflect the possible automation of data collection, aimed at achieving uniform appearance and structure of the collected internal or sourced external data.

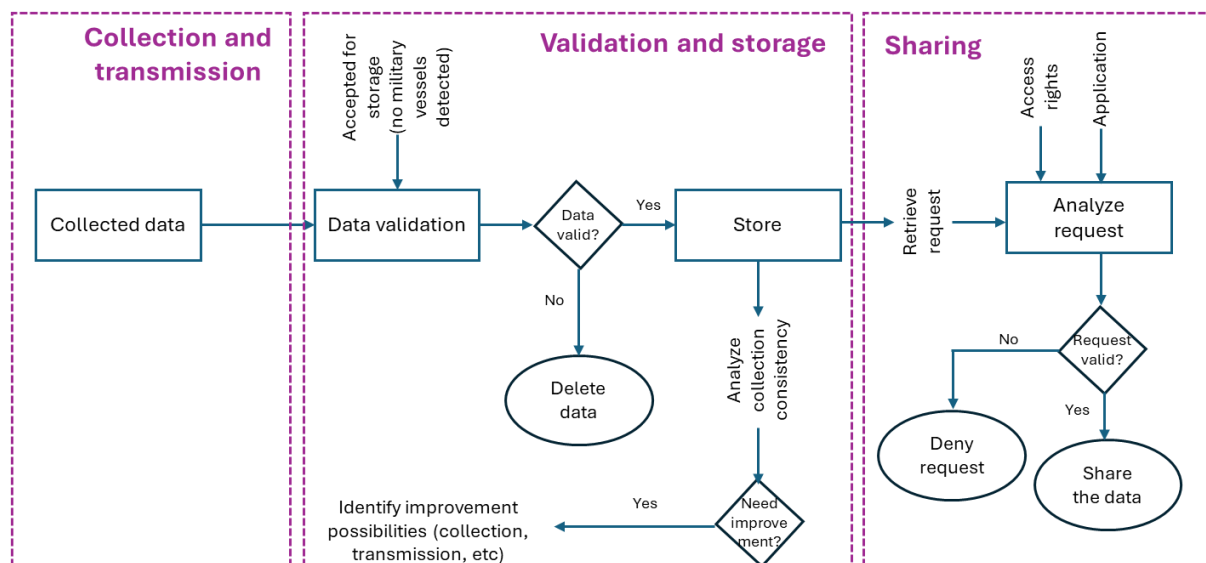


Figure 2: Data management workflow

In order to provide reliable access to collected telemetry and sensing data, ICON uses the Telemetry/Sensing as a Service concept to collect, transport, store and share/represent the data. The conceptual block diagram showcasing the end-to-end service layer, physical OLS domains including both physical fibre infrastructure and OLS devices, and T/SaaS layer is presented in Figure .

The physical aspects, such as the data collection, transport, and storage of the platform, are investigated in Task 2.3, while the sharing and representation are investigated in Task 5.3.

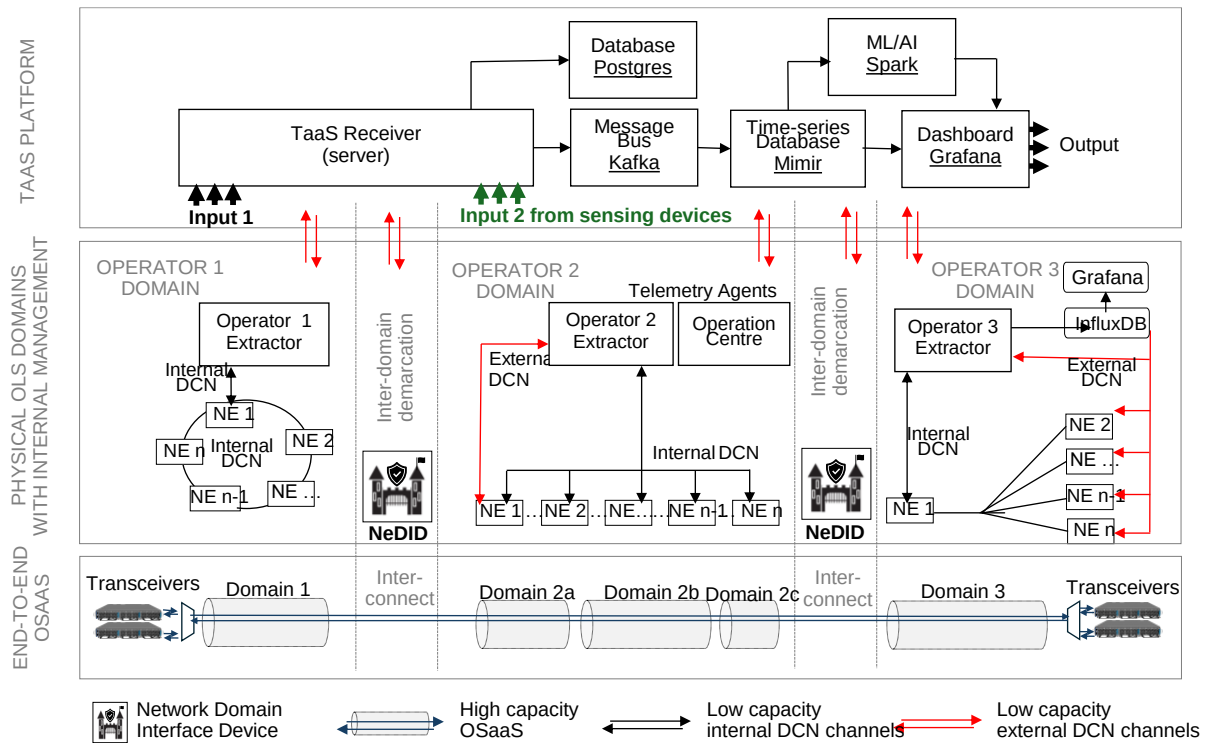


Figure 3: Telemetry/Sensing as a Service platform proposal

5. Conclusions

The ICON project aims at laying the groundwork for demonstrating how advanced physical sensing can be integrated into optical communication networks to address critical operational and environmental challenges. This document discusses sensing-enabled use-cases—such as detecting trawling events, anchor drags, and environmental stressors—that will enhance network resilience and operational awareness.

Expected Impact and Ambition:

By embedding sensing capabilities into existing infrastructure, the project aims to deliver a paradigm shift from reactive to proactive network management. This ambition extends beyond technical robustness to strategic benefits, including improved reliability metrics (FIT, MTBF, MTTR), reduced downtime, and enhanced compliance with environmental and safety regulations. Ultimately, the project aspires to position sensing as a cornerstone for future-proof, context-aware networks that support both industry and societal needs.

Perspectives and Next Steps:

To realise this vision, further work is needed to refine sensing algorithms, validate performance under diverse real-world conditions, and develop intuitive operational tools such as the Availability Assistant. Expanding collaboration with stakeholders and exploring cross-domain applications—such as environmental monitoring and early-warning systems—will be essential to maximise impact. Continued research and pilot deployments will ensure that the project not only demonstrates feasibility but also sets the stage for large-scale adoption across Europe and beyond.