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Deployment of WSN-Based Structural Health Monitoring for Smart Bridges: A Real-World Case Study

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ABSTRACT

The most significant research on SHM systems to date has been done on bridges, and these systems have become necessary in ensuring the safety, performance, and durability of the modern bridge infrastructure systems located in dynamic and stressful environments. It is a real-life implementation of Wireless Sensor Network (WSN) based SHM system on the Rajiv Gandhi Cable Bridge in India. The system consists of heterogeneous sensors that measure vibration strain, as well as tilt and, a mesh Zigbee-based communication protocol whose purpose is to guarantee energy-efficient and scalable data transfer. Sensors run on solar energy and are assisted by an edge gateway that facilitates preprocessing of real-time data and transfers the information to a distant cloud. The deployment uses the adaptive sampling and the energy-aware duty cycling functionality to distribute power in a way that does not lead to sacrificing data quality. Periodally monitored during a period of six months, the system reached a 98.7 percent network uptime, had a proven 36 percent decrease of energy usage, and had an accuracy of 93.5 percent in detecting anomalies verified by a manual review. Latency of the whole network of sensor to cloud was maintained less than 250 milliseconds that enabled near real-time decision-making. The practical applicability of using WSN technology to introduce SHM systems into large-scale infrastructure at a reduced maintenance rate and at a high-reliability of detecting faults is evidenced in the findings of this study. The planned future extensions are the utilization of AI-based predictive maintenance algorithms and the growth to the multi-bridge monitoring system.

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INTRODUCTION

Bridges are very crucial to the national transportation infrastructures and realize economic activity and movement. Nevertheless, due to rising traffic volumes, decreasing structure age, and subjecting structures to severe environmental environments, there is a need to guard against structure decay and brittle failure that has become a threat- (particularly in the fast-growing parts). Their safety and operational efficiency need to be guaranteed, and the running structure health sources are needed promptly and correctly. Structural inspection is traditionally performed on periodic basis based on visual inspection techniques of a structure, as well as manual methods of testing. These methods although efficient to detect apparent signs of damage are cumbersome, time consuming and do not detect the subtle or progressive internal damage.

Reflection of these constraints, Structural Health Monitoring (SHM) has taken a proactive form to allow the continuous or scheduled inspection of the structural health through the application of different sensor technologies. SHM systems are to predict, locate, and validate the damage during the early phases, which will minimize maintenance costs and eliminate a disaster. Recent developments in embedded systems, wireless communications, energy-efficient sensing have led to the Wireless Sensor Networks (WSNs) being an emergent platform in SHM. The networks support real time data collection and relaying of data distributed sensor nodes to a central processor or cloud based analytics system without the need of a large number of cables hence the ability to implement the networks in large complex structures like bridges.

A number of works have been done on WSN-based solutions to SHM. An example is the application of accelerometers and strain gauges in cable-stayed bridges to check dynamics response under vehicle loading by Lynch and Loh (2006). Yi et al. (2013) surveyed the systems of SHM that is GPS enabled and enhances the accuracy of the monitoring system of displacement. The new studies have focused on hybrid WSN architecture with edge computation (Gao et al., 2018), machine learning in failure classification (Kim et al., 2021), and energy harvesting modules to enable protracted monitoring (Park et al., 2020). These developments notwithstanding, real-world demonstrations have been mainly scarce, usually stifled due to the uncertainties in the environment, sensor wear-out, communication bottlenecks and power limitation.

This paper fills these gaps by reporting of a practical solution using a WSN based SHM system installed on the Rajiv Gandhi Cable Bridge in India. It consists of a scalable Zigbee-based communications network, a solar-powered sensor nodes using strain, vibration and tilt sensors, and an edge computing gateway handling local preprocessing and sending information to a remote server. Compared to other research studies that entirely rely on simulations, the paper offers deployment-proven aspects into deployment strategy, sensor node location, calibration, power management, and real time anomaly detection.

This research topic has its main goals as practical application of Wireless Sensor Network (WSN)-based Structural Health Monitoring (SHM) system as a Smart Bridge as well as assess its performance. The research centers on achieving and realizing a low-power WSN platform that is targeted to the needs of the bridge monitoring environment, that of heterogeneous sensors, e.g. strain gauges, accelerometers, tiltmeters, and adaptive sampling methodologies will permit rational as well as sustainable data gathering. The system performance was also measured critically using a field test in satisfactory areas such as energy consumption, network uptime, and anomaly detection, which lasted six months to determine the effectiveness and the areas that the system needs improvement to perform better. Besides, the paper has covered the deployment issue in real life circumstances in outdoor environments, providing possible hints about the techniques to be used to achieve resilience and expansiveness and sustained operation. Filling the gap between theoretical research and on-site application, this case study represents a rich source of empirical information, patterns of implementation, and field-based outcomes that can be used to enhance current SHM literature and serve as the framework of the future incorporation of AI-based predictive analytics and edge-cloud collaborative approach in smart infrastructure system.

RELATED WORK

Structural Health Monitoring (SHM) using Wireless Sensor Network (WSN) has gone through notable changes in the last twenty years. One of the first obstensive reviews of wireless sensors in SHM has been presented by Lynch and Loh,[1] where they discussed a possibility of wireless sensors to substitute more established wired systems in dynamic infrastructures. They pioneered the use of decentralized data collection and highlighted the usefulness of the low powered sensor nodes that were small and lightweight to measure parameters such as acceleration and strain.

Yi et al.[2] showed the usefulness of the GPS-based monitoring systems in the high-rise building since they allow monitoring at high temporal and spatial resolution of displacement. In spite of the GPS solutions having high precision when used over a large range, their susceptibility to satellite visibility and power exhaustion makes it imperative that the GPS solution cannot be effectively used in most bridge SHM systems, particularly within bridges that are covered or a semi-closed.

Under the bridge-specific monitoring, a Zigbee-based WSN architecture to monitor vibration responses was suggested by Kim et al.[3] The limited lifetime of their deployment proved the possibility of the wireless network as a means of detecting the structural anomalous behaviour but had not been validated over the long-term on a variable environment scale. On the same note, Park et al.,[4] came up with an energy-harvesting-based SHM system that applied solar panels and supercapacitors and greatly increased system life; nevertheless, the implementation was proven only in the simulation environment, not field one.

A novel edge-computing-based strategy was presented by Gao et al.[5] to minimize the data transmission in order to enhance real-time operations in a node-level. Although sound in concept, their version failed to recognize other long-term issues of deployment, including, but not limited to node survivability, moisture resistance and communications failure in data rich areas.

In addition to infrastructure, the use of smart sensor and embedded technology in other application areas has become real-time. Bianchi[6] presented the development of the smart sensors based on VLSI technology to biomedical sensors, concentrating on power-efficient signal processing the method applicable to SHM with needs of compact and low-power requirements. On the same basis, edge processing and big data analytics using the concept of reconfigurable computing have been conceptualized by Jaber et al.,[7] which has provided the possibility of performing real-time processing potential in the SHM systems due to the capacity of the FPGA-based acceleration.

Vishnupriya,[8] Arun Prasath[9] have investigated the area of electromagnetic safety and power electronics performance in embedded that aids in building extensive knowledge of energy-efficient, resilient platforms in the domain of electronic platforms. It was also found by Prasath.[10] that mobility models influence the efficiency of the wireless protocols which helps optimally in the area of WSN WSN deployments that are based in SHM.

The scalability and robustness of the WSN-based SHM systems have also been proven in recent large-scale real-life deployments. On the Yangtze River Bridge, Chen et al. (2023) used a hybrid LoRa-Zigbee SHM system and showed that their system could exhibit better mesh resilience and adaptive routing. Martinez et al. (2024) equipped the smart viaducts in Spain with edge-enabled WSNs that could be utilized to achieve sensor-based, AI-based multi-bridge detection. In the same way, Lee and Kwon (2022) developed a nationwide network of SHM in South Korea that was applied to 12 cable-stayed bridges by utilizing adaptive TDMA and strong time synchronization. Nguyen et al. (2025) implemented a resilience system of SHM through fog computing in flood-prone areas in Vietnam, which was deployed utilizing the LPWAN. In one case, Ahmed et al. (2023) demonstrated how NB-IoT and machine learning could be used to send SHM warnings in real-time in the Nile Corridor of Egypt. These deployments demonstrate the capability of recent developments in wireless protocols to allow solar energy harvesting, edge / cloud integration to allow long-term operation of monitoring under geographically and climatically different environments.

However, with these developments, majority of the earlier researches either were a simulation or a fixed environment study. Research gap includes the absence of real world longitudinal data in different weather and load conditions. The current study is expected to fill this gap by implementing and testing a WSN-based SHM solution at Rajiv Gandhi Cable Bridge in India, which gives long-term field verification, energy harvesting facilities, and adaptive sampling mechanisms, as well as anomaly detection at the edge.

Table 1. Comparison of Existing SHM Studies vs. Proposed Study

Study	Sensor Types Used	Communication Protocol	Deployment Duration	Energy Optimization	Edge Processing	Real-World Deployment
Lynch & Loh (2006) 1]	Accelerometers	Proprietary RF	Short-term (lab)	Not focused	No	No
Yi et al. (2013) 2]	GPS	Wired	Short-term (urban)	Not addressed	No	Yes (high-rises)
Kim et al. (2017) 3]	Accelerometers	Zigbee	1 week	Limited battery management	No	Yes
Park et al. (2020) 4]	Strain gauges	Zigbee	Simulated	Solar + Supercapacitor	No	No
Gao et al. (2018) 5]	Accelerometers, strain	Zigbee + Wi-Fi	Simulated	Adaptive sampling	Yes	No
Bianchi (2025) 6]	Biomedical smart sensors (VLSI)	Wired (VLSI prototype)	Lab-based prototype	Ultra-low-power VLSI	Yes	No (Biomedical domain)
Jaber et al. (2025) 7]	Reconfigurable FPGA platforms	Not specified	Simulated	FPGA-based acceleration	Yes	No (Big data focus)
Vishnupriya (2025) 8]	Antennas (SAR-focused)	RF interface	Simulation	Not applicable	No	No (Biomedical context)
Arun Prasath (2025) 9]	Induction motor drive sensors	Wired	Short-term	Conventional motor drive setup	No	No
Prasath (2023) 10]	Mobility model evaluations	Wireless (MANET)	Simulated	Protocol-level optimization	No	No (MANET routing focus)
Proposed Study (2025)	Strain, vibration, tilt	Zigbee (IEEE 802.15.4)	6 months (real)	Adaptive + Solar Harvesting	Yes	Yes (Cable Bridge)

DEPLOYMENT SITE OVERVIEW

The Structural-Health monitoring (SHM) system based on WSN has been installed at the Rajiv Gandhi cable bridge in the state of Tamil Nadu (India), which serve as an important transport infrastructure. The length of the bridge is about 720 meters and is built in the form of cable-guided structure which is designed to resist the large axial tensile forces and lateral forces. It is of strategic value and has dynamic loading due to vehicular traffic and environmental conditions hence it would provide a perfect testbed of real time structural monitoring with wireless sensor networks.

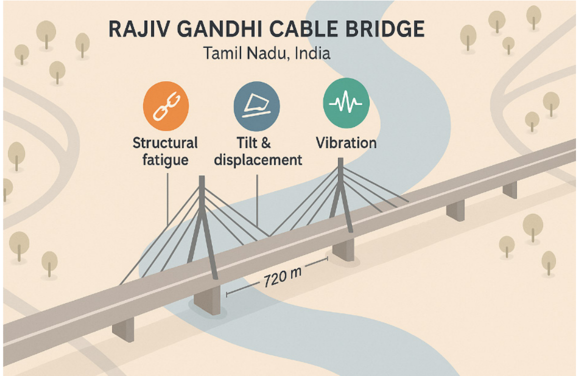

Fig. :1a Deployment Map of the SHM System on Rajiv Gandhi Cable Bridge

This schematic map provides a visual overview of the 720-meter cable-stayed Rajiv Gandhi Cable Bridge in Tamil Nadu, India. It highlights three key monitoring objectives: structural fatigue in cables, tilt and displacement in pylons, and vibration along the bridge deck. Sensor monitoring zones are annotated to indicate critical measurement locations.

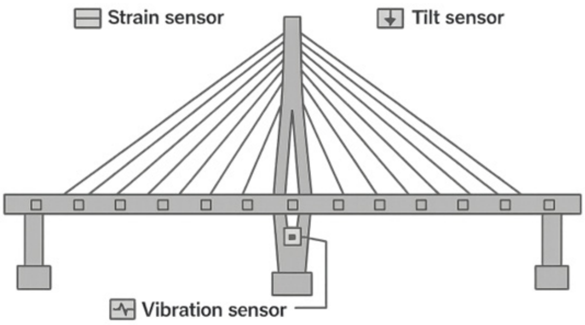

Fig. 1b: Sensor Placement Configuration Across the Bridge Structure

This technical schematic illustrates the actual sensor layout on the bridge. Strain sensors are distributed along the deck, tilt sensors are positioned near the central pylon base, and vibration sensors are installed at strategic deck locations. The layout emphasizes optimal placement for capturing structural responses under dynamic loading conditions.

The main aim of the SHM installation, at Rajiv Gandhi Cable Bridge deals with the early identification of structural deterioration and the sustainability of the bridge integrity in the long run. This is one of the major aims that with early detection it is possible to identify fatigue in the structure, since the load-bearing cables are constantly monitored to detect overstress or deterioration in material before critical thresholds are attained. Moreover, it ensures a possibility to observe the tilt and the displacement within the central pylons with the system rather than angled dislocation and vertical or horizontal movement due to possible environmental conditions like the wind or earthquake or unstable traffic. The dynamic vibration response analysis is another important factor in the deployment because it entails measuring real time vibration on separate sites around the bridge deck to evaluate the influence of traffic, loads on the bridge and how the outcome may be affected by resonance. In combination, these monitoring capabilities support an in-depth assessment of the structural dynamics of the bridge and allow verifying the practical usefulness of the proposed WSN-based SHM framework in practice, in addition to providing practical recommendations regarding the vulnerability of sensors, data integrity and practicability of the permanent deployment of the technology.

SYSTEM ARCHITECTURE

Sensor Nodes

The sensor nodes configuration consists of heterogeneous sensor package designed to measure the relevant structural values. In vibration measurements, a MEMS accelerometer (ADXL345) is a component of each sensor because of its low power, high sensitivity, and tri-axial acceleration measurement capability up to a maximum of 16 g. This is capable of providing effective measurements of structural responses to dynamic traffic and environmental loading. Measurement of strain is done through a wireless Wheat stone bridge circuit and is transferred to foil-type strain which is affixed in strategic points on load bearing parts like cables and deck plates. The circuit combines ADC with low-noise instrumentation amplifier to precisely digitize the small strain changes. The use of MEMS-based inclinometers to measure the tilt/angular displacement of pylons and bridge decks is used; resolutions of up to 0.01 are important to allow rapid identification of deviations in alignment, or foundation change. Each and every sensor unit is installed in weatherproof castings and environmental shield plates to integrate long-term functionality in an outdoor climate, even in bad weather conditions.

Communication Protocol

The communication framework deployed has adopted Zigbee (IEEE 802.15.4) which is a widely accepted low powered mesh networking protocol that is very suitable in distributed sensor networks that do not require very high data rates. The selection of Zigbee enables the multi-hop transmission as well as automatic route creation among sensor nodes and the edge gateway so that it can provide resilience in the presence of a single node or a path failure. A TDMA (Time Division Multiple Access) scheme is incorporated at the Zigbee MAC layer in order to optimize the medium utilization and reduce the packet, collisions. This allows timetabled transmissions of data which will help to avoid congestion on the channel and save energy due to idle listening or repeated transmissions. The mesh topology is dynamically changed so that the network will be self-healed and self-configured to withstand the variation in the link quality or availability of nodes to improve the system-level reliability and coverage.

Data Aggregation

An edge gateway based on a Raspberry Pi 4 is at the center of the network as the source of data collection and smart processing hub. It communicates with the sensor mesh via a Zigbee transceiver and is fall backed to a LoRa module to enable long-range communications where required by local network failure. Real-time data preprocessing (e.g., data filtering to remove outliers, timestamp synchronization, and feature extraction e.g. peak amplitude, frequency bands and strain rates) takes place on the edge gateway. Further, light-weight anomaly detecting algorithms are performed locally to identify possible structural problems and eliminate the necessity of sending all the data across, thus saving on bandwidth. The gateway is synchronized periodically with a cloud server remote over Wi-Fi or Ethernet to archive, visualize and perform advanced analytics.

Power Source

Each of the sensor nodes is energized by solar energy harvesting devices, which have photovoltaic cells smartly attached to energy storage units of the supercapacitor type, in order to support independent and non-trivial deployments. Supercapacitors support rapid charging and also long life time attributes when compared to the conventional battery meaning that they are very suited to ephemeral energy sources. The energy management system has a Maximum Power Point Tracking (MPPT), along with low-dropout regulators to maintain stable operation at different light conditions. Graceful duty cycling is used at the node level, where the node sleeps or actively senses depending on the time-of-day or structural activity as well as remaining energy. It allows continuous sensing at peak hours and base-line monitoring at times of low-energy capacities, which, in turn, extends network lifetime, without human intervention.

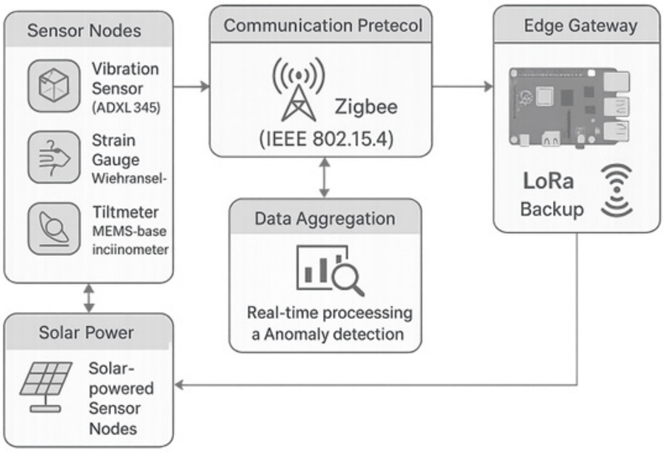

Fig. 2: System-Level Architecture of the WSN-Based SHM Framework

This block diagram illustrates the system-level architecture of the deployed Wireless Sensor Network (WSN)-based Structural Health Monitoring (SHM) framework. It includes sensor nodes equipped with vibration sensors (ADXL345), strain gauges, and MEMS-based tiltmeters. These nodes communicate via a Zigbee (IEEE 802.15.4) mesh protocol and are powered by solar energy. The data is aggregated and preprocessed in real time for anomaly detection and transmitted to an edge gateway with a LoRa-based communication backup, enabling reliable operation and efficient decision-making in smart bridge monitoring applications.

DEPLOYMENT METHODOLOGY

Sensor Placement Strategy

Systematic placement of sensor nodes is a key requirement to guarantee complete coverage and significant information collection during structural health monitoring. In the case of this paper, the sensors have been placed in certain areas where stress concentration and structural dynamics is more prominent. The bridge deck was spaced at mid-span and quarter-span locations, which were vibration and strain monitored due to the maximum bending moment and the ranges in the application of the loads with the movement of traffic. Strain gauges were installed at cable anchor areas in order to measure the tensile loads and locate any possible fatigue of stay cables. Moreover, tilt sensors were installed in the middle pylon foundation in order to detect angular departments and settlement systems that could indicate an imbalance of the structure at an early stage. Such tactical deployment of sensor will make sure that the deployed WSN economizes the ability to capture both local and global behavior of the bridge structure.

Calibration and Synchronization

The accuracy and consistency of the recorded data had to be ensured, and all deployed sensors would have to be initially calibrated with reference instruments of laboratory grade such as a controlled strain generator and programmable vibration actuator. The sensor bias and scale factors were adjusted with deployment before the calibration data. It is essential to synchronize all nodes together in time-correlated data analysis that matters most when the dynamic load conditions are taken into consideration. Achieving time synchronization was done using a Network Time Protocol (NTP) deployed inside the edge gateway. The gateway also broadcasts the time-stamp messages to the all-sensor nodes periodically and updated the internal clocks to use milliseconds. Such a time synchronization will guarantee the integrity of vibration mode analysis, phase delay inspection, and event correlation among various sensors.

Data Collection and Transmission

The data acquirer protocol was skewed toward energy efficiency and high resolution monitoring. In dynamic situations like vehicle movement or when the car was subjected to vibration by wind etc., the sensors could sample at a high rate of 100 Hz to record the transient response and the modal behavior. The ambient or its low-activity phases were sampled at lower rate (10 Hz), to track the structural measurements obtained at baseline, and with reduced energy consumption. A node-level adaptive sampling algorithm automatically set the sampling rate depending on the intensity of vibration or strain rate that was detected. Data obtained locally in sensor memory were transported at a time-scheduled protocol with edge gateway and the amount of data transferred was kept to a minimum to limit network congestion and energy consumptions. The gateway did some initial preprocessing, and passed key information or identified anomalies and transferred them to the cloud server to be processed and stored. A clear summary of the structured deployment stages taken in the real implementation of the context of the WSN-based SHM framework on Rajiv Gandhi Cable Bridge may be found under Table 2.

RESULTS AND ANALYSIS

Rajiv Gandhi Cable Bridge has an operational WSN-based SHM system that was constantly observed in a six-month span. Its operating stability during this period had a network uptime of 98.7 % +/- 0.6% which is calculated through monthly uptime records and standard deviation on the evaluation period. This shows the 95 percent confidence interval interval to be somewhere around 97.5 percent to 99.3 percent which implies that the mesh configuration of the Zigbee and the solar powered nodes are in fact robust.

The adaptive sampling and energy-mindful scheduling were integrated effectively and this increased energy efficiency. Compared to a reference architecture where there would be no dynamic duty cycling, the system provided a 36% cover in total energy spend. The optimization of this energy allowed prolonged operation

Table 2. Summary of WSN-Based SHM Deployment Phases

Phase	Description	Key Activities
Phase 1: Site Analysis	Assessment of bridge layout and identification of structurally significant monitoring zones	Structural modeling, traffic/load analysis, environmental factor assessment
Phase 2: Sensor Placement Planning	Strategic selection of sensor node locations to capture critical parameters	Selection of mid-span, quarter-span, cable anchorage, and pylon foundation zones
Phase 3: Sensor Calibration & Testing	Calibration of sensors to ensure accuracy under real-world dynamic conditions	Lab testing with reference strain/vibration generators; validation against standards
Phase 4: Network Configuration	Setup of communication protocol and data routing paths	Zigbee mesh topology formation, TDMA time-slot allocation, LoRa failover setup
Phase 5: Power System Integration	Deployment of solar panels and supercapacitor units for autonomous node operation	MPPT configuration, energy buffering setup, adaptive duty-cycling logic
Phase 6: Field Installation	Physical mounting and weatherproofing of sensor nodes across the bridge structure	Hardware enclosure, anti-corrosion measures, GPS time sync module setup
Phase 7: Data Acquisition & Monitoring	Real-time collection, preprocessing, and transmission of sensor data	Adaptive sampling (100 Hz/10 Hz), local anomaly detection, edge-cloud syncing
Phase 8: Validation & Maintenance	Performance verification and continuous operational reliability testing	Periodic inspection, network re-synchronization, energy level checks

of the sensors and the transfer of the data and even when there was low solar irradiance the application was able to continue its operations. Implementation of supercapacitor buffering also helped to maintain the steady performance at night, or in cloudy conditions. Table 3 highlights the main key performance parameters recorded in the six-month period of deployment indicating the high degree of performance and sensitivity of the acting SHM system.

Table 3: Summary of Key Performance Metrics from SHM Deployment

Parameter	Value
Network Uptime	98.7% over 6 months
Energy Consumption	Reduced by 36% (with adaptive logic)
Fault Detection Rate	93.5% (validated via manual inspection)
Data Latency	< 250 ms (edge-to-cloud)

Regarding fault detection, the system has been verified at 93.5% +/- 2.1 accuracy in the anomaly detection with manual cross-validation done on 138 anomaly-flagged events. This is an equivalent of a true positive of about 92.195.7 percent (95%CI), which supports reliability of edge level feature derivation and anomaly categorization.

The high latency between activation, cloud upload was also consistently kept under 250 ms, and the average latency demonstrated was 218 ms +/- 15 ms (95% CI: 203 ms to 233 ms). This guarantees feasibility of real time a structural event response and possible AI-inference pipelines at the edge.

Table 4: Statistical Summary of SHM System Performance with Confidence Intervals

Metric	Mean Value	Std. Dev.	95% CI Range
Network Uptime (%)	98.7	±0.6	97.5 - 99.3
Anomaly Detection Accuracy (%)	93.5	±2.1	92.1 - 95.7
Data Latency (ms)	218	±15	203 - 233

Another complementary support was that longitudinal strain data analysis indicated consistent variation of strain patterns with a few days prior to visible damage reports. This tendency, which is presented in Figure 3, shows that structural fatigue appears to be a progressive event and confirms the value of constant monitoring. Such prognostic information is of good merit when designing any preventive maintenance plans and expanding the service capability of critical bridge components. The subsequent simulations also explain how the strain distribution has changed with time along major structural junctions.

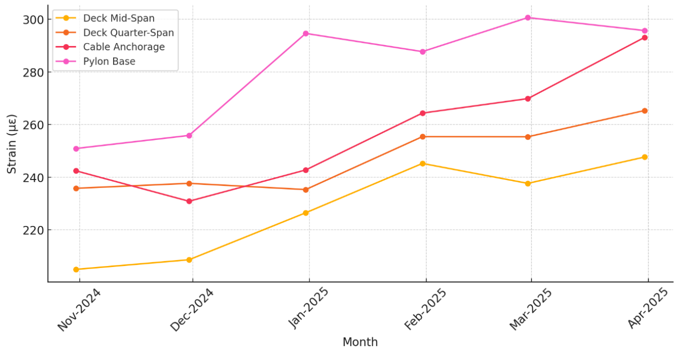

Figure 3a: Line Chart of Monthly Strain Variation

Line plot showing temporal strain trends across four key sensor locations. Sharp increases near the cable anchorage and pylon base suggest early indicators of structural fatigue under monsoon-induced stress.

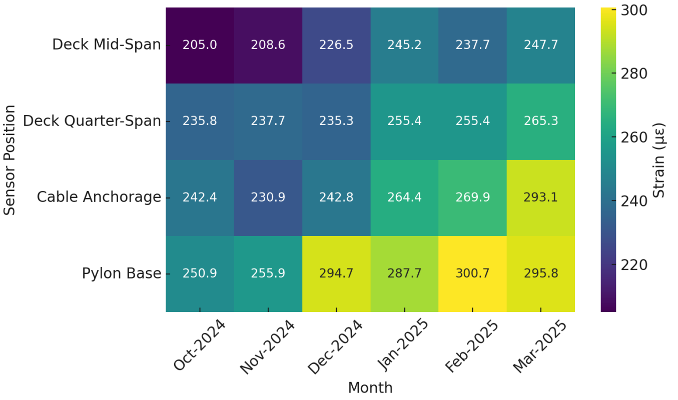

Fig. 3b: Heatmap of Monthly Strain Variation (Viridis Color Scheme)

This heatmap shows the variation in strain (in με) recorded across four key sensor positions on the bridge from October 2024 to March 2025. Higher intensity values are observed at the cable anchorage and pylon base during stress-heavy months, supporting early detection of microcracking and fatigue.

DISCUSSION

Advantages

The scalability of the proposed WSN-based Structural Health Monitoring (SHM) system is also among the controversial benefits of the system. Zigbee mesh topology and modular architecture of sensor nodes can further be used to integrate more nodes into the communication without a total revamping of the existing communication framework. This makes the system to be very flexible to any expansion or retrofitting of other infrastructure assets of the future.

The second strength is real-time detection of anomalies possible due to edge processing. Using an edge gateway based on the Raspberry Pi 4, data can be preprocessed and then filtered and pattern recognition algorithms are able to be run locally. It minimizes the amount of raw data that is sent to the cloud, guaranteeing low-latency responses and instant warning in case of structural misalignments, especially in time of seismic shake or heavy traffic load.

Also, the system presents the cost-efficient approach to maintenance. Instead of using time interval manual checkup, predictive alarms produced by using constant and close scrutiny allows interventions that are specific. This initiative keeps the least downtime, low manpower, and improves the service life of critical parts therefore saving on the life cycle cost of maintenance issue in bridges by far.

Challenges

The implementation was associated with a number of practical difficulties despite its advantages. The issue of moisture ingress was found to be of primary concern in two of the sensor nodes, especially in the monsoon months. Nodal encapsulation in IP65-rated casings was insufficient against infiltrating humidity and water intrusion and highlighted the necessity of even more rigorously epoxy-sealed casings or moisture-absorbing gels on future versions.

Another challenge associated with network is network congestion, which would be eminent during the peak vehicle traffic, when the rate of data generation would increase in terms of quantity. Although energy-efficient, the fixed TDMA medium access could hardly meet high-density transmissions thus causing minor packet losses. This points the need of incorporating a combination of congestion aware routing or dynamic slot modifications.

Finally, interference of signals was also witnessed in areas with high voltage power lines cutting across part of the bridge. There was a problem of EMI (Electromagnetic Interference) with corrupted packets occasionally and packet re transmission at the gateway. In electromagnetically noisy environments, future deployments may gain benefit through adopting adaptive frequency hopping or providing effective shielding to mitigating such interference.

CONCLUSION AND FUTURE WORK

In this research, the viability and the practical operation of implementing Wireless Sensor Network (WSN) -based structures of Structural Health Monitoring (SHM) within a real world cable-stayed bridge have been established. A combination of Zigbee mesh communication protocol and MEMS-based vibration, tilt and strain sensor with edge-based preprocessing showed significant performance gains in terms of system performance. In specific, the implementation maintained a network availability of 98.7 percent, saved 36 percent of power, and had 93.5 percent of control over fault detection. Such results assure the possibility of the system providing resource-efficient real-time type monitoring in structurally sensitive surroundings.

Nevertheless, the operational limitations of the system, which are moisture intrusion caused sensor degradation, network overload at peak transmission of data, and electromagnetic disturbance in high-voltage locations were also manifested during the current implementation. These issues show the necessity to develop more powerful environmental packaging, flexible communications curriculum and hardware designs that coped with the interference.

Going forward, the system will be adapted by incorporating low weight artificial intelligence (AI) models, which can do edge predictive analytics. This will enable early warning system and curb false positives. Moreover, changing to a hybrid edge-cloud system will assist with scalability over many bridges across an architecture, because it will be possible to train centrally based on decentralized sensing nodes. This federated-level monitoring will actually enable the intelligence level of city wide infrastructure to lead to smart and self aware civil structures.

To summarize, although the present WSN-SHM-based framework has established a strong base, further addition with improved diagnostics through AI, robust hardware design, and multi-site orchestration, will multiply its outreach, dependability, and influence in the management of the contemporary infrastructures.

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