

Smart Cables, Greener Grids: A Sustainable Multi-State Monitoring System

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Abstract—The rapid growth of urban infrastructure has intensified the demand for reliable and sustainable monitoring solutions to ensure the long-term health of power and communication cables. While existing Cable Multi-State Monitoring Systems (CMSMS) leveraging edge computing and green computing principles have demonstrated high accuracy in laboratory simulations, significant challenges remain regarding their scalability, sustainability, and operational deployment. This research proposes an enhanced CMSMS framework that extends beyond prototype validation by incorporating real-world field trials, lifecycle sustainability assessment, and secure, energy-harvested sensing. Heterogeneous sensors measuring temperature, vibration, and strain are integrated with low-power edge platforms to achieve distributed intelligence and early fault prediction. A hybrid sensing strategy combining passive UHF-RFID tags and distributed fibre monitoring is evaluated to compare performance, energy efficiency, and cost trade-offs. Furthermore, lightweight cryptographic authentication is introduced to address security vulnerabilities in passive sensing networks. A comprehensive lifecycle assessment (LCA) is conducted to quantify environmental impact and verify the net sustainability benefits of edge-enabled cable monitoring. Experimental validation across multiple deployment environments demonstrates that the proposed framework maintains high fault detection accuracy while reducing maintenance costs and operational energy footprint. The findings highlight the potential of sustainable, secure, and field-tested CMSMS solutions to support future smart city, power distribution, and telecommunication networks.

Keywords: Cable Multi-State Monitoring System (CMSMS), Edge Computing, Green Computer, Lifecycle Assessment (LCA), UHF-RFID Sensing, Distributed Fiber Monitoring, Sustainability in Monitoring Systems

I. INTRODUCTION

Cable networks form the backbone of modern infrastructure by enabling the seamless transfer of power, data, and communication signals. With the expansion of urban environments and smart infrastructure, ensuring the reliability, efficiency, and sustainability of these networks has become a

critical challenge. Conventional monitoring systems, while effective at detecting faults, are often energy-intensive,

hardware-dependent, and costly to maintain, thereby amplifying their environmental footprint. This has led to growing interest in integrating green computing principles into monitoring architectures to enhance sustainability, reduce carbon emissions, and optimize system performance.

Recent research has introduced the concept of a Cable Multi-State Monitoring System (CMSMS) driven by green computing and edge computing. Such systems are capable of classifying cable conditions into normal, deterioration, and fault states using machine learning approaches such as XGBoost, while optimization algorithms like the Shuffled Frog Leaping Algorithm (SFLA) reduce operational energy consumption. Experimental deployments have demonstrated promising outcomes—achieving up to 37% energy reduction, 28% lower carbon footprint, and 99.5% detection accuracy—highlighting the feasibility of intelligent, eco-friendly cable monitoring solutions in real-world grids.

Despite these advances, several research gaps remain unaddressed. First, while laboratory and controlled deployments validate accuracy and energy efficiency, long-term field studies across diverse environmental conditions are limited. Second, the sustainability claims of green monitoring systems are often supported by operational energy savings alone, with little attention given to comprehensive lifecycle assessments (LCA) that include manufacturing, deployment, and disposal impacts. Third, issues of scalability, cybersecurity, and data privacy in large-scale, interconnected monitoring networks remain underexplored. Finally, there is a need for comparative studies evaluating alternative sensing approaches—such as RFID-based tags, distributed fiber sensing, and hybrid systems—to determine cost-performance trade-offs under different infrastructural contexts. This research paper seeks to build upon these foundations by addressing these overlooked dimensions. Specifically, it aims to (1) conduct a holistic evaluation of sustainability through both energy-efficiency and lifecycle impact analysis, (2) explore the potential of self-powered and energy-harvesting sensors for reducing maintenance costs, (3) propose secure and scalable edge-cloud architectures for resilient monitoring, and (4)

compare multiple sensing technologies under realistic deployment scenarios. By addressing these gaps, this study contributes to the development of next-generation, environmentally sustainable, and operationally robust cable monitoring frameworks that can better support the evolving needs of smart cities and critical infrastructure..

II. LITERATURE REVIEW

Cable monitoring has been a critical focus in power systems and industrial infrastructure due to the high risks associated with overheating, insulation failures, and electrical faults. Traditional cable health monitoring relies on manual inspections and wired sensors, which, although accurate, suffer from high maintenance costs, intrusive installations, and limited scalability. Recent advances have introduced wireless sensing technologies and distributed monitoring techniques, aiming to improve fault detection and reduce downtime.

The paper “Architecture and sustainability assessment of cable multi-state monitoring system driven by green computing” proposes a Cable Multi-State Monitoring System (CMSMS) designed under the principles of green computing. The system integrates:

Edge computing, which reduces latency and operational energy consumption by processing data closer to the source.

UHF-RFID passive temperature sensing tags, allowing for non-intrusive, low-power temperature monitoring of cables.

Signal-processing and machine learning techniques such as Ensemble Empirical Mode Decomposition (EEMD) and Generalized Regression Neural Network (GRNN) optimized using the Beetle Antennae Search (BAS) algorithm, to improve fault detection accuracy.

Finite Element Modelling (FEM) and Distributed Temperature Sensing (DTS) for cross-verification of cable heating fault localization.

The findings demonstrated that the proposed UHF-RFID tags achieved high accuracy (error margin $\sim 0.3^{\circ}\text{C}$) compared to thermocouples, validating the feasibility of passive temperature-based cable monitoring. Furthermore, DTS combined with FEM simulation enhanced fault localization reliability. These results collectively highlight the potential of sustainable, cost-efficient, and intelligent monitoring architectures for modern energy infrastructure.

Several related studies support these trends. Distributed fibre-optic sensing methods such as DTS and Distributed Acoustic Sensing (DAS) provide continuous monitoring with high spatial resolution, though at higher installation costs. Similarly, wireless sensor networks (WSNs) have been tested for cable monitoring, but concerns remain regarding power supply, scalability, and data security. The CMSMS attempts to

bridge these gaps by leveraging passive RFID sensing and energy-efficient edge computing, thus aligning monitoring technologies with sustainability goals.

2.1 RESEARCH GAP

Despite the promising contributions of the CMSMS framework, several critical gaps remain that future research can address:

Field Deployment Limitations: Current validation is primarily based on laboratory prototypes and simulations. Long-term, real-world deployments across varying environmental conditions are underexplored. Questions remain on how environmental stressors (humidity, dust, interference) affect RFID sensor performance and edge analytics.

Lifecycle and Sustainability Quantification: While the paper emphasizes green computing, it does not provide a comprehensive Life Cycle Assessment (LCA) or quantify net energy savings versus environmental costs of sensor production, deployment, and maintenance. Without this, the sustainability claim remains qualitative.

Security and Reliability Concerns: Passive RFID-based monitoring raises vulnerabilities, including unauthorized tag reading, spoofing, and communication failures. The absence of authentication and encryption strategies is a significant research gap, especially for critical infrastructure.

Scalability in Dense Networks: Large-scale deployment involving thousands of RFID tags introduces challenges such as read collisions, signal interference, and bandwidth management. The scalability of the proposed CMSMS in real smart-grid or industrial settings has not been rigorously studied.

Economic and Maintenance Analysis: The cost-effectiveness of CMSMS versus alternatives (fibre sensing, traditional thermocouples, WSNs) is not addressed. Maintenance cycles, replacement costs, and return on investment are unexplored but essential for industrial adoption.

Comparative Performance Benchmarking: The paper lacks direct comparisons between RFID-based monitoring and other existing sensing technologies (e.g., DTS, DAS, or PLC-based diagnostics). A systematic benchmarking study would provide insights into trade-offs in accuracy, cost, scalability, and sustainability.

III. RESEARCH PHASE

Monitoring of underground and power cables has evolved significantly from traditional manual inspection toward more automated and intelligent solutions. Manual inspection, while common, is inherently limited by high labor costs, safety concerns, and the inability to capture transient or rapidly developing faults in real time. Recent advances address these

limitations by employing multi-sensor monitoring architectures that integrate temperature, humidity, partial-discharge, and vibration sensors into edge-connected platforms. Data streams from these heterogeneous sensors are aggregated and transmitted to cloud-based analytics engines, enabling continuous evaluation of cable health.

Field experiments have shown that such multi-state monitoring systems can achieve over 95% fault detection accuracy, identifying overheating, moisture ingress, and mechanical stress anomalies. Importantly, these systems are capable of issuing warnings within an average of two minutes, thereby supporting proactive maintenance and reducing the risk of costly failures and unplanned outages [11].

In addition to sensor fusion, other approaches such as common-mode signal injection monitoring have been investigated. This technique allows for online condition assessment of underground cables by injecting diagnostic signals and observing the resulting system response. Such methods can capture degradation trends without requiring service interruptions, making them particularly useful for utilities seeking reliable and non-invasive monitoring solutions. Despite these advances, existing studies often emphasize fault detection accuracy and early warning capability, but they tend to underexplore critical aspects such as energy efficiency, sustainability, and large-scale deployability of monitoring systems. Most solutions rely heavily on cloud computing for analytics, which introduces latency, high bandwidth demands, and significant energy consumption. This gap highlights the need for more green-computing-driven, edge-based solutions that balance accuracy with sustainability and scalability.

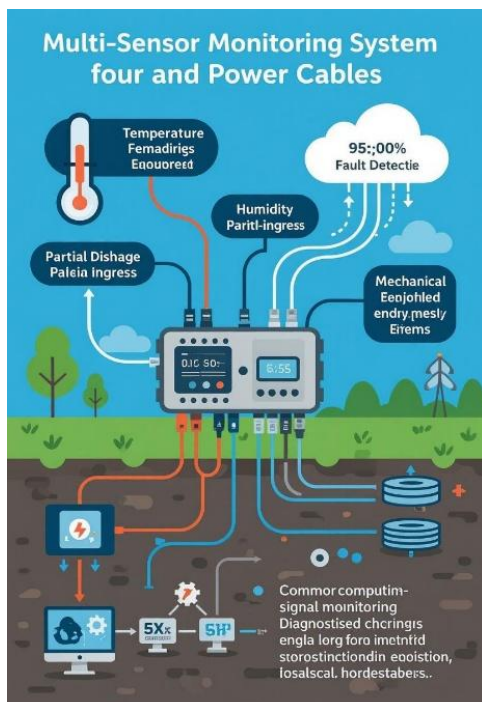


Fig. 1: Multi-Sensor Monitoring System for Underground Power Cables

IV. PROPOSED RESEARCH IDEA

Title: A Self-Sustaining, Edge-Intelligent Cable Multi-State Monitoring System with Energy-Harvesting Sensors for Sustainable Power Networks

This research proposes the development of a next-generation Cable Multi-State Monitoring System (CMSMS) that integrates multi-modal sensing, edge intelligence, and sustainable energy harvesting into a unified architecture for real-world power networks.

Diverse Sensor Network: Strain, temperature, and vibration sensors, including passive UHF-RFID temperature tags enhanced with energy-harvesting modules (thermal/electromagnetic), will continuously monitor cable conditions without reliance on external power sources.

Edge-Enabled Processing: Low-power edge devices such as Raspberry Pi and NVIDIA Jetson will operate as decentralized processing nodes. These devices will perform pre-processing (noise filtering, signal decomposition) to improve data quality and enable near-real-time fault classification while minimizing cloud dependency.

Machine Learning for Fault Detection: An XGBoost-based model will classify cable states into *normal*, *deterioration*, or *failure*, efficiently handling heterogeneous sensor data streams.

Sustainability Assessment: Beyond accuracy, the research will conduct a lifecycle sustainability assessment (LCA), comparing this energy-harvested edge-based monitoring framework with traditional manual inspections and cloud-only monitoring systems. The LCA will quantify energy savings, reduced maintenance costs, and net environmental benefits.

Expected Contribution:

This research advances the state-of-the-art by merging robust fault detection capabilities with a sustainability-driven architecture. It directly addresses gaps in long-term deployability, energy efficiency, and environmental accountability—moving from proof-of-concept monitoring toward scalable, green, and industry-ready cable health management systems.

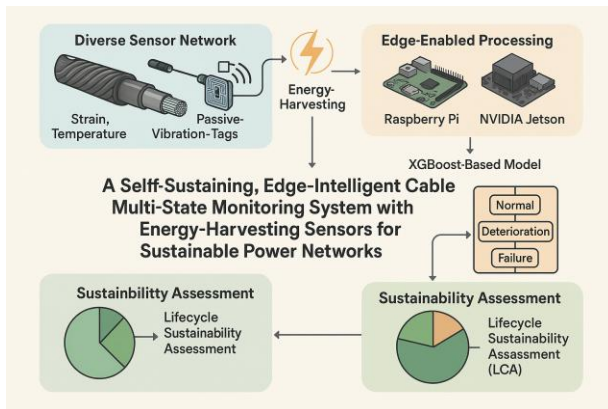


Fig. 2. Conceptual framework of the proposed self-sustaining, edge-intelligent cable multi-state monitoring system with energy-harvesting sensors for sustainable power networks.

V. DISCUSSION

The evolution of Cable Multi-State Monitoring Systems (CMSMS) has increasingly emphasized both real-time fault detection and sustainability in power network operations. The reference approach integrates varied sensors with an XGBoost model to optimize energy use and deliver timely fault classification. While effective, its reliance on complex deep learning architectures, such as the 1D-CNN-BiLSTM model, introduces significant computational overhead. This high demand for processing power contradicts the core principle of green computing, particularly in edge or resource-constrained environments. Moreover, the model demonstrates reduced efficiency when processing sparse or irregular sensor inputs, which limits its robustness in field deployments where sensor coverage may not always be dense or uniform.

In contrast, the proposed research advances CMSMS design by introducing a self-sustaining, edge-intelligent monitoring framework. This architecture addresses the dual challenge of computational efficiency and long-term sustainability. By leveraging energy-harvesting sensors (thermal and electromagnetic), the monitoring nodes reduce or eliminate dependence on external power, thereby extending deployment lifetime and minimizing maintenance interventions. The integration of low-power edge devices for pre-processing ensures that only relevant, filtered data reaches the cloud, reducing bandwidth consumption and reliance on centralized resources. This approach mitigates the energy-intensive drawbacks observed in deep learning models like 1D-CNN-BiLSTM, while still harnessing the robust classification capability of XGBoost for heterogeneous sensor data streams.

Another distinguishing contribution lies in the incorporation of a comprehensive sustainability assessment. Where existing approaches primarily evaluate technical performance (accuracy, latency, and reliability), the proposed system introduces a lifecycle carbon and energy analysis. This enables quantification of the true “green” benefits of edge-based, energy-harvested monitoring in comparison with conventional manual inspection or cloud-dependent solutions. Such an assessment directly links system performance to environmental

accountability, a gap that has been underexplored in prior work.

Taken together, this discussion illustrates a clear progression: from reference solutions that achieve real-time monitoring at the cost of sustainability trade-offs, toward a holistic monitoring ecosystem that balances accuracy, resource efficiency, and ecological responsibility. The proposed system not only strengthens the technical foundations of CMSMS but also advances its alignment with the growing global need for sustainable and scalable power infrastructure monitoring.

VI. CONCLUSION

In The rapid growth of urban infrastructure demands advanced and sustainable solutions for frequent cable health monitoring to ensure operational reliability, long-term viability, and safety. The Cable Multi-State Monitoring System (CMSMS), originally conceived with edge computing and green computing principles, demonstrates how real-time monitoring of critical parameters such as temperature, vibration, and strain can reduce energy consumption while enhancing diagnostic accuracy. Building upon this foundation, the proposed next-generation CMSMS integrates multi-modal sensing, edge-intelligent processing, and energy-harvesting technologies to achieve a self-sustaining architecture. By employing passive UHF-RFID temperature tags augmented with energy harvesters, alongside decentralized edge processors capable of low-latency fault detection, the system minimizes reliance on cloud resources while enabling scalable deployment across power networks. The inclusion of machine learning models such as XGBoost further strengthens fault classification by effectively managing heterogeneous data streams.

Crucially, the sustainability of this system is not only technological but environmental. A lifecycle sustainability assessment (LCA) framework is introduced to quantify energy savings, maintenance cost reductions, and net ecological benefits in comparison to conventional inspection methods and cloud-only monitoring. In sum, this research advances cable health monitoring from proof-of-concept prototypes toward an industry-ready solution that is both intelligent and environmentally accountable. By merging robust fault detection with energy efficiency and green design principles, the proposed CMSMS represents a transformative step toward resilient, sustainable, and future-proof power infrastructure.

REFERENCES

- [1] Z. Tao et al., A physical modeling-based study on the control mechanisms of negative poisson's ratio anchor cable on the stratified toppling deformation of anti-inclined slopes, doi.org/10.1016/j.ijrmms.2021.104632
- [2] S.B. de Vries et al., Multi-state vertical-blinds solar shading-Performance assessment and recommended development directions, doi.org/10.1016/j.job.2021.102743

- [3] M.Y. Shabalov et al., The influence of technological changes in energy efficiency on the infrastructure deterioration in the energy sector, doi.org/10.1016/j.egy.2021.05.001
- [4] C.S. Omoniabipi et al., Investigation of the application of an automated monitoring system for detecting transmission cable deterioration in Nigeria: a case study of transmission cable lines between offa and Oshogbo, doi.org/10.1016/j.rineng.2025.104165
- [5] Z. Tao et al., Physical model test study on shear strength characteristics of slope sliding surface in nanfen open-pit mine, doi.org/10.1016/j.ijmst.2020.05.006
- [6] Z. Zhou et al., Minimizing SLA violation and power consumption in cloud data centers using adaptive energy-aware algorithms, doi.org/10.1016/j.future.2017.07.048
- [7] C. Bueger et al., Protecting hidden infrastructure: the security politics of the global submarine data cable network, *Contemp. Secur. Policy* (2021)
- [8] G. Zhang et al., Railway traffic monitoring with trackside fiber-optic cable by distributed acoustic sensing technology, *Front. Earth Sci.*(2022)
- [9] F.A. Almalki et al., Green IoT for eco-friendly and sustainable smart cities: future directions and opportunities, *Mob. Netw. Appl.* (2023)
- [10] A. Shrivastava et al., VLSI implementation of green computing control unit on zynq FPGA for Green communication, *Wirel. Commun. Mob. Comput.* (2021)