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ENHANCED DETECTION AND MONITORING OF UNAUTHORIZED ACTIVITIES IN HIGH-VOLTAGE POWER GRIDS USING DISTRIBUTED ACOUSTIC SENSING (DAS) IN TURKISH TRANSMISSION GRID

Faruk Uyar[1,3], Barış İyidir[1], Ümit Aktaş[2], Mete Uzar[2], Ceyhun Cengiz[2], Ekmel Özbay[1]

Abstract: This study presents the implementation and evaluation of a fiber-optic Distributed Acoustic Sensing (DAS) system for monitoring overhead high-voltage transmission lines in the Turkish Transmission Grid. The DAS system, deployed on a 154-kV transmission line spanning 40 km, utilizes existing optical ground wires (OPGW) for real-time acoustic and vibrational sensing. The study outlines the fundamental principles of DAS technology, detailing how optical fiber functions as a distributed sensor to detect mechanical disturbances along the transmission line. Signal processing algorithms and feature extraction techniques were developed to analyze recorded acoustic signatures associated with different types of activities, including structural impacts, mechanical tampering, and environmental stressors such as wind-induced vibrations and icing effects. Key signal features, including root mean square (RMS) amplitude, crest factor, zero-crossing rate, spectral centroid, power spectral density (PSD), and wavelet entropy, were extracted and analyzed for their suitability in activity classification. Extensive field tests were conducted, including controlled experiments such as hammering, mechanical and manual unscrewing, and metal cutting at various distances from the interrogation unit. A signal processing pipeline was implemented to enhance detection accuracy, utilizing noise reduction, spectral analysis, and feature-based classification. The developed detection algorithm processes real-time acoustic data and assigns an activity score based on extracted features, enabling efficient identification of anomalies and security threats along the transmission line. The system demonstrated high sensitivity to impulsive events, reliably detecting 22 out of 23 activities with a near-zero false alarm rate. The results indicate that DAS technology is capable of accurately monitoring and detecting unauthorized activities around high-voltage transmission towers and it can serve as an effective non-intrusive monitoring solution for power transmission infrastructure. The DAS technology presented herein has the potential to become an essential tool in ensuring the safety and reliability of Türkiye's energy infrastructure, enabling rapid response to both human-made and natural threats.

Keywords: Grid resilience, distributed acoustic sensing (DAS), optical ground wire (OPGW), fiber optics, signal processing, feature extraction, activity detection, transmission line, high-voltage, power towers

INTRODUCTION

In recent years, with the acceleration of the energy transition, the electrification infrastructure has undergone significant expansion, making the operational activities of electrical grids increasingly complex. The integration of renewable energy sources, the widespread adoption of electric vehicles, and the growing energy demand have rendered grid systems more intricate and vulnerable, highlighting the critical importance of grid resilience. Grid resilience refers to the ability of energy systems to withstand unexpected disruptions, such as natural disasters or technical failures, recover quickly, and continue operating sustainably. Extreme weather events, natural disasters, cyberattacks, and human-induced failures pose significant threats to the reliability of energy transmission lines, while the increasing prevalence of unauthorized activities such as theft, vandalism, and illegal access to power infrastructure further exacerbates these risks. Additionally, natural hazards such as strong winds, lightning strikes, wildfires, and short circuits further challenge grid stability. Strengthening grids against these risks is essential to ensure uninterrupted energy supply, minimize economic losses, and protect critical infrastructure.

In this context, next-generation monitoring and sensing technologies enable a proactive approach to grid management by providing early intervention capabilities

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[1] *Bilkent University, Nanotechnology Research Center (NANOTAM), Ankara, Turkey*
[2] *Turkish Electricity Transmission Corporation (TEIAS), Ankara, Turkey*
[3] *Correspondence email: faruk.uyar@bilkent.edu.tr*

for potential failures [1-4]. Among these, fiber-optic distributed acoustic sensing (DAS) has emerged as a transformative solution, leveraging existing optical fiber infrastructure to provide continuous, real-time monitoring of transmission lines over extensive distances [5-9]. By detecting and analyzing acoustic signals along power lines, DAS enhances situational awareness, enabling rapid response to both operational challenges and security threats, thereby improving the overall resilience and reliability of modern electrical grids.

DAS technology operates by transmitting coherent laser pulses through an optical fiber and analyzing Rayleigh backscattering variations induced by external acoustic and vibrational disturbances. These disturbances, which may arise from mechanical impacts, environmental factors, or unauthorized activities, cause minute strain variations in the fiber, which DAS systems interpret as characteristic signal patterns. By deploying DAS over Optical Ground Wire (OPGW) cables integrated within transmission grids, utilities can achieve cost-effective, large-scale monitoring with high spatial resolution [9-11].

High-voltage power lines, particularly those forming part of national transmission grids, are frequently targeted for material theft, especially of conductive elements like copper and aluminum, as well as the mechanical connection components of overhead line towers [12-13]. The economic and operational consequences of such thefts are substantial, often leading to service interruptions, safety hazards, and increased maintenance costs [14-16]. Beyond security threats, environmental stressors such as extreme winds, icing, and mechanical oscillations can compromise the structural integrity of transmission lines, necessitating early detection to prevent failures. Moreover, electrical faults, including short circuits, pose significant risks to system stability and require rapid detection and localization for effective mitigation [17 20].

As of 2025, the transmission line length in Türkiye is approximately 75,000 km, making it one of the largest transmission systems in Europe. With planned investments in the coming years, this length is expected to increase further. This extensive infrastructure comprises over 172,000 transmission towers, extending across a country and are mostly established in rural areas and outside city centers. Therefore, in addition to ensuring the efficient and periodic execution of operation and maintenance activities, it is crucial to continuously monitor large-scale systems to detect damage and external impacts. Historically, the physical inspections of transmission lines have been conducted at specific intervals through operational personnel or aerial surveillance systems that capture visual recordings. These methods help detect damage to conductors, towers, and connection equipment of transmission lines. However, in a country like Türkiye, which has a large-scale transmission infrastructure, there is a critical need to detect equipment and location-specific damages caused by extreme weather conditions or human interventions before any electrical outage occurs. Otherwise, the collapse of a transmission tower or the breakage of a conductor could lead to regional power outages or cascading failures, causing significant economic losses for the country.

While electrical fault conditions in a transmission line can be detected and operationally managed through protection and monitoring systems [21-23], certain issues—such as the theft of tower components or the gradual weakening of a tower's mechanical strength—cannot be remotely identified before a power outage occurs. In such cases, the collapse of a single transmission tower could result in the loss of a significant section of a transmission line, leading to severe disruptions in the grid. In the past, numerous incidents of material theft have been reported in transmission grids across the country, highlighting the widespread nature of the problem. To address this issue, TEIAS has been investing in fiber-optic-based monitoring systems along transmission grids to enhance detection and response capabilities. Currently, TEIAS has approximately 40,000 km of OPGW infrastructure, enabling fiber-optic access to all substations. The corporation now aims to effectively implement DAS monitoring systems on this existing infrastructure to improve the real-time detection and management of potential threats to the transmission grid.

The integration of DAS into power transmission monitoring frameworks presents several advantages. First, it enables comprehensive surveillance across entire transmission corridors, reducing the need for discrete sensors and manual inspections. Traditional surveillance methods, such as visual inspections, drone monitoring, and ground-based sensors, often have limitations in coverage, cost, and response time. DAS, on the other hand, provides real-time, continuous monitoring over long distances without requiring additional power sources along the transmission line. Second, DAS exhibits high sensitivity to minute mechanical and acoustic perturbations, allowing for early detection of potential threats. The system can differentiate between various acoustic signatures, enabling the identification of distinct events such as electrical discharges, corona activity, and arcing on cables [24-26], as well as hammering, metal cutting, tower climbing, and unauthorized movements on or near towers. Third, its real-time operation facilitates rapid localization of disturbances, improving response efficiency. Operators can be alerted to potential security breaches or environmental threats in near real-time, allowing for immediate dispatch of maintenance or security personnel to the affected area. Finally, utilizing existing OPGW cables as sensing elements minimizes additional infrastructure costs, making DAS a cost-effective solution for large-scale deployment.

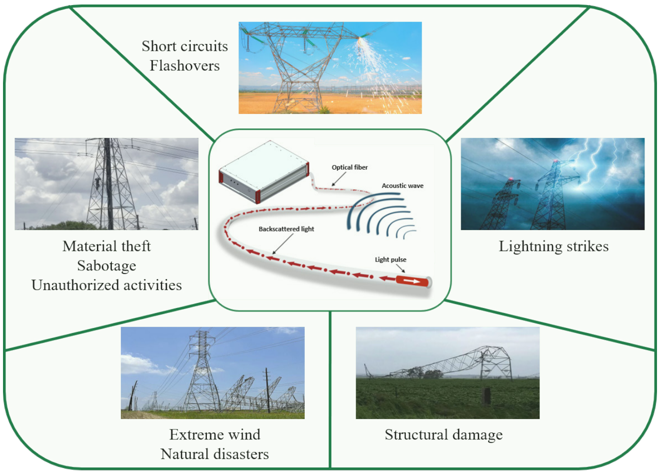

Figure 1: Overview of key DAS application scenarios in power transmission grids [27]

Various case studies have demonstrated the effectiveness of DAS in different operational environments. For instance, recent implementations of DAS in power grids across South America and North America have successfully detected and prevented unauthorized activities such as tower climbing and conductor theft [28 29]. In some cases, early detection allowed security personnel to intervene before significant damage occurred, reducing repair costs and service interruptions. Furthermore, DAS has been employed in earthquake-prone regions to monitor ground vibrations and assess the impact of seismic activity on power transmission infrastructure, further expanding its utility beyond conventional applications [30-31]. Figure 1 provides an overview of key DAS application scenarios in power transmission grids.

This paper aims to explore the capabilities and applications of DAS in securing high-voltage power lines in Turkish Transmission Grid, with a specific focus on its role in detecting unauthorized activities and environmental disturbances. By examining real-world case studies and technological advancements, this study seeks to provide a comprehensive overview of DAS as a critical asset in modern power transmission monitoring and security systems.

1. PRINCIPLE OF DAS SYSTEM

DAS system utilized in this study consists of a narrow-linewidth laser operating at a wavelength of 1550.12 nm. This laser serves as the primary light source, generating a continuous wave (CW) lightwave. It is subsequently modulated into interrogation pulses by an acousto-optic modulator (AOM), which is driven by a radio frequency (RF) driver with a center frequency of 110 MHz. Once the CW light is converted into pulsed signals, a high-power pulsed erbium-doped fiber amplifier (EDFA) amplifies the peak power of these pulses up to 1 watt. However, due to the finite extinction ratio of the AOM, a residual leakage signal can persist, potentially degrading the system's signal-to-noise ratio (SNR). To mitigate this issue, a second AOM is employed after the pulsed EDFA, effectively filtering out unwanted leakage signals and ensuring a high on-off ratio for the interrogation pulses [32]. Additionally, in order to maintain signal integrity and prevent distortion caused by transient effects in the EDFA, the pulses are pre-shaped before amplification [33-34]. Following amplification, the optical pulses are injected into optical circulator (CIR) which directs them to the fiber link. The DAS configuration is illustrated in Figure 2. The system is capable of covering a range of up to 50 km with a spatial resolution of up to 10 m. In the field tests conducted for this study, a pulse width of 200 ns was selected, corresponding to an optical resolution of 20 meters. This choice was made to balance the need for precise event localization while maintaining adequate coverage over long distances.

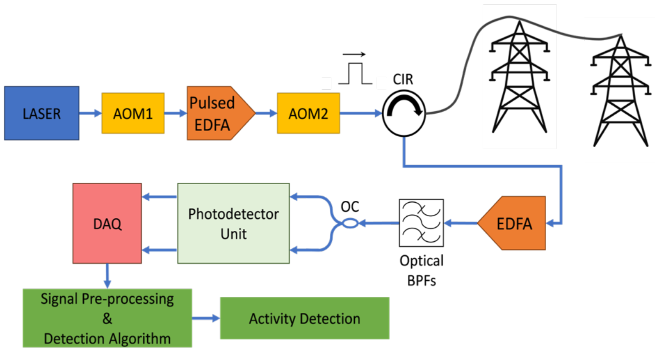

Figure 2: DAS configuration (abbreviations given in the text)

The fundamental sensing mechanism of the DAS system relies on detecting Rayleigh backscatter signal from the fiber under test (FUT). The weak backscattered signal returning from the fiber is routed through the CIR and directed toward the receiver path. Since the returned signal is typically of very low intensity, each receiver path incorporates a high-gain pre-amplifier EDFA to enhance the signal strength. Following amplification, the signal passes through a series of optical bandpass filters (BPFs) designed to selectively transmit only the relevant spectral components while removing unwanted amplified spontaneous emission (ASE) noise. The filtering process is implemented in multiple stages to achieve optimal SNR. A coarse BPF is first applied to eliminate a broad range of ASE noise, followed by a more precise etalon-based sharp filter that further refines the spectral response, ensuring that only the desired wavelength region around the laser emission is retained [32]. This multi-stage filtering approach significantly enhances the quality of the received signal, improving the system's sensitivity to acoustic perturbations. After filtering, the optical signal is split using a 90/10 optical coupler (OC) to separately detect signals originating from both the near-end and far-end sections of the fiber. This division enhances the dynamic range of the system, allowing it to capture acoustic events occurring at various locations along the fiber length with improved accuracy. The OC output is then photodetected by two photodetectors, and the signals are digitized using a high-speed data acquisition (DAQ) card. Signal pre-processing and advanced detection algorithms are then applied to analyze and classify acoustic events.

2. FIELD INSTALLATION AND PARAMETER OPTIMIZATION

The initial field trials of the system were conducted on a 40 km-long 154 kV overhead transmission line in Ankara, as shown in Figure 3. This transmission line consists of 112 towers, with variations in tower types observed along different sections of the route due to terrain and structural requirements. Additionally, the line includes 11 splice boxes, ensuring connectivity and stability throughout the fiber optic infrastructure. The total optical loss in the fiber cable remains below 0.3 dB per kilometer, maintaining high signal integrity for the DAS application, which is critical for reliable monitoring and event detection.

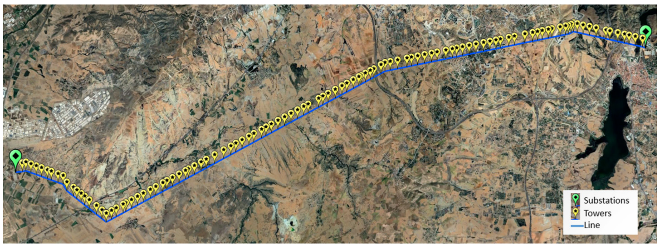

Figure 3: A map displaying the 40 km, 154 kV overhead transmission line in Ankara, with power towers shown along the route

Figure 4: Installation and fiber optic connection of the DAS system within a rack cabinet

The interrogation unit is securely installed within a rack-mounted cabinet located in a controlled environment within the substation control room, where ambient factors such as temperature and humidity are maintained within stable operating limits (Figure 4). The fiber optic connection from the rear panel of the interrogation unit is routed to the switch panel, where it is integrated into the test transmission line. The first 30 meters of the cable run through the interior of the building, protected from external environmental influences. Upon exiting the control room, the cable continues for an additional 350 meters underground. At the end of this section, the cable emerges above ground and is securely connected to an all-dielectric self-supporting (ADSS) fiber optic cable mounted on the first transmission tower closest to the substation. The ADSS cable is spliced to the OPGW located at the top of the transmission tower. The OPGW, which serves both as a lightning protection conductor and as a high-bandwidth communication medium [35-36], extends over a total distance of ~40 km, forming a continuous sensing path across multiple power transmission structures. The DAS system leverages this fiber optic link to monitor acoustic and vibrational signatures along the transmission corridor, covering a total of 112 transmission towers.

A user interface software was deployed in the operator room to facilitate real-time monitoring and interaction with the system. The raw data acquired through this interface was systematically recorded to enable offline post-processing and detailed analysis, allowing for a more comprehensive assessment of acoustic events along the transmission infrastructure.

The system's operating parameters were configured to achieve a total sensing range of 50 km, with a spatial resolution of 20 meters, corresponding to 2,500 sensing points—referred to as channels—along the fiber. Considering the speed of light propagation in the fiber core (~200,000 km/s), each round trip over the 50 km fiber requires approximately 500 µs. Accordingly, the interrogation interval was set to 500 µs, corresponding to an interrogation frequency of 2 kHz. This configuration establishes an acoustic sensing bandwidth of 1 kHz, ensuring effective detection and analysis of acoustic signals generated by mechanical disturbances, environmental effects, and unauthorized activities occurring in proximity to the transmission line.

The position along the fiber is determined based on the time-of-flight principle. The detected local intensity is the result of interference between scattered light components originating from scattering centers within

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the pulse envelope. Given the fact that the pulse covers 1 meter of fiber every 10 ns (round-trip), the arrival time of the backscattered signal can be directly converted into distance.

In this system, each channel corresponds to 20 meters. For instance, in Figure 5 (bottom), the signal appears to end at channel 2020, indicating a location of 2020 × 0.02 km = 40.4 km along the fiber. Similarly, in the waterfall plot shown in Figure 6, an acoustic event with a characteristic V-shape begins at channel 1924, corresponding to a location of 38.48 km. By mapping the DAS location information to the tower positions obtained from the map shown in Figure 3, the DAS system can identify which transmission tower is affected by a specific event and determine its distance from the central DAS control station.

For data analysis and visualization, a specialized dashboard software was developed to facilitate offline post-processing of the recorded data (Figure 5). The software provides detailed representations of the acquired acoustic signals through time-frequency analysis techniques, including waterfall plots for visualizing transient signal variations (Figure 6), channel spectrograms for spectral decomposition and feature extraction (Figure 7), and statistical representations of the interrogation data (Figure 8).

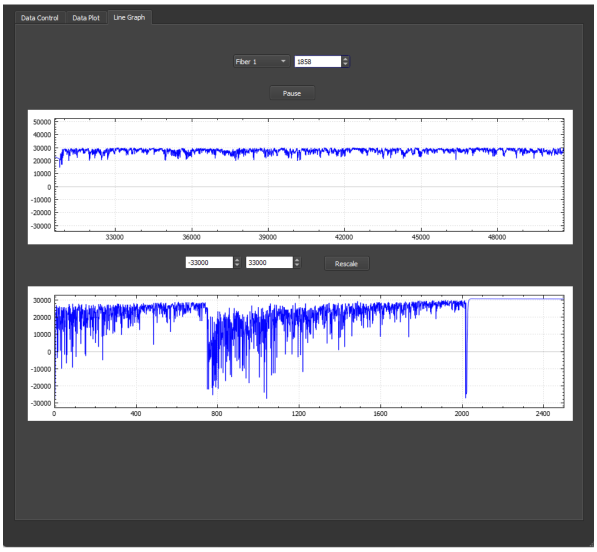
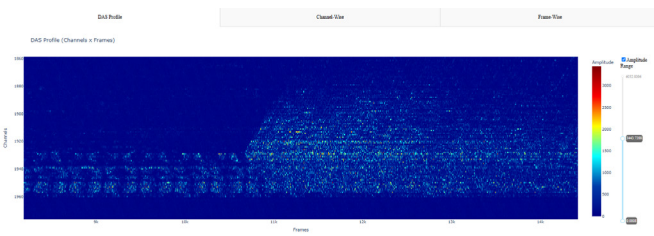


Figure 5: Rayleigh backscattering signal display screen



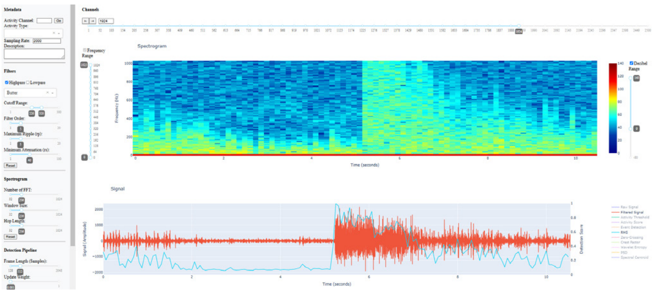


Figure 7: Channel spectrogram and selected signal features

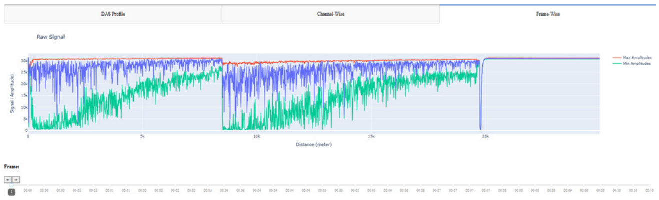


Figure 8: Raw data visualization and fundamental statistical parameters

3. PRELIMINARY DATA ANALYSIS AND SELECTION OF SIGNAL FEATURES

In the initial phase of data analysis, various signal features commonly referenced in the literature [37-40] were examined to evaluate their effectiveness in characterizing acoustic signals captured by the DAS system. These features, extracted from the acquired signal data, provide critical insights into signal characteristics, enabling the identification and classification of relevant acoustic events along the monitored transmission line. The key signal features considered in this study include the following:

- Energy: Measures the total power of the signal, providing an overall assessment of signal strength.
- Root Mean Square (RMS): Represents the root mean square value of the signal amplitude, which is indicative of signal intensity and power distribution.
- Peak Value: Identifies the maximum amplitude within the signal, highlighting extreme variations that may correspond to specific transient events.
- Crest Factor: Defined as the ratio of the peak value to the RMS value, this feature is useful for detecting sudden, sharp fluctuations in signal amplitude.
- Zero Crossing Rate: Counts the number of times the signal crosses the zero-amplitude line, serving as an indicator of signal frequency content and complexity.
- Spectral Centroid: Represents the center of mass of the signal spectrum, providing a measure of the dominant frequency components.
- Spectral Bandwidth: Measures the width of the frequency spectrum, reflecting the range of frequencies present within the signal.
- Spectral Roll-off: Identifies the frequency below which a certain percentage of the total spectral energy is contained, often used in signal classification tasks.

- Dominant Frequency: Determines the frequency component with the highest power, crucial for distinguishing between different types of acoustic events.
- Skewness: Assesses the asymmetry of the signal amplitude distribution, which can reveal deviations from normal signal behavior.
- Kurtosis: Measures the sharpness or peakedness of the signal distribution, indicating the presence of transient or impulsive events.
- Power Spectral Density (PSD): Represents the signal's power distribution across frequency components, essential for frequency-domain analysis.
- Wavelet Entropy: Utilizes wavelet transform to quantify signal complexity, capturing variations across different time-frequency scales.
- Sample Entropy: Evaluates the regularity and predictability of the signal, aiding in the detection of structured or chaotic patterns.
- Autocorrelation: Measures the similarity between a signal and its time-delayed version, providing information about periodicity and repetition in signal patterns.
- Temporal Centroid: Represents the center of mass of the signal's time envelope, indicating the temporal distribution of signal energy.

Following a detailed assessment of these features based on their relevance, robustness, and alignment with the acquired data, six features were identified as the most significant and effective for further analysis. These selected features demonstrated strong correlation with the observed signal variations and provided meaningful insights into the acoustic events detected along the transmission line. The key features retained for further processing and classification include:

- Root Mean Square (RMS): A measure of the signal's overall intensity and power distribution.
- Crest Factor: Useful for detecting transient peaks and abrupt changes in signal amplitude.
- Zero Crossing Rate: An indicator of signal frequency content and variability.
- Spectral Centroid: A frequency-domain feature that characterizes the dominant spectral components.
- Power Spectral Density (PSD): Essential for analyzing the energy distribution across frequency bands.
- Wavelet Entropy: A measure of signal complexity that captures transient and structured variations.

The selection of these features was guided by their ability to effectively distinguish between different acoustic events, such as hammering, unscrewing, metal cutting around the overhead line tower. These features will be utilized in subsequent analysis stages, including event classification and anomaly detection, to enhance the reliability and accuracy of the DAS-based monitoring system.

4. FIELD TESTS AND RESULTS

For over more than 8 months, the collaborative teams from TEIAS and NANOTAM have conducted over 20 field operations to collect and analyze data related to unauthorized activities on high-voltage transmission lines. These field studies have resulted in more than 200 distinct data recordings, encompassing a range of simulated activities designed to assess the system's detection capabilities. The experimental scenarios include the following:

- Case I: Hammering (Single impact or a series of five impacts with varying force levels)
- Case II: Unscrewing using a screw gun
- Case III: Unscrewing manually by hand
- Case IV: Metal cutting

Each activity was performed over a period of approximately five minutes, with the initial 30 seconds remaining passive to establish baseline conditions. The environmental conditions varied depending on the season in which the experiments were conducted. These activities were carried out on a total of 25 different transmission towers, located at distances ranging from 1 km to 40 km from the substation. A field operator performing controlled tests, including unscrewing by a screw gun and by hand on a transmission tower, is shown in Figure 9.

Figure 9: Controlled field test demonstrating unscrewing by screw gun and by hand on a transmission tower

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Figure 10: 154-kV transmission tower with removed iron components and structural weakening

5. CASE I: HAMMERING

Hammer impact tests were primarily conducted to refine the determination of fiber distances along the transmission line and to analyze the propagation behavior of acoustic signals along the OPGW. Initial observations from waterfall plots revealed that the vibrations induced by hammer strikes persisted on the tower structure for more than 4 seconds and propagated along the OPGW cable in both directions at a velocity of approximately 5000 m/s, forming a characteristic V-shaped pattern (Figure 11).

Further analysis indicated that acoustic signal transmission weakened significantly at fiber splicing points, where only minimal acoustic vibrations were detected (Figure 11, red arrow). This phenomenon was attributed to the structural configuration of the transmission towers, where the splicing enclosures were mounted at lower sections, and the OPGW cable was routed to these points using a different installation technique.

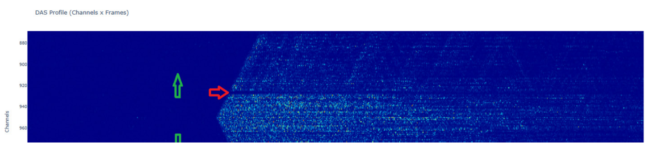

Figure 11: Waterfall representation of a single hammer strike on the transmission tower

To enhance the robustness of hammering detection, additional tests were conducted using five sequential impacts at varying force levels. The results, illustrated in Figure 12, show that as the applied impact force decreased, the high-frequency components of the acoustic signal diminished. Furthermore, as expected, the duration of the acoustic signal generated by hammering decreased to approximately 2 seconds.

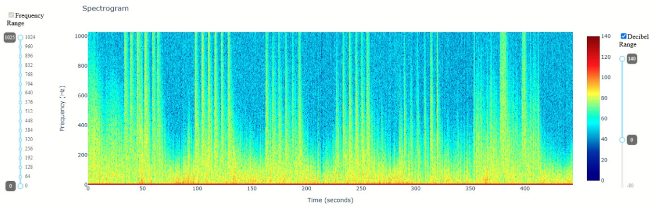

Figure 12: Spectrogram of hammering test with 5×5 repeated strikes

6. CASE II: UNSCREWING BY SCREW GUN

Automated unscrewing tests using a screw gun produced highly distinct acoustic signatures due to the repetitive and forceful nature of the mechanical operation. The resulting impact signals were distributed across the entire frequency spectrum, as depicted in Figure 13. Given the consistency of the force applied and the lack of significant acoustic noise between successive impulses, these characteristics make automated unscrewing events highly identifiable and distinguishable from other sources of acoustic disturbances.

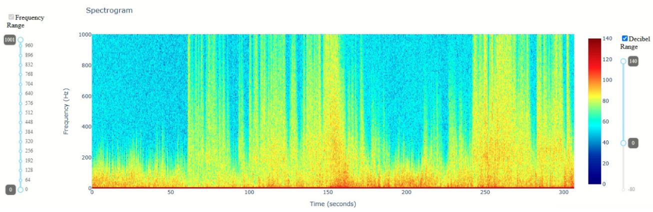

Figure 13: Spectrogram of unscrewing by screw gun

The influence of this activity on various signal attributes is clearly demonstrated in Figure 14, where significant variations in key signal features can be observed.

Figure 14: Feature representation of unscrewing by screw gun

7. CASE III: UNSCREWING BY HAND

Manual unscrewing tests exhibited considerable variability in detectability due to the dependence of the signal characteristics on individual operator behavior. The interaction between the worker and the tower structure led to variations in detection time and the potential for misclassification with surrounding environmental noise. As illustrated in Figure 15, weak interactions (green arrow) lacked high-frequency components, whereas strong interactions (red arrow) resulted in energy distributions spanning the entire frequency spectrum.

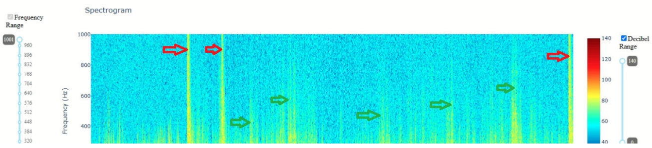

Figure 15: Spectrogram of unscrewing by hand

Additionally, the influence of manual unscrewing on signal attributes was found to be less pronounced compared to other activities, as depicted in Figure 16.

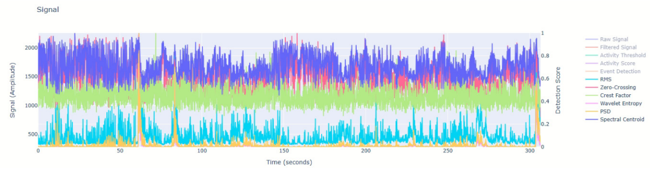

Figure 16: Feature representation of unscrewing by hand

8. CASE IV: METAL CUTTING

The acoustic signals generated during metal cutting tests were comparable to those observed in the automated unscrewing scenario, as shown in Figure 17. However, unlike screw gun operations, the cutting process did not exhibit impulsive characteristics. Instead, metal cutting produced continuous acoustic emissions with intermittent silent gaps, corresponding to moments where the cutting tool was not actively engaging the material.

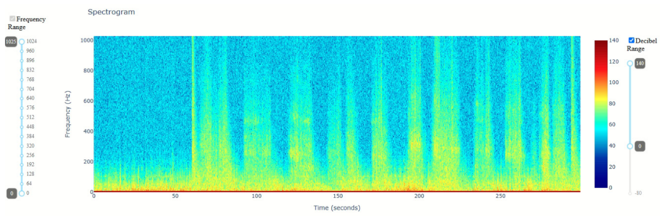

Figure 17: Spectrogram of metal cutting

Similar to screw gun activity, metal cutting significantly affected signal attributes, as demonstrated in Figure 18.

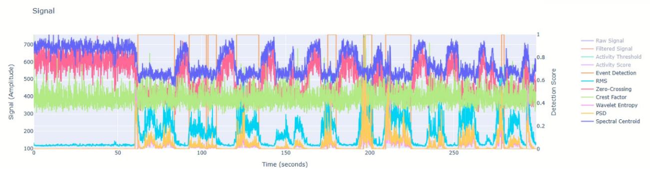

Figure 18: Feature representation of metal cutting

9. SIGNAL PROCESSING AND ACTIVITY DETECTION ALGORITHM

To detect unauthorized activities on TEIAS transmission lines, a signal processing and activity detection framework was implemented. Initially, the analog optical signals collected from the system were converted into digital format using analog-to-digital (A/D) converters. Subsequently, a preprocessing step was applied to the digital signal to remove background noise and enhance the signal-to-noise ratio (SNR).

Following preprocessing, activity-specific feature sets, details of which are explained in “Preliminary Data Analysis and Selection of Signal Features” section, were extracted to facilitate classification. In this study, two distinct feature sets were implemented: one based on RMS and another based on the crest factor. The selection of these features was guided by the following key criteria:

- The chosen features must contain sufficient information to distinguish activities.
- The selected features should be minimally affected by external factors such as wind.
- To enable real-time activity detection on the hardware platform developed within the scope of this project, the selected features must be computable in real time using the RAM and processor available on the Zynq Ultrascale+ platform.

Considering these criteria, frequency-domain FFT-based algorithms were not selected due to their high CPU and memory requirements. Additionally, the Zero Crossing Rate was found to be insufficient in terms of the data it provides for activity detection. The use of the Peak Value feature alone was also avoided, as it is highly susceptible to sudden changes caused by external factors such as wind. RMS and Crest Factor features were ultimately chosen because they not only provide sufficient information for activity detection but are also computationally feasible for real-time implementation on the Zynq platform.

The extracted features were utilized to compute an activity score, which was then fed into an activity detection module. This module evaluated the computed scores over specific time intervals to determine whether an activity had occurred. The overall workflow of the signal processing and activity detection methodology is illustrated in Figure 19.

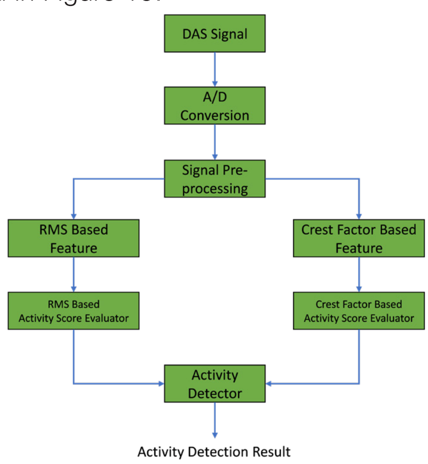

Figure 19: Flow diagram of signal pre-processing and activity detection

10. SYSTEM PERFORMANCE AND ACTIVITY DETECTION RESULTS

The developed algorithms were tested offline using 32 recorded data sets encompassing seven different activity scenarios. To minimize false alarms, 200 minutes of data were collected from periods without any activity. Additionally, 25 minutes of data resembling non-critical events—activities not requiring an alert within the project scope—were recorded.

To assess the system's detection performance under expected operational conditions, 60 minutes of hammering data were recorded. Furthermore, 55 minutes of activity data corresponding to manual unscrewing, automated unscrewing, and metal cutting scenarios were collected. The distribution of recorded data types and durations is summarized in Table I.

Table I: Summary of recorded activity types and corresponding durations

Activity Type	Number of Recordings	Total Duration (min)
No Activity	4	200
Limited Activity	5	25
Hammering	12	60
Unscrewing by Screw Gun	3	15
Unscrewing by Hand	6	30
Metal Cutting	2	10
Total	**32**	**340**

Using the recorded data, the signal processing and activity detection algorithms were systematically evaluated. During these tests, the system successfully detected 22 out of 23 activity events, yielding a high detection accuracy with only a single missed event (metal cutting using a jet saw). Importantly, no false alarms were recorded. A summary of the detection results is presented in Table II.

Table I: Detection performance results for various activity scenarios

Activity Type	Detected Activity	Missed Activity	False Alarm
Hammering	12	0	0
Unscrewing by Screw Gun	3	0	0
Unscrewing by Hand	6	0	0
Metal Cutting	1	1	0
Total	**22**	**1**	**0**

11. CONCLUSION

The findings of this study underscore the feasibility and effectiveness of fiber-optic Distributed Acoustic Sensing (DAS) technology for real-time monitoring of high-voltage power transmission lines in the infrastructure of the Turkish Transmission Grid. The system demonstrated robust detection capabilities across various controlled test scenarios, reliably identifying acoustic signatures associated with mechanical disturbances and unauthorized activities. The integration of advanced signal processing techniques enabled the extraction of meaningful features, facilitating accurate classification of different types of anomalies. Field tests confirmed that the DAS system could detect impulsive mechanical events such as hammering, unscrewing and metal cutting with high precision. Additionally, the analysis of vibrational patterns allowed for differentiation between normal environmental influences and potentially damaging activities. The successful application of feature-based classification and activity scoring methods further validated the potential of DAS technology as a powerful tool for grid security and maintenance. Furthermore, the near-zero false alarm rate observed during testing indicates that the system is reliable for practical deployment in real-world conditions. By leveraging the existing optical fiber infrastructure, the proposed system offers a scalable and cost-effective solution for continuous monitoring without requiring additional hardware installations at individual power towers. Additionally, expanding the system's coverage to longer transmission corridors and integrating it with predictive maintenance frameworks could further enhance its operational value. Overall, this study provides strong evidence supporting the adoption of DAS technology as a transformative approach to power grid monitoring, offering substantial benefits in terms of security, reliability, and operational efficiency.

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