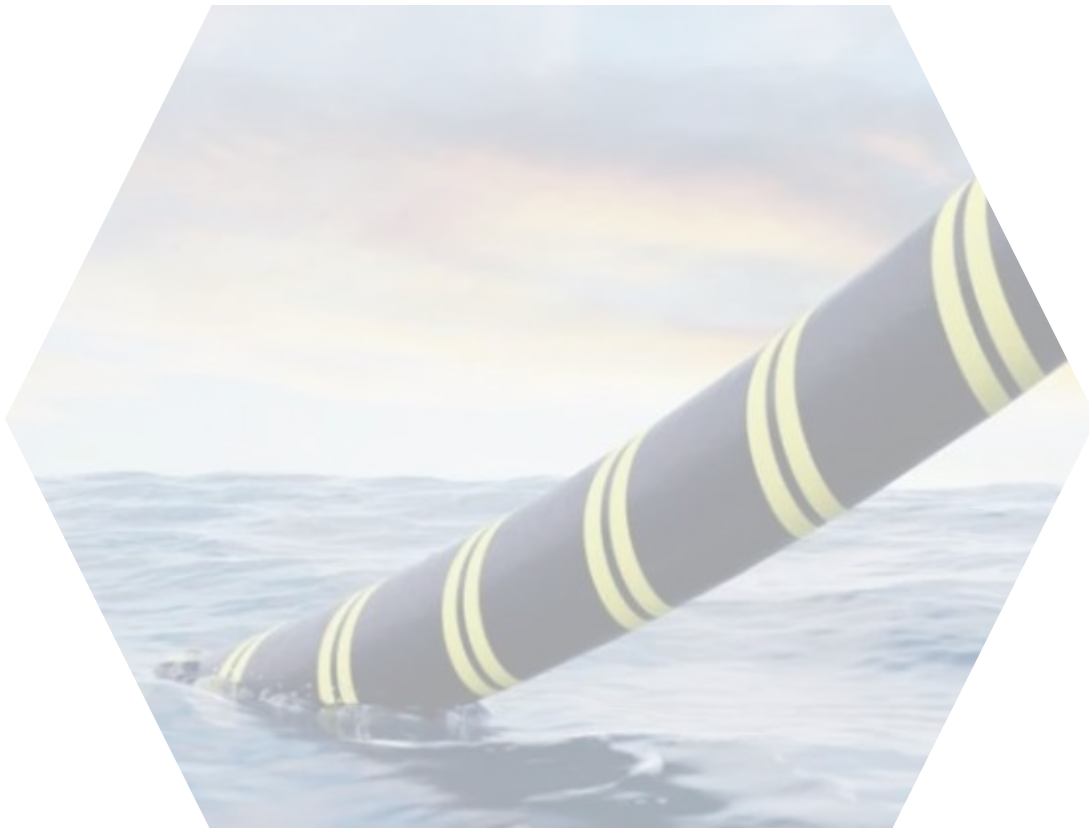




D6.3



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
OB	Optical Box
TDM	Time Division Multiplexing
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
PD	Partial Discharge
PBS	Product Breakdown Structure
KPI	Key Performance Indicator
MQTT	Message Queuing Telemetry Transport
HVDC	High-Voltage Direct Current
TDM	Time Division Multiplexing
CW	Continuous-wave

1 INTRODUCTION

1.1 Objectives of WP6 and its Relation to Vibration Detection and Fault Location

WP6 focuses on the development and validation of advanced fibre optic sensing technologies for real-time condition monitoring of large-scale HVDC cable systems. A central objective is the creation of an accurate fault location system that integrates data from multiple complementary sensing technologies (DAS, DTS, and PD monitoring) to provide a comprehensive picture of cable health.

Within this framework, fibre optic interferometric vibration sensors are designed to address critical monitoring points such as cable joints and terminations, where fault-induced mechanical events are most likely to originate or be detected with higher fidelity. By capturing high-sensitivity, point-based measurements of pressure and vibration waves caused by fault events, these sensors complement the spatial coverage of DAS, enabling a more robust and precise localization process.

The combination of distributed and point-based technologies aims to improve fault location accuracy, reduce diagnosis and intervention times, and feed the integrated algorithms that will be deployed in T6.3 in the Edge infrastructure.

1.2 Purpose of Deliverable D6.3

The D6.3, New fibre-based vibration measurement structures present the work performed in T6.2 on the design, implementation, and preliminary validation of new vibration measurement structures based on fibre optics. In this first phase, they are tested on Lumiker's laboratory to evaluate their performance under controlled conditions.

The report also covers the signal processing workflow developed to estimate the fault location from the sensor outputs, as a first step towards the multi-technology integration foreseen in T6.3. The prototypes described here will later be incorporated into the T6.3 rack, which combines the vibration monitoring technology from T6.2 with DAS/DTS solutions from T6.1, and connects to the project's Edge node.

Within the project's timeline, this deliverable is positioned before the full system integration stage. Specifically, it:

- Documents the design, prototyping, laboratory installation, and controlled testing of the new vibration sensors.
- Ensures traceability to the requirements defined in WP3/T3.3 for vibration monitoring and fault location.



- Prepares first draft of the interoperability framework for T6.3, including initial definitions for the rack, API, communication protocol, timestamping, and data formats, ensuring compatibility for the later fusion of vibration, DAS, and DTS datasets in the fault location algorithms.

A complete PBS and final system specifications are intentionally out of scope here and will be delivered in D6.4, together with pictographic evidence of the integrated prototype and consolidated test results.

1.3 Document Structure

This report is organized to reflect the design, prototyping, and preliminary laboratory validation of new fibre-based vibration measurement structures under T6.2, prior to full system integration.

- **Section 1 – Introduction:** context of WP6, purpose and scope of D6.3, positioning within the project timeline and this document roadmap.
- **Section 2 – Requirements:** functional/performance requirements derived from WP3/T3.3; constraints and high-level interfaces relevant to T6.2 and the upcoming T6.3 integration.
- **Section 3 – Development progress (T6.2):** description of sensor prototype iterations and the preliminary multiplexing and interrogation approaches.
- **Section 4 – Signal processing and preliminary localization method:** method to localize the cable fault between a pair of vibration sensors.
- **Section 5 – Lumiker laboratory test:** instrumentation and scenarios handling for controlled excitation and first trials at Lumiker (LMK) laboratory.
- **Section 6 – Preliminary validation results:** limitations and lessons learned from test.
- **Section 7 – Readiness for T6.3 integration:** draft data formats, timestamping, and communication-protocol required by the T6.3 rack and Edge node; actions before integration.
- **Section 8 – Risk management and mitigation:** technical risks identified in T6.2 and mitigation plan.
- **Section 9 – Conclusions and next steps:** summary of achievements and the planned work towards **D6.4** (PBS, final specs, pictographic evidence, and KPIs).



2 REQUIREMENTS

2.1 Functional & performance requirements from WP3/T3.3

Requirements in this section are derived from WP3, particularly T3.3, which sets implementation benchmarks for fibre-optic monitoring and fault location systems (DTS, DAS, point vibration sensors, PD). It explicitly includes frequency bandwidth, sensitivity, real-time capability and communications/data transfer among the parameters to be specified, linking these to project-wide monitoring and accuracy objectives.

Functional objectives (D6.3 scope):

- Detect fault-induced vibrations at cable joints and terminations using point interferometric fibre sensors.
- Demonstrate fault localization capability by processing time-of-arrival differences between sensors.
- Provide signals and metadata compatible with the future T6.3 system (timestamp, formats) to enable later fusion with DAS/DTS and the Edge.

Performance targets (conceptual, aligned with WP3/WP6 results):

- **Frequency** for vibration detection: up to 0–5 kHz.
- **Sensitivity**: sufficient to detect bench-generated events representative of fault-induced waves at joints/terminations.

2.2 Constraints & high-level interfaces (draft for T6.3)

Environmental & mechanical constraints:

- Design and testing must consider TSO-grade requirements (e.g., IP, IK, EMC) that will be pre-validated at LMK facilities (T6.2). Final compliance demonstration belongs to later phases.

Data, timing and communications constraints:

- High-level interfaces must anticipate T6.3 needs: a common visualization layer, communication protocol, timestamp policy and data formats to guarantee integrated functionality of the rack and Edge node. D6.3 provides a draft definition to ensure forward compatibility; full implementation and testing occur in D6.4/D6.5.

Interoperability constraints (conceptual):

- The point vibration sensors shall be multiplexable to support several sensing heads per connection zone. The final multiplexing topology is reserved for D6.4.

- Interfaces should permit later fusion with DAS/DTS outputs to achieve location accuracy at system level.



3 DEVELOPMENT PROGRESS

This section describes the progress made in the development of the fibre optic system for vibrations detection, covering theoretical modelling to sensor prototyping and testing.

3.1 Preliminary Work – Mathematical Modelling

During this reporting period, significant progress was achieved in the mathematical modelling of the interferometric sensing system based on a coupler architecture. The primary objective has been to establish a framework capable of accurately representing the demodulation process under mechanical perturbations of the sensing arms. The model was constructed starting from the well-known intensity transfer relations of the fibre coupler, where each output can be expressed as a phase-shifted combination of the optical field. These relations form the foundation for retrieving the interferometric phase, which directly encodes the vibration-induced variations in optical path difference.

The fundamental sensing principle relies on the modulation of the optical phase in the interferometric arms when the fibre is subjected to external mechanical perturbations.

A time-varying perturbation induces a variation in the physical length and the refractive index. Both contributions alter the optical path length, resulting in a dynamic phase shift.

In practice, both mechanisms contribute simultaneously, with relative weighting determined by the geometry of the perturbation and the material constants of the fibre. For vibrational excitation, the perturbation can be represented as a harmonic strain field.

The expected outcome of this development is a reliable tool to predict the frequency response of the sensor under controlled perturbations. Fault-induced vibrations, which typically appear in the range of a few hertz to several kilohertz, can now be simulated within the model to evaluate their impact on the sensing performance. The model therefore serves as a crucial bridge between theoretical principles and practical implementation, providing confidence that the system can be adapted to field scenarios where vibration signatures act as indicators of structural or electrical faults.

3.2 Vibration Sensor Development

The proposed sensing architecture is based on an interferometer topology employing a fibre coupler and the fibre sensing head, as depicted in Figure 1. This configuration ensures polarization diversity compensation; thus the interferometer maintains stable interference fringes even under varying polarization conditions, which is essential for long-term monitoring in real-world environments.



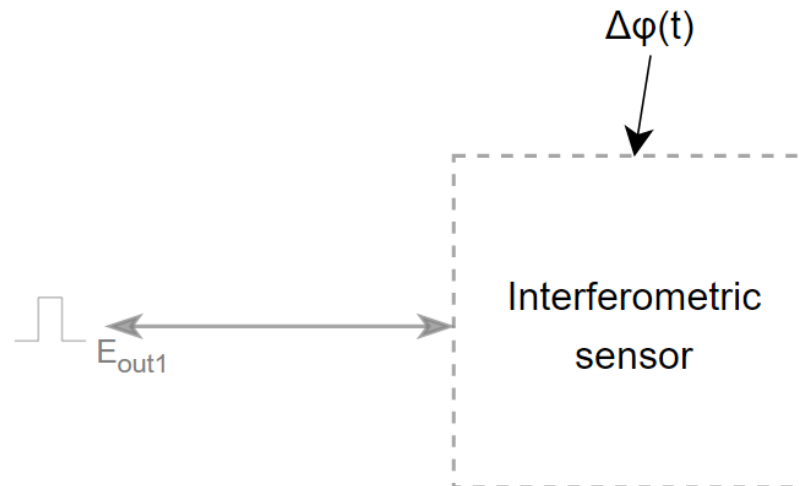


Figure 1. Vibration sensor architecture

The sensing principle relies on the modulation of the optical phase by mechanical vibrations acting on the fibre loops. This accumulated phase shift is directly proportional to the induced strain on the fibre. At reception, the coupler architecture provides multiple output complementary interference signals. This structure ensures that the received signals contain redundant phase information, enabling accurate reconstruction of the vibration-induced phase.

In addition, the sensing system is designed for multiplexing. The individual sensor heads are addressed in the time domain by introducing fibre delay lines, such that each interferometric loop reflects to the detection unit at a distinct time slot, TDM. This approach allows multiple sensing points (e.g., at cable joints or terminations) to be interrogated over a single fibre link, while preserving the phase sensitivity of each individual sensor.

To validate this architecture experimentally, a series of practical tests were conducted. (1) Initially, a CW interferometric configuration was implemented to confirm the stability of the optical setup and the correct behaviour of the sensing principle under controlled laboratory conditions. This preliminary test allowed the identification of noise sources, signal offsets, and the typical spectral features associated with the optical. (2) In the following stage, pulsed operation will be introduced to emulate the final interrogation conditions and evaluate the system's capability to detect and resolve vibration events in time and frequency domains which will be explain in D6.4.

3.3 Multiplexing Approach

The interrogator system uses the Time Domain multiplexing approach to distinguish each of the system sensor.

TDM uses light pulses emitted at specific intervals. Each sensor reflects its signal based on the arrival time of the pulse, enabling individual identification and analysis of each reflected response.

This technique requires precise synchronization between the emitter and receiver, as well as high-speed data acquisition systems to distinguish the reflected pulses from multiple sensors.

- **Advantages:**

- Allows the integration of a large number of sensors within a single fibre, thanks to the absence of wavelength limitations, enabling multiple sensors to operate at the same wavelength.

- **Disadvantages:**

- Higher technical complexity due to the need for highly stable pulsed light sources and precise synchronization.
- Data acquisition and processing systems must be fast and robust to manage the large volume of reflected information.

3.4 Vibration Interrogator Development

3.4.1 Vibration interrogator PCB and electronic control development

The core control electronics of the vibration interrogator has been implemented on a dedicated multi-layer PCB. The board is organized into functional blocks, each responsible for managing a specific subsystem within the interrogator.

1. **Power Management Stage**

This area is responsible for regulating and distributing power to the entire system.

2. **Main Control Unit**

This unit is the core digital control logic of the interrogator. Based on multiple logical processing IC, system light sources control, signal reception process and signal processing is performed.

3. **Light Emission Control Interface**

This section provides the interface and control logic required to manage the operation of the laser modules. C-band centered high power pulser light source is controlled to transmit form specific light pulses to achieve precise time domain based operation.

4. **Receiver Modules**

The PCB supports up to three independent reception modules, each comprising:

- A photodiode for optical-to-electrical conversion with a corresponding transimpedance circuit to amplify the received signal.
- An additional first amplification stage to condition the signal before processing. This programable gain stage assures a wide dynamic range of the receiver modules for adequation to different systems characteristics.

5. **Optional optical amplifier**



The PCB layout includes reserved space and electrical interfaces for the optional integration of an EDFA (Erbium-Doped Fibre Amplifier) module.

This addition has been considered to extend the system's optical power capabilities in future configurations where a higher number of sensors need to be sensed or higher losses are present in the specific application.

6. Central Processing:

Three main microcontrollers:

- Light emission and thermal control management.
- Reception management: Acquires and processes the signals reflected by the sensors.
- Communications management: Synchronizes the application's operation and manages external communications.

7. Ethernet Communication Module

This section handles high-level communication with external systems via Ethernet.

8. RS-485 / Modbus Communication Interface

Provides connectivity for industrial fieldbus protocols over copper or fibre, enabling remote configuration and integration.

3.4.2 System logic and control sequence

The vibration interrogator operates as part of a larger system (Figure 2) composed of two main elements:

1. An **industrial computer**, which manages high-level control, configuration, and data processing. Handles the control and configuration of the vibration monitoring system.
2. The **opto-electronic interrogator**, which manages the optical interface with the sensors and ensures correct system operation. Transfers the sensors' vibration data to the industrial computer for frequency analysis.

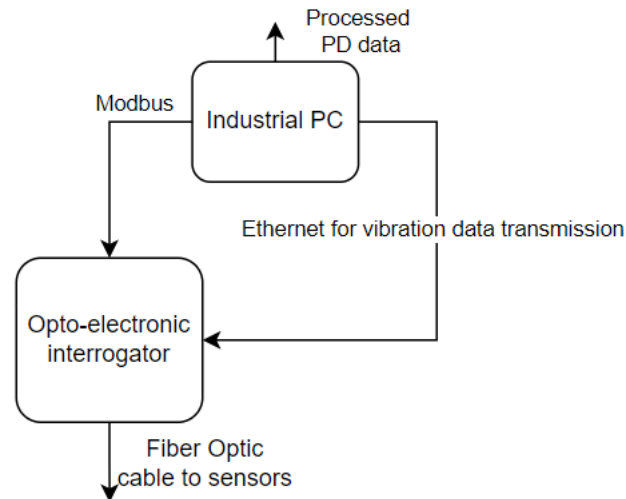


Figure 2. Vibration system structure.

The interrogator's role is to manage the optical layer and ensure the generation of valid vibration data. Its operational logic follows a well-defined sequence.

The interrogator emits light pulses from its integrated light source through the output fibre. These pulses are received by different vibration sensors at different times, and the response from each sensor is thus received sequentially at known moments. This allows the acquisition of reflected pulses for further signal processing of each sensor's response. Once the reflected pulses from all sensors in the system have been received, the interrogator generates a new pulse to repeat the sequence.

While the sensors are being optically interrogated, signal processing and communication with external equipment are performed. Sensor information is sent to an industrial PC for vibration event characterization and detection.

4 SIGNAL PROCESSING AND PRELIMINARY LOCALIZATION METHOD

The system is adapted to operate under pulsed emission. In this mode, light is launched into the interferometric sensing network as a sequence of optical pulses, each of duration t_p and separated in time by an interval T_p , the pulse repetition frequency. Each pulse propagates along the sensing fibre and interacts sequentially with the various sensing points distributed along the optical path (see Figure 3).

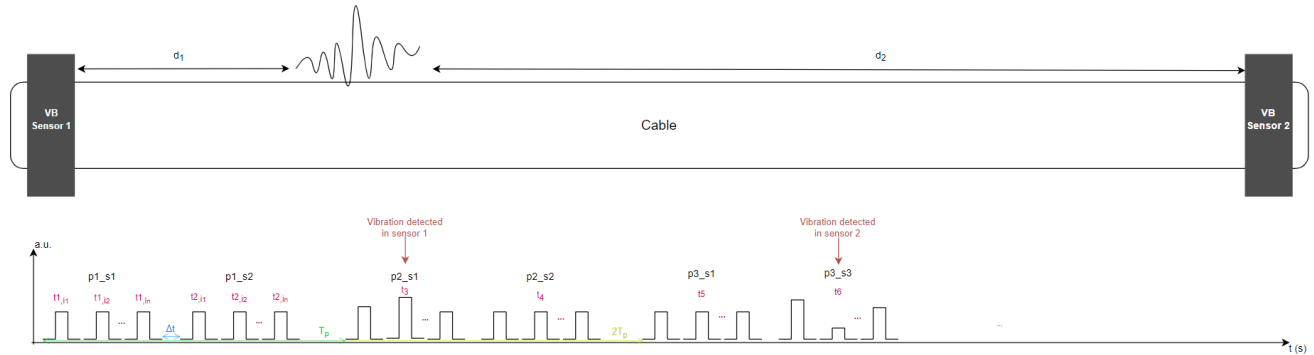


Figure 3. Fault localisation method.

Since light travels through the fibre with a well-known group velocity v_g , the time-of-flight of each reflected interfered pulse can be directly converted into a spatial position. Thus, by recording the arrival time t_i of each pulse, the system can map temporal events to precise positions along the sensing line.

By comparing the arrival times of the affected pulses (when a perturbation occurred) and analysing the sample indices at which variations occur in consecutive acquisitions, it is possible to infer the relative position of the disturbance between the distributed sensors. For example, if a vibration is detected earlier in the signal associated with Sensor 1 and later in that of Sensor 2, the event can be localized proportionally to the delay difference Δt between the corresponding pulse responses. The accuracy of this localization depends on the sampling period pulse emitting frequency, and the pulse duration.

This time-domain multiplexing approach effectively transforms the optical sensing network into a distributed vibration mapping system, where each sensing point corresponds to a unique time slot within the observation window, governed by the emitter's sampling time. In this way, not only can the presence of a perturbation be detected through phase or envelope analysis, but its approximate position along the fibre can also be inferred from timing information.

5 LUMIKER LABORATORY TESTS

5.1 Description and Instrumentation

An experimental setup was arranged to evaluate the response of the optical sensing setup operating in CW mode. The system includes a laser source, a fibre-optic interferometric sensing head, and photodetectors connected to the outputs of the coupler. The optical signals are acquired simultaneously through a multi-channel digital oscilloscope, which provides synchronized time-domain measurements for subsequent processing and analysis. All elements were placed on a stable optical table to minimize external mechanical vibrations and ensure consistent measurement conditions (see Figure 4).

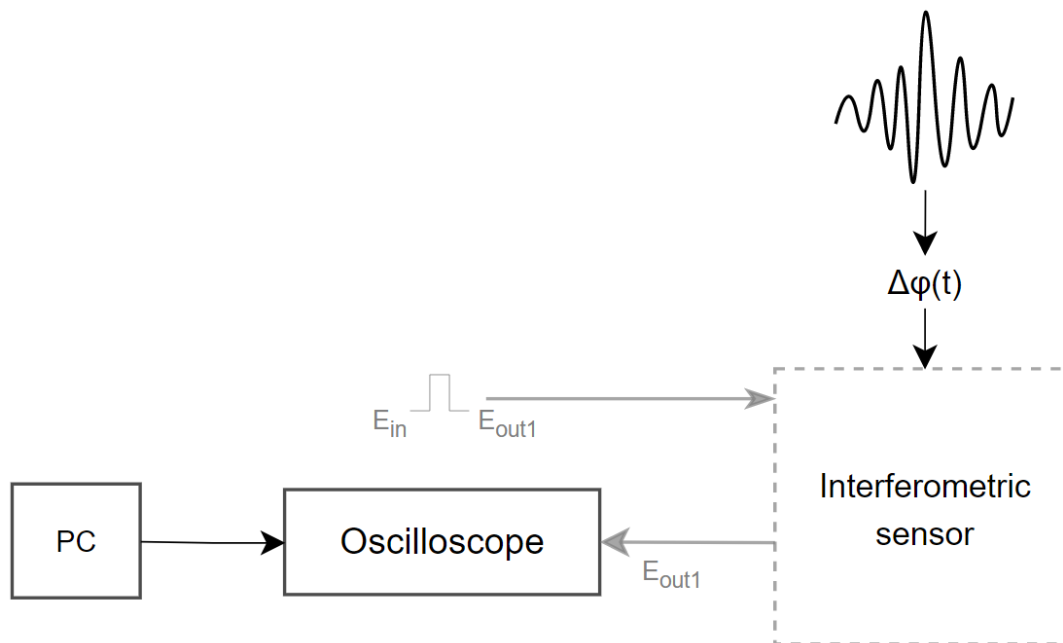


Figure 4. Block diagram measurement setup.

5.2 Test Scenarios and Excitations

To evaluate the sensor response under different excitation conditions, the following tests were performed: (1) acoustic-wave perturbation generated by a mobile phone application at precise frequencies f_0 , allowing verification of the system's ability to detect and reproduce known periodic disturbances, (2) an induced perturbation (hit on sensor's PCB), simulating fault-like events similar to those expected along a cable under stress or partial discharge activity, (3) and reference measurements under normal environmental conditions (no induced excitation) were also recorded to characterize the baseline response and noise level of the sensing system.

5.3 Safety, EMC and Handling Considerations

All experiments were carried out following standard laboratory safety practices. Optical power levels were kept within safe operating limits, and appropriate laser safety measures were always observed. Care was taken in handling fibre-optic components to prevent mechanical stress, bending losses, or contamination of connectors, ensuring the reliability and longevity of the optical links.

The first batches of experiment under CW-mode were not conducted under strong electric stress, however the passive optical setup of the vibration sensing system ensures immunity to electromagnetic interference.



6 PRELIMINARY VALIDATION RESULTS FROM LAB TEST

The data collected from the photodetector's outputs were post-processed to evaluate the presence and characteristics of mechanical perturbations in the sensing system. The optical interference signals were first normalized to remove amplitude imbalances between channels, followed by phase demodulation derived from the coupler configuration.

Spectral analysis was performed by applying the Fast Fourier Transform (FFT) to both the demodulated phase and the output intensities. Under steady, non-disturbed conditions, the spectrum typically exhibited low-frequency noise and weak broadband components (see Figures 3 (a) and 3(b)), whereas strong hits were performed on the sensor (Figures 4 and 5). Finally, controlled excitations introduced well-defined spectral peaks at the fundamental excitation frequency f_0 and, depending on the amplitude of the perturbation, its harmonics (see Figures 6 and 7). These peaks provided a reliable indicator of vibration-induced phase modulation within the interferometer arms.

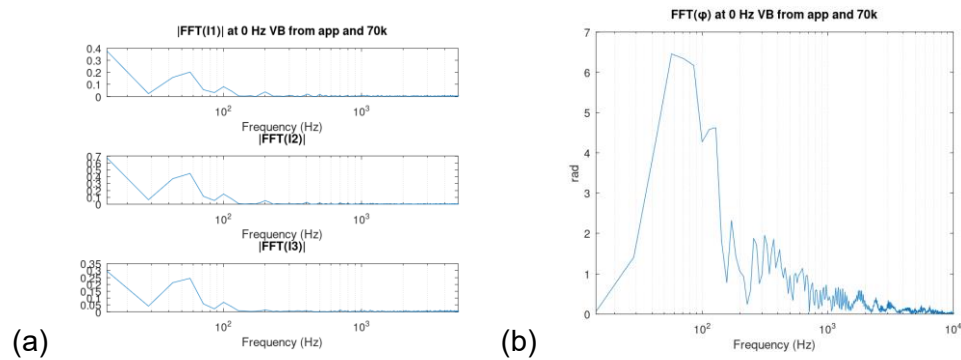


Figure 5. Non-disturbed vibration sensor. FFT of (a) the output intensities and (b) the demodulated phase got from the output of the coupler.

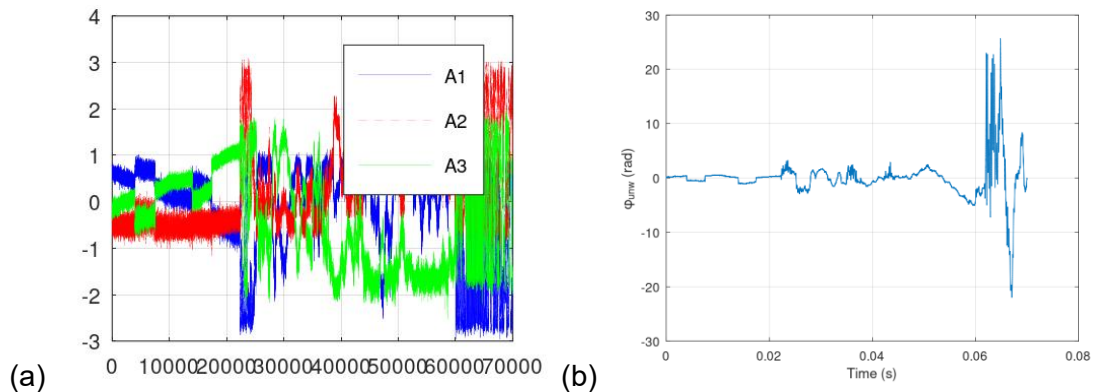


Figure 6. Vibration sensor under disturbance (strong hit applied to it). (a) Output intensity and (b) demodulated phase of the mechanical perturbation.

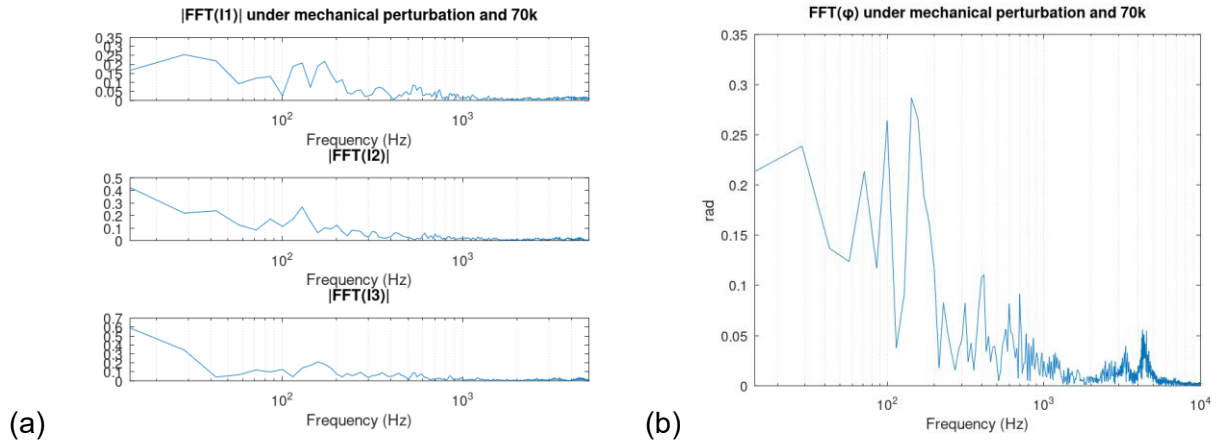


Figure 7. Vibration sensor under disturbance (strong hit applied to it). FFT of (a) the output intensities and (b) the demodulated phase got from the output of the coupler.

A strong DC component can still be observed even after applying digital filtering, such as Butterworth high-pass or band-pass filters. This behaviour is mainly attributed to the presence of slow or quasi-static variations in the interferometric signal, which can arise from bias drifts, temperature fluctuations, optical power imbalance, or long-term phase offsets between the interferometer arms. These effects introduce low-frequency content, resulting in a dominant DC contribution in the spectral domain.

During quasi-controlled excitation tests using a cell phone vibration app, the system was subjected to a well-defined frequency f_0 . The interferometer responded consistently at this excitation frequency, showing a clear spectral peak at f_0 in both the phase-demodulated and intensity-based FFT analyses.

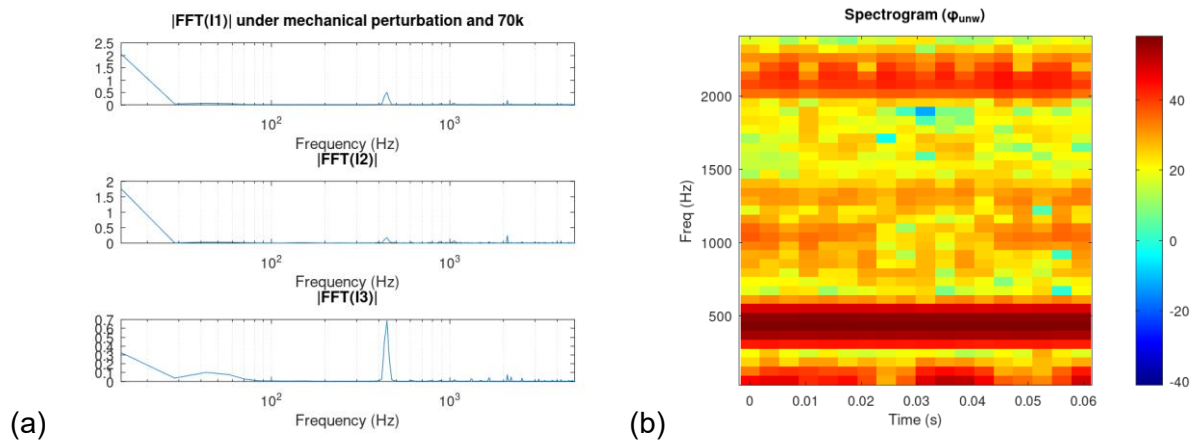


Figure 8. Vibration sensor under 440 Hz vibration. FFT of (a) FFT of the output intensities and (b) the spectrogram of the demodulated phase along time.

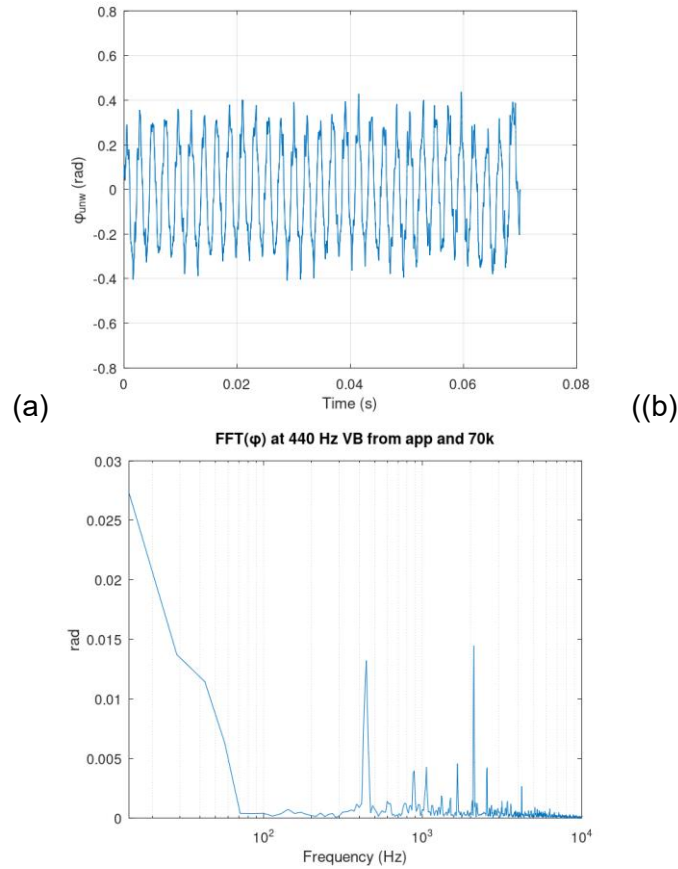


Figure 9. Vibration sensor under 440 Hz vibration. (a) The demodulated phase and (b) its FFT.

The interferometer produces an output intensity governed by a cosine function of the optical phase difference between its arms. Under small phase excursions, this cosine dependence can be approximated as linear, enabling straightforward interpretation of the phase and amplitude responses. However, when the vibration amplitude increases, the system enters a nonlinear regime in which the intensity response follows a Bessel-type behaviour.

In this regime, higher-order harmonics appear in the frequency spectrum, and the proportionality between the detected intensity and the induced displacement no longer holds, as can be seen in Figure 7 above, where the frequency spectrum of the phase has peak component at 440 Hz but also at its harmonics. These harmonics confirm the nonlinear nature of the interferometric response under stronger amplitude disturbance and provide valuable insight into the system's dynamic range and phase sensitivity.

7 READINESS FOR T6.3 INTEGRATION

The goal of this section is to demonstrate the readiness of the fibre-based vibration measurement structures developed under T6.2 for their upcoming integration into the T6.3 rack and the Edge Node infrastructure.

This integration aims to enable interoperability between the vibration sensing subsystem (LMK), the distributed sensing subsystems (DAS/DTS, APS), and the digital Edge environment (BAR).

The vibration system developed by LMK is capable of detecting mechanical disturbances occurring along the cable span between two consecutive vibration sensors. Once a vibration event is detected, the system estimates the approximate location of its origin based on the time-of-arrival differences between sensors. The current accuracy of this estimation is still under validation and will be consolidated in Deliverable D6.4.

The data associated with detected events will be transmitted to the Edge through a secure MQTT broker, where the timestamp, location and relevant signal parameters will be recorded, displayed and further processed in combination with DAS and DTS data to enhance the global fault location accuracy.

- **Draft Data Format Definition**

The proposed preliminary data structure for MQTT messages is as follows:

<i>Field</i>	<i>Type / Format</i>	<i>Description</i>	<i>Example</i>
<i>timestamp.UTC</i>	<i>ISO8601 (string)</i>	<i>UTC time when vibration was detected</i>	<i>2025-10-10T14:32:05.256Z</i>
<i>sensor_pair_id</i>	<i>string</i>	<i>Identifier of the section between two vibration sensors</i>	<i>VIB_SEC_03</i>
<i>event_location</i>	<i>uint16</i>	<i>Estimated location of vibration origin within section (m)</i>	<i>2655</i>
<i>dominant_frequency</i>	<i>uint16</i>	<i>Dominant vibration frequency (Hz)</i>	<i>350</i>
<i>event_flag</i>	<i>bool</i>	<i>Event trigger (1 = anomaly detected)</i>	<i>1</i>

The proposed data definition ensures forward compatibility with the common visualization layer and the Edge database schemas defined in WP7.

- **Communication Protocol and Data Flow**

Data transmission from the vibration system to the Edge Node will only occur when an anomaly or vibration event is detected. This event-based communication strategy reduces network load and allows the Edge algorithms to focus processing resources on the relevant time and cable segment.

The integration will rely on the MQTT protocol for the transmission of vibration event data from the LMK vibration system to the Edge Node.

This approach aligns with the communication framework established by WP7 (BAR), which defines an MQTT broker running in the Edge Node for receiving and redistributing sensor data to different microservices (visualization, data storage, and AI processing).

Vibration Sensors → Interrogator (LMK) → Industrial PC (Event Detection Algorithm) (LMK) → MQTT Publisher → Edge Node Broker → Database (time-series) → Multi-sensor Fusion Algorithm (T6.3) → Visualization Dashboard

Only vibration events (not continuous streams) will be published, allowing the Edge system to trigger the DAS/DTS modules to focus their processing on the corresponding cable segment, thereby confirming the event and refining the exact fault location.

- **Conclusion**

Although the final definitions of the data structure, timestamping policy, and MQTT-based communication protocol are still pending joint agreement with APS and BAR during the early stages of T6.3, these aspects involve minor implementation adjustments that can be easily integrated into the current system architecture.

The hardware and software developed under T6.2 already support flexible configuration of data fields, synchronization sources, and communication parameters, ensuring smooth adaptation once the final standards are established.

Therefore, the system can be considered technically ready for integration in the upcoming T6.3 phase, where it will operate in conjunction with the DAS/DTS subsystems and the Edge Node to contribute to the multi-technology fault location framework defined within WP6 and WP7.

8 RISK MANAGEMENT AND MITIGATION (T6.2)

8.1 Technical Risks

During the development of the fibre-based vibration measurement structures, several technical risks have been identified, primarily related to the optical signal characteristics, environmental factors, and the mechanical interface of the sensor with the monitored structure.

Low Signal-to-Noise Ratio (SNR)

The magnitude and spectral content of the vibrations to be detected are still uncertain. As a result, there is a risk of obtaining a low SNR in the measured signal, making it difficult to distinguish between genuine vibration events and background or environmental noise.

Mechanical Coupling Uncertainty

Depending on the sensor's installation point and the mechanical configuration of the prototype, the mechanical coupling between the cable joint or termination and the fibre sensor can vary. These variations may affect how the vibration energy is transmitted to the sensor and, therefore, modify the expected amplitude and frequency response, making it difficult to identify specific vibrations events.

Environmental and System Noise

External noise sources such as nearby equipment, electrical converters, or mechanical vibrations present in the test environment may interfere with the measurement signal. This may hinder the discrimination between real vibration events and ambient disturbances.

Aliasing Risk Due to Unbounded Sensor Bandwidth

The optical system operates in a pulsed mode with a defined sampling frequency, while the sensor's mechanical response is not bandwidth limited. If vibration frequencies in the monitored structure exceed the sampling capacity of the interrogator, aliasing effects could occur, where higher-frequency components appear as lower-frequency artefacts in the measured signal.

Scalability and Optical Power Distribution Limitations

When scaling the vibration monitoring system to a large number of sensing points, optical power losses introduced by successive power splitters can significantly reduce the available signal level per sensor. As the number of connected sensors increases, both the total optical loss and the accumulated noise at the receiver side grow, limiting the total number of sensors that can be connected to a single interrogator. This may compromise the system's scalability for long-distance or high-density monitoring configurations.

8.2 Mitigation Plan and Next Iterations

To address the risks identified above, the following mitigation strategies will be implemented during the next development and validation phases of Task 6.2:



Low Signal-to-Noise Ratio (SNR)

Each test configuration will be analysed individually to adapt the acquisition parameters and signal processing methods to the specific environment. The analysis will focus on identifying frequency bands or transient events clearly distinguishable from background noise. Once representative datasets are available, adaptive filtering and thresholding strategies will be tuned to enhance detection reliability.

Mechanical Coupling Uncertainty

After validating the basic functionality of the first vibration sensor prototype, subsequent iterations will focus on optimizing its mechanical design. These efforts will aim to improve robustness and ensure consistent vibration transfer, regardless of the mounting position or structural characteristics of the monitored element.

Environmental and System Noise

Signal processing will incorporate spectral and time-domain filtering to identify continuous or repetitive noise components typical of the surrounding environment. The detection algorithm will be configured to monitor variations that differ from the established background noise profile, improving discrimination between genuine vibration events and unwanted signals.

Aliasing Risk Due to Unbounded Sensor Bandwidth

Characterization campaigns will determine the typical vibration frequency range expected in the monitored cable systems. This will confirm whether the frequencies fall within the safe sampling range of the optical interrogator. If higher-frequency vibrations are present, mechanical damping or filtering elements may be introduced to limit the effective bandwidth of the sensor and avoid aliasing artefacts.

Scalability and Optical Power Distribution Limitations

Future versions of the vibration interrogator could integrate an optical amplifier to compensate for power division losses and extend the system's reach to a higher number of sensors. In parallel, improvements in the optical design of the sensor, such as the selection of components with lower insertion loss or more efficient power splitting schemes, will be explored to increase the number of multiplexable sensors per system without compromising signal integrity.



9 CONCLUSIONS AND NEXT STEPS

Summary of Achievements in T6.2

During T6.2, new fibre-based interferometric vibration measurement structures have been designed, implemented, and preliminarily validated under controlled laboratory conditions at LMK facilities.

The main achievements can be summarised as follows:

- **Sensor concept and architecture:** Design and prototyping of point-based vibration sensors based on fibre interferometry, suitable for installation at joints and terminations.
- **Measurement principle validation:** Successful laboratory trials demonstrating the capability to detect and discriminate mechanical disturbances representative of fault-induced vibrations.
- **Localisation algorithm definition:** Definition of the event localisation logic based on time-of-arrival differences between consecutive sensors, and generation of validated experimental data sets that will support the algorithm development and calibration in the subsequent project phases.
- **Traceability to system requirements:** Compliance with functional and performance objectives defined in WP3/T3.3 regarding frequency range, sensitivity, and interoperability with DAS/DTS systems.

These outcomes confirm the technological maturity achieved in T6.2 and provide the basis for the integration and final validation activities of T6.3.

Planned Improvements towards T6.3 and D6.4

Work in the upcoming T6.3 and D6.4 will focus on consolidating the current developments into a fully integrated and validated vibration monitoring subsystem within the EasyDC-FOS multi-sensing architecture.

The key activities and improvements planned are:

- **Final Product Breakdown Structure (PBS):** Definition of the full vibration monitoring system architecture, including interrogator hardware, sensing heads, multiplexing topology, power and communication interfaces.
- **Final specifications:** Completion of quantitative performance parameters (sensitivity, bandwidth, timestamp precision, localisation accuracy, environmental robustness).
- **Pictographic evidence:** Assembly and visual documentation of the complete system prototype (rack integration, sensor installation, data flow).
- **Consolidated KPIs:** Verification of detection and localisation accuracy, latency of alert transmission, and interoperability with DAS/DTS in the integrated setup.



- **Improved localisation algorithm:** Refinement of the event position estimation logic and calibration procedures, using the validated data from T6.2 and new test campaigns on the Lumiker test bench cable. These tests will reproduce fault-like mechanical excitations to verify the performance of the detection and localisation algorithm under realistic propagation conditions.
- **Edge data integration:** Implementation of the final data schema, MQTT message structure, and secure communication to the Edge Node, in alignment with WP7 protocols.
- **Interoperability test with DAS/DTS:** Joint trials with APS to validate cross-triggering and confirm the multi-sensor correlation workflow (vibration-triggered DAS analysis).
- **Mechanical optimisation:** Development of improved sensor packaging and mechanical mounting solutions to facilitate installation on cables of different diameters and configurations. This includes designing adaptable clamping or attachment mechanisms ensuring proper coupling of the sensor to the cable surface while maintaining environmental protection (IP/IK compliance).

All these improvements will be consolidated and documented in **Deliverable D6.4 – New fibre-based vibration monitoring system**, which will mark the completion of the integration and performance validation phase.

