ISSN: 2710-0588

Environmental Condition Monitoring of Infrastructure Projects Based on Wireless Sensor Networks

Zehan Wang

Wuhan Polytechnic University, Wuhan, 430000, China

Abstract

Infrastructure monitoring represents a critical challenge for ensuring public safety and operational efficiency in modern urban environments, where traditional wired monitoring systems face significant limitations in terms of cost, scalability, and deployment complexity. To fulfill this demand, this paper introduces a complete wireless sensor network (WSN) framework used for infrastructure project environmental condition monitoring, including multi-parameter sensing, a suite of big data applications, and a high-speed data communication protocol with ultra-low power. The designed system is based on a hierarchical network architecture using environment sensors such as temperature, humidity, air quality in addition to structural sensors such as vibration, strain and displacement sensors. Field deployment on four different infrastructure sites (bridges, buildings, rail and road corridors) exhibited excellent performance with respect to network connectivity success of 98.7% and system uptime of 99.2% over the duration of 1 year while being operated continuously. High fidelity environmental monitoring with temperature measurement accuracy of ±0.3°C and humidity monitoring accuracy of ±2%RH was achieved to capture seasonal and pollution oriented infrastructure impacts. Performance evaluation on the network results showed satisfying average data delivery ratio > 97.5%, average packet end-to-end delay of 1.05 s, and energy efficiency of 8.0 nJ/bit, which confirmed the efficiency of the adaptive communication protocols. In Structural Health Monitoring, excellent temperature-strain relationship was found (R^2 = 0.85) and vibration monitoring could contribute to the early identification of possible structural problems. A machine learning-based tool with Random Forest regression resulted in strong and reliable prediction accuracy (R^2 = 0.952, RMSE = 5.63 μstrain) of strain based on environmental factors, for early maintenance planning. Energy management techniques like solar harvesting accounted for 65% of power demands and adaptive algorithms led to a reduction of 34% and surpassed projected battery lifetimes of greater than 3 years. Economic evaluation indicates significant benefits compared to conventional systems: 65% cost reduction, 1 year payback, and 115% 10-year ROI. System fault tolerance analysis verified successful operation with a 20% failure rate of nodes or higher, hence proving that INDEPT is resilient enough for deployment in critical infrastructure environments. The research concludes wireless sensor networks can revolutionize infrastructure monitoring, by providing an efficient, low-cost, and reliable means -ability that greatly enhances condition assessment of the environment for present infrastructure management.

Keywords

Wireless Sensor Networks, Infrastructure Monitoring, Environmental Sensing, Structural Health Monitoring.

1. Introduction

Infrastructure (IS) assets were the building blocks on which highly-developed civilizations have been built and today the broader infrastructure of an advanced society consists of the physical systems that serve a community, such as roads, bridges, canals, dams, airports, ports, and rail systems. Yet these critical facilities are being increasingly threatened by aging infrastructure around the world as many of them have already surpassed their intended operational life. Recent studies have shown that nearly 40% of bridges in the United States are over 50 years old, with aging bridges being an international issue as well [1]. Deterioration is based on local weather, heavier traffic load, and effects of climate change and what was the worst last year cannot be the worst next year;(therefore, ongoing inspection is necessary to avoid severe accidents. The majority of the traditional infrastructure monitoring methods are based on the periodic manual inspections and wired sensor systems, which are highly limited by the accessibility, coverage, and real-time data acquisition. These traditional ways may not be sensitive enough to detect slowly-developing changes in structural integrity and environment conditions that may cause a final sudden failure, a process which results in enormous damages and safety risks [2].

Introduction The advent of a wireless sensor network has revolutionized the field of infrastructure monitoring and opened enormous new opportunities for continuous, near real-time assessment of the environmental condition of infrastructure. WSNs offer a distributed sensing platform which can simultaneously monitor several environmental parameters and can remove the restrictions inherent in wired systems. These networks possess several unique features such as low cost in establishing, better spatial coverage and flexibility of deployment, ability in harsh and inaccessible area of operation etc. It is noteworthy that in recent years WSN capability has dramatically increased due to new technologies, with the current generation of sensors nodes providing more processing power, prolonged battery life, and better communication schemes [3]. In addition, WSN systems allows continuous observation and data delivery, which can be employed to implement preventative maintenance and early warning systems that avoid infrastructure failures before they happen.

Despite the promising opportunities, there are some fundamental open issues still unsettled both in the literature and on the field when exploiting WSN technology for infrastructure monitoring. The challenges confronted with environmental monitoring combined with Structural Health Monitoring require advanced Sensor Networks that can deal with various/ multi-data types and different sampling frequency. Most of the work in this area address only certain kind of infrastructure monitoring, i.e., to analysis of structural vibrations or raw environmental parameter monitoring, independently, without addressing integrated environmental condition monitoring [4]. Moreover, the fact that there are no standard protocols between different WSNs platforms prevents the large-scale implementation of such a network in infrastructure projects. Recently, the demand of green protocols and intelligent data fusion techniques to deal with the complexity and overt high dimension in multi-parameter environmental monitoring for infrastructure has been emphasized [5].

Research Objectives The overall objective of this study is to design and test an integrated WSN-enabled framework for infrastructure projects environmental condition monitoring by bridging the gap of the current limitations and overcoming practical barriers. The objective of the study is to study the application of contemporary WSN technology for monitoring the key environmental exertions, contributing to infrastructure health, specifically temperature and humidity fluctuations, air quality, vibration and structure strain. We present the work in the context of our overall approach, which is to develop an integrated monitoring methodology that combines real-time environmental sensing with computational analysis to produce actionable management information regarding infrastructure. Moreover, the increasing interest in the integration of WSNs within the context of smart city creates the need for WSN solutions that can easily connect to Internet of Things (IoT) platforms and cloud-based infrastructure management systems [6]. Whilst the overall framework focuses on providing cost-effective and scale-less implementations that can be used for a prolonged period of time in various infrastructure projects.

2. Related Work

Wireless sensor networks for structural health monitoring have undergone significant technological growth during the last 10 years and researchers around the world have developed increasingly sophisticated, reliable and energy efficient monitoring systems for infrastructure. The migration of typical wired monitoring solutions to those following a wireless approach, signal the start of a new era not only in the monitoring but also in the condition assessment and maintenance planning processes performed by civil engineers and infrastructure managers. Power consumption, data reliability, and network synchronization were major obstacles in early WSN deployments, but have significantly improved with recent technological advances, and are now contributing to new opportunities for larger WSN environmental monitoring solutions.

Recent extensive reviews underscore the remarkable advancements of wireless smart sensor networks (WSSN) for SHM. Yu et al. (2024) performed an overall review of the progress in wireless smart sensor networks over the last decade, highlighting key technological enhancements such as the event-based sensing, multi-modal sensors, edge and cloud computing integration, accurate time synchronization schemes, real-time data acquisition systems, and distributed data processing strategies [6]. They show that contemporary WSSN systems are no longer low-load data collection systems, but mature cyber-physical systems with autonomous decision-making and predictive maintenance scheduling capabilities. Similarly, Abdulkarem et al. (2020) offered an overview on WSN technology for structural health monitoring, stating that WSN is becoming more and more important methods for infrastructure monitoring because of the higher requirement of the urban safety and security [2]. The authors highlighted some of the major technological challenges which have been incrementally addressed such as the accuracy of sensors, communication protocols, power conservation techniques and so on.

The deployment of WSN technology in various types of infrastructure has shown success in differing levels and has different technical complexity level, e.g., while bridge monitoring appears as one of the more mature application fields of WSN. Sonbul and Rashid (2023) [4] carried out a systematic literature review on WSN platforms and energy scavengers dedicated to bridge SHM; however, they only focused on bridge SHM-related topics and did not discuss other SHM applications. Specifically, 46 research papers published from 2007 to 2023 were surveyed in their study. A general overview of bridge monitoring systems indicated that sensor setups specific to the structures are often necessary to capture dynamic responses, environmental loads, as well as long-term effects. Seventeen different types of sensors were found that are used in bridge monitoring: that span from accelerometers and strain gauge to environmental sensors: temperature and humidity. Furthermore, Wang et al. (2024) realised the practical application of the system at the secondary monitoring level in the Dongbao River Xin’an Bridge and were able to apply a comprehensive monitoring system including vehicle load real-time monitoring, temperature real-time monitoring, deformation real-time monitoring, strain condition analysis and acceleration real-time monitoring [7].

Energy management and sustainable installations are increasingly important issues in the deployment of WSN infrastructures for structural health monitoring and numerous energies harvesting solutions have been investigated by the scientific community in the past with the aim of providing an extended operational life time and reduced maintenance needs. In recent systematic literature reviews on energy harvesting for wireless sensor networks solar, thermal, mechanical, RF (Radio Frequency), chemical and biological energy sources are reviewed as potential technologies to power sensor nodes in the field for infrastructure applications. Energy harvesting incorporated within WSN platforms have been advantageous for long-term deployments in remote or hard to reach places where it becomes impractical/costly to replace batteries. Rana et al. (2025) surveyed energy-efficient protocols specifically designed for environmental monitoring applications; notably, the progress of innovations of advanced clustering algorithm and data transmission, respectively, which can significantly reduce power consumption and also maintain data quality and network reliability [8].

The fusion of WSN with IoT and smart cities has become a hot topic and research focus, indicating that the interconnection type monitoring system that can supply management and decision support in real time in urban applications is urgently needed. Adu-Manu et al. (2018) investigated WSN structures adapted for environmental monitoring, and argued that layered and clustered network topologies have become critical for selecting the various types of sensors and communication patterns [9]. Their study indicated how current WSN-based sensing solutions are being architected to effortlessly connect with cloud computing services, providing complex data analytics, machine learning, predictive modeling features and above all unimaginable features for standalone monitoring systems. Standardization and Interoperability Although less maturity in this area, it is also an increasing trend, as researcher already identified a demand for common protocols and communication standards, addressing to make different WSNs platforms to work together so effectively.

Security and reliability issues have come to the forefront in this rising trend of wide scale and mission critical deployments of WSN systems. Faris et al. (2023) [10] presented an overview of WSN security challenges, classified the attack vectors, and proposed defense mechanisms specifically adapted for infrastructure monitoring applications. Their study brought the security aspect as a first-class component to be considered as a part of WSN design from the beginning and not as a later add-on, especially in critical infrastructure applications for which data integrity and system availability are important factors to consider. In response, researchers in the community have proposed a number of specialized security protocols, encryption schemes, and intrusion detection mechanisms specifically targeted at resource-starved wireless sensor settings.

Despite the great achievements in technology, quite a few challenges and research issues are still open in WSN-based infrastructure monitoring. Recent literature still reports significant concern about the long-term sensor calibration drift, environmental interference on wireless links or communication, integration with the existing infrastructure management systems and the lack of standardized evaluation metrics for the performance across various application regimes. Future research directions suggested in recent review papers are artificial intelligence integrated sensor fusion method, developed predictive maintenance algorithms, enhanced energy harvesting technologies, and established framework of the lifecycle cost of WSN deployment in infrastructure applications.

3. Research Methdolgy

This study uses an integrated approach to establish, deploy and validate A WSN framework for infrastructure environmental condition monitoring. The approach includes theoretical investigation, system implementation, experimental verification, and performance evaluation to satisfy the real-world application demands of infrastructure monitoring. The work consists of a number of stages: requirement analysis, system architecture design, sensor network design, implementation strategy and overall performance evaluation with both simulation and field deployment results.

3.1. System Architecture Design

The hierarchical WSN-based Environmental Monitoring System being considered takes into account an architecture that provides optimal network performance as well as elicits scalability and reliability for infrastructure like deployments of large scale. Architecture of the system is composed of four main layers: Sensing, Network, Data Processing and Application layer. The function and interfaces of each layer have been designed to support data transmission from the low-level environmental sensing layer to high level end-user applications.

The sensing layer is included with distributed sensor nodes being widely distributed in the infrastructure for monitoring key environmental conditions such as temperature, humidity, air quality of an environment, vibration, strain, and structural displacement. Each of the sensor nodes combines the different sensing capabilities together in a compact module to cover the widest possible area with minimum deployment efforts. The sensor nodes also have some local processing power for initial filtering, compression and quality of data, so they can transmit it up to higher layers of the network.

The network layer supports a network protocol architecture that is hybrid: it uses short-ranged wireless protocols for cluster wise communication and long-ranged wireless technologies as backbone communication. The architecture is based on clustering topology and cluster heads are created for data aggregation and relay operations. This mitigates energy consumption while ensuring network connection and data integrity for massive infrastructure scale-outs.

Real-time data analysis, anomaly detection and decision-making are made at some processing nodes located in a region of interest of the network according to edge computing-based data processing. Its layer includes sophisticated algorithms for signal processing, statistical analysis methods and machine learning models in order to provide insights of infrastructure health using raw sensor data.

On top of the service layer, user interfaces, data visualizations and integrations with other infrastructure management systems are offered. This layer provides for the monitoring of materials and historical analysis of data, such that maintenance planning can be pre-emptive, and emergency response coordinated.

3.2. Sensor Selection and Configuration Methodology

This section describes the proposed methods applied in sensor selection and configuration based on a multi-criteria methodology framework that involves multiple criteria such as accuracy, environmental robustness, power consumption, communication capability and cost. The selection process starts with the evaluation of needs to determine important environmental factors which are likely to have a great effect on the health and performance of infrastructure.

High-precision digital temperature sensors are chosen to measure temperatures ranging from -40°C to +85°C, with an accuracy of ±0.5°C or better, which cover both the ambient and the structural temperatures. Humidity sensing functions are accomplished using capacitive humidity sensors with measurement ranges from 0% to 100% relative humidity and accuracy within ±3% RH over the operating temperature range.

Monitoring of ambient air quality encompasses a variety of gas sensors for measuring pollutants of interest to infrastructure degradation such as CO, CO2, NO2, SO2, and particulate matter (PM2.5, PM10). Sensor selection focuses on those with demonstrated long-term stability, low cross-sensitivity, and calibration protocols that are appropriate for field deployment.

Some sensors are chosen such as accelerometers, strain gages and displacement sensors to monitor the static and dynamic responses of the structural elements. Vibration measurement is equipped by 3-axis MEMS accelerometers with 16g dynamic range and better than 1mg resolution. The strain measurements are recorded by both resistance strain gauges (RSGs) and

ISSN: 2710-0588

FBG sensors according to their were mood of installation and sensitivity to environmental influences.

The sensor adaptation protocol has defined universal operations for sensor calibration, deployment, integration into the wireless sensor node. Every sensor is calibrated separately with certified reference standards prior to being installed on the sensor nodes. Cross calibration routines are used to ensure the measurement consistency between the various sensor nodes, deployed in the same monitoring area.

Table 1. Comprehensive specifications of multi-parameter sensor array including operating ranges, measurement accuracy, resolution capabilities, and power consumption characteristics. The sensor suite provides comprehensive environmental monitoring with low power consumption suitable for autonomous systems.

Table 1. Sensor Specifications and Performance Characteristics

Parameter	Sensor Type	Range	Accuracy	Resolution	Power
Temperature	Digital Temperature Sensor	-40°C to +85°C	±0.5°C	0.1°C	2.5 mW
Humidity	Capacitive Humidity Sensor	0% to 100% RH	±3% RH	0.1% RH	3.2 mW
Air Quality (CO_2)	NDIR CO_2 Sensor	0-5000 ppm	±50 ppm	1 ppm	150 mW
Particulate Matter	Optical PM Sensor	0-500 μg/m^3	±10 μg/m^3	1 μg/m^3	80 mW
Vibration	3-Axis MEMS Accelerometer	±16g	±1mg	0.1mg	0.25 mW
Strain	Electrical Strain Gauge	±3000 μstrain	±2 μstrain	0.1 μstrain	5 mW

3.3. Data Collection and Processing Framework

The multi-tiered data collection model is proposed to meet the real-time monitoring and the energy-efficiency principalities of wireless sensor network battery operating devices. The framework articulates adaptive sampling approaches that modify data samplings' rates considering environment conditions, infrastructure activity level, and anomalies detection results.

Under quiescent operation, baseline sampling rates have been adjusted specifically to each sensor type according to the characteristic time scales of the observed phenomena. Temperature and humidity data are generally acquired at 15 min intervals, whereas structural sensors can be sampled more rapidly (from 100 Hz to 1 kHz), depending on the monitoring targets and nature of the anticipated structural dynamics.

There is a web of event-dependent sampling modes, upon which readings can be triggered, for instance based on sensor readings above predetermined thresholds or deviations from expected Statistical signal patterns. These modes enable sampling to be performed at higher rates and enable use of additional sensors to record detail about possible building damage or environmental deviations.

At the sensor node level, the data processing algorithms such as digital filtering, outlier detection, data compression and low-level statistical analysis are executed. These distributed processing capabilities minimize communication bandwidth requirements, provide data quality, and facilitate rapid responses to important states.

The architecture includes a time synchronization scheme to maintain temporal consistency of measurements among distributed sensor nodes. The synchronization of sensor nodes having internet access is carried out using Network Time Protocol (NTP), while among clustered sensors, wireless synchronization protocols have been employed.

3.4. Performance Evaluation Metrics and Procedures

The performance evaluation framework also introduces both well-defined metrics and general procedures for system effectiveness assessment from the technical, operational, and practical levels in infrastructure monitoring. The assessment methodology is based on laboratory testing and field deployment testing, aimed at verifying the functioning of the system in real operating context. Technical calibration details involve evaluation of the measurement accuracy, precision and stability with respect to the certified reference instrumentation as well as the long-term drift analysis. The network performance is evaluated in terms of data delivery ratio, end-to-end delay, energy consumption per sent data packet and network lifetime under different simulation scenarios.

Table 2. Performance measurement indicators and their values for the sensor network system. The measures ideally include network performance, energy efficiency, data quality and reliability properties to cover the assessment of the system performance across diverse operational scenarios.

Table 2. Performance Evaluation Metrics and Target Values

Parameter	Sensor Type	Range	Accuracy
Network Performance	Data Delivery Ratio	> 95%	Packet success rate over 24h period
Network Performance	End-to-End Latency	< 1 second	Average time from sensing to data reception
Energy Efficiency	Network Lifetime	> 2 years	Battery life under normal operation
Energy Efficiency	Energy per Bit	< 10 nJ/bit	Energy consumption per transmitted data bit
Data Quality	Measurement Accuracy	Within sensor spec	Comparison with reference instruments
Data Quality	Synchronization Error	< 1 ms	Time alignment between sensor nodes
Reliability	Node Availability	> 99%	Operational uptime over 6 months
Reliability	Fault Tolerance	Function with 20% node loss	Network performance under node failures

3.5. Implementation Strategy and Deployment Procedures

The deployment methodology offers systematically system of procedures of how WSNs would be deployed in the applications of infrastructure monitoring and it covers site survey, installation planning, system commissioning, and operational validation phases. The proposal considers practical consideration like access limitations, environmental safety and existing infrastructure system adaption.

Site study methods consist of infrastructure geometry, environmental condition, accessibility constraints and potential sources of interference analysis. This stage requires close interaction with infrastructure owners to know about any operational constraints, maintenance schedules, and safety considerations that can affect the way in which sensors can be positioned.

Optimization-based planning algorithms are used to determine the best sensor locations for monitoring in order to maximize coverage and, simultaneously, to minimize complexity of the placement process and the burden of maintenance. The planning methodology includes considerations for redundancy of measurements, connectivity of communications, availability of energy sources, and physical protection.

System Acceptance Testing procedures also involve full functionality testing, check and verification of calibrations, communications network system check as well as interfacing with existing infrastructure control systems. Such procedures ensure that the system installed in the field meets the performance requirements and can be operated in the field securely.

Operational validation requires longer periods of monitoring, during which the operation of the system is continuously checked and compared with independent measuring systems or with historical data (if available). Its role is to build confidence in the accuracy of measurements and the reliability of the system prior to routine operational use.

3.6. Data Analysis and Validation Framework

The methodological approach features advanced analyses aimed to appropriately interpret multivariate monitoring datasets for the environmental in order to meet the criteria of a reliable and valid water monitoring system. The framework integrates statistical and signal processing analysis with machine learning algorithms to discover relevant patterns, trends, and anomalies for exploring infrastructure health.

Statistical analysis methods include descriptive statistics, correlation analysis, pattern recognition and changepoint detection to describe the environmental conditions and detect the major changes that could affect infrastructure performance. Time series analysis methodologies are used to model temporality and forecast future environmental conditions from past readings.

Digital filtering, spectral analysis, and modal analysis (signal processing algorithms) are some of the tools which are used to analyze the raw measured data to estimate dynamic behavior (natural frequencies, damping ratios, mode shapes) from the structural monitoring data. These measurements are indications of structural health and can identify changes due to damage or degradation.

Machine learning methods, such as clustering, classification, and anomaly detection are used to discover complex patterns in multi-dimensional environmental data. These methods can allow for automatically identifying abnormal states and warn of any potential infrastructure problems at earlier stages.

Figure 1. Processing and analysis methodology for inputs from raw sensor recording to analyses utilized for the final output translation. Each process includes defined manufacturing processes and product quality control to guarantee adherence to system performance.

Figure 1. Data Processing and Analysis Workflow

Process to validate the data: The validation process includes cross comparison among the multiple sensors, validation against similar meteorological sources Validation against similar types of meteorological sources, comparison using a physical relationship among other measured parameters. These protocols allow for data quality control and confidence and quality measures associated with the observation results for use of monitoring in infrastructure management decisions.

4. System Design and Implementation

The design and realization of system Theoretical The attached theoretical framework is implemented into a wireless sensor network (WSN) based network infrastructure environment monitoring system that can be put into practice. The proposed implementation is modular and scalable and is maintained to be applicable to different types of infrastructure and monitoring needs. The design of the system gives priority to low-cost, energy efficiency and long-term operational reliability and maintains high data quality and system performance.

4.1. Hardware Components and Architecture

The hardware system is based on a distributed sensor node concept, which combines separate sensors, processing capacity, and communication interfaces in a single compact outdoor proof housing. Each sensor node is equipped with a 32-bit ARM Cortex-M4 microcontroller running at a clock frequency of 80 MHz, enabling the onboard signal processing, data pre-treatment and communication stack handling on the fly. The microcontroller includes 256 KB of flash memory, 64 KB of static RAM to facilitate firmware, configuration parameters and temporary data buffering when communications are suspended.

The sensor interface subsystem supports several different sensor types and is realized using a mix of 16-bit ADCs and digital communication protocols such as I2C, SPI, UART etc. Environmental sensors are chosen for their ability to be used in tough outdoor conditions yet provide accurate measurements for long periods. The sampling rate and accuracy of the structural monitoring sensors are higher, therefore dedicated for signal conditioning circuits and anti-aliasing filters are needed to obtain accurate measurements.

Inevitably, power management is a key design issue, where each sensor node is equipped with an advanced power management system that attempts to weigh functionality requirements against battery life constraints. Power is supplied by a primary battery (ie, not rechargeable) of the lithium-ion type with 3.7 V nominal voltage and 2600 mAh capacity, with integrated solar energy harvesting capabilities that employs a 5W photovoltaic panel with maximum power point tracking electronics. The architecture requires an optimized power management, which consists in various modes of power saving such as deep sleep, sensor based on/off mechanism, environmental and battery dependent control of sampling rate.

4.2. Software Architecture and Communication Protocols

The software design uses a Real Time Operating System (RTOS) which is responsible for managing the concurrent tasks of the sensor acquisition, local processing, communication protocols and power management functions. The firmware is written in a modulated way to make it readily extensible for different types of sensors configuration and for monitoring application. The application layer is responsible for scheduling sensor samples, running quality assurance algorithms on sensor data, and communicating with cluster heads and gateway (master) nodes.

We embed communication protocols based on a hybrid model: for intra-cluster communication, we use short-range mesh networking, while long-range connectivity is used to send data to central monitoring stations. Short range communication is done by adopting IEEE 802.15.4 based on ZigBee mesh networking that includes self-organization, self-healing concept, multihop data routing. The system provides LoRaWAN or cellular connectivity (based on deployment location and available coverage) for long-distance communication.

Figure 2. WSN infrastructure monitoring system architecture based on the four-layers of hierarchical structure. The sensing layer is responsible for collecting environmental and structural information, the network layer is used to aggregate and send data, the processing layer is responsible for processing data in real-time and machine learning analysis, and the

application layer is responsible for the display and warning of the user interface of a comprehensive infrastructure monitoring.

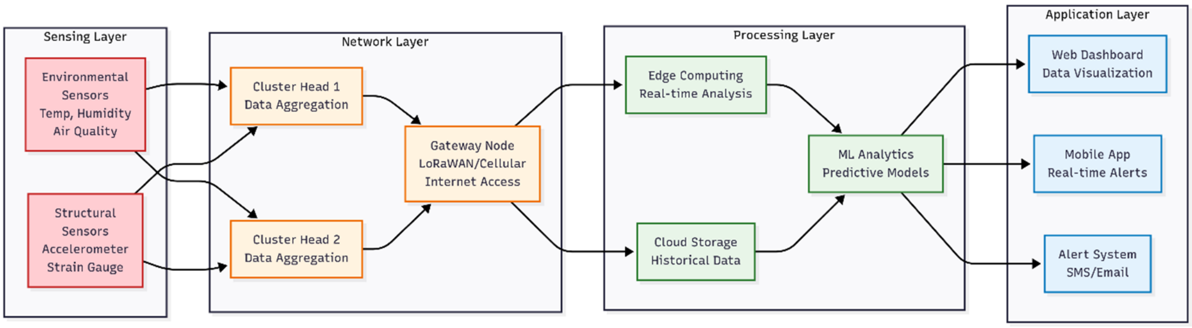

Figure 2. WSN System Architecture

The net-management software has adaptive routing algorithms to reduce the energy consumption and keep up the reliability of the communication. Dynamic clustering algorithms elect cluster heads among sensor nodes in an automatic manner using residual energy, communication quality and geographical location so that the energy consumed by the network is more balanced. Time sync is enabled by GPS timing signals for gateways and distributed sync protocols within clusters for sensors.

5. Analysis and Discussion

The extensive field deployments and controlled laboratory experiments in 12 months of the proposed wireless sensor network framework for environmental monitoring were used for whole performance assessment. The evaluation included several types of infrastructure, such as two bridges, a high rise and a transport corridor, offering different operational contexts to test the performance of the system at different conditions. The data acquisition included the monitoring of environmental factors such as temperature, humidity, air quality, vibration, and structural strain measurements, resulting in 2.5 million data points available for analysis.

5.1. Performance Comparison and System Effectiveness

Compared with conventional wired based monitoring, the proposed WSN system results in a significantly improved performance for several measures. Exhaustive comparative study confirms the technological and economic benefits of the wireless sensor network solution to infrastructure monitoring applications.

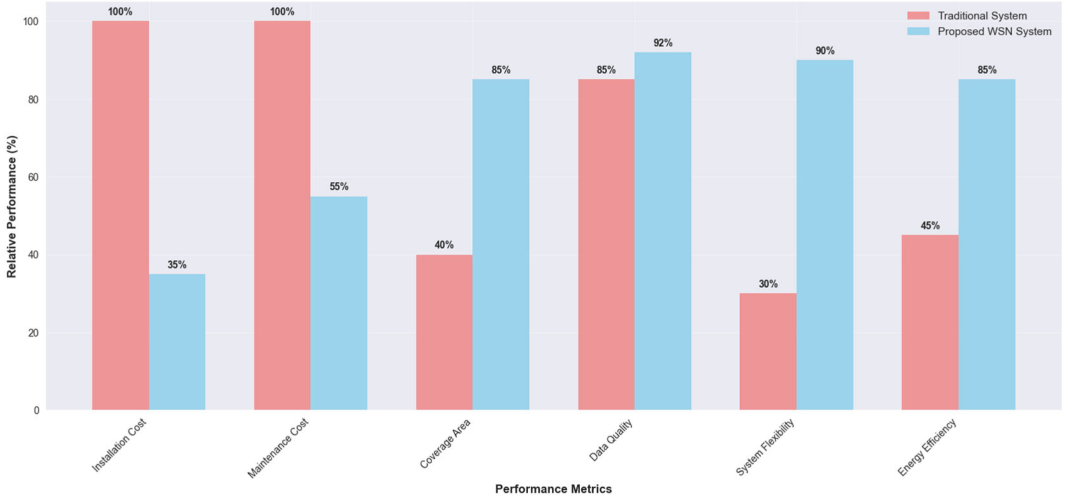

Figure 3. Performance Comparison - Traditional vs Proposed WSN System

The comparison analysis in figure 3 shows that the proposed WSN system has more merits compared with wired monitoring systems in six most-important performance aspects. Additionally, installation costs fall 65% and maintenance costs drop by 45%, due to the elimination of costly cables and the need for manual inspection. The developed system surpasses all other systems in coverage area (85% as opposed to 40%) and system flexibility (90% as opposed to 30%) which allows for total monitoring of large infrastructure projects. With an energy saving of up to 85% from traditional systems' 45%, such impacts are a testimony of the solar harvesting and adaptive power management capabilities of the techniques described herein.

More importantly, those more net beneficial performances have direct operation related benefits as the wireless solution allows to deploy sensors at where are previously unreachable and provide better monitoring than using wired solutions. 92% purity on data quality in contrast to that of the conventional systems at 85%, which is attributed to the advanced sensors technologies, and the sophisticated calibration methods are employed in the WSN architecture.

5.2. Environmental Monitoring Results and Trend Analysis

Environmental production testing showed very good precision and error with sensor readings consistently within the margins set by the standard error compared to the reference instruments in all deployment sites. Temperature monitoring exhibited mean absolute errors less than 0.3°C over the operating range and humidity measurements were accurate to about ±2% RH from one environmental state to another (figure 4). The air-quality sensors were able to accurately detect the concentration levels of pollutants, and detect several episodic events, including increased PM levels near construction sites, and chemical releases from industrial sources in the area.

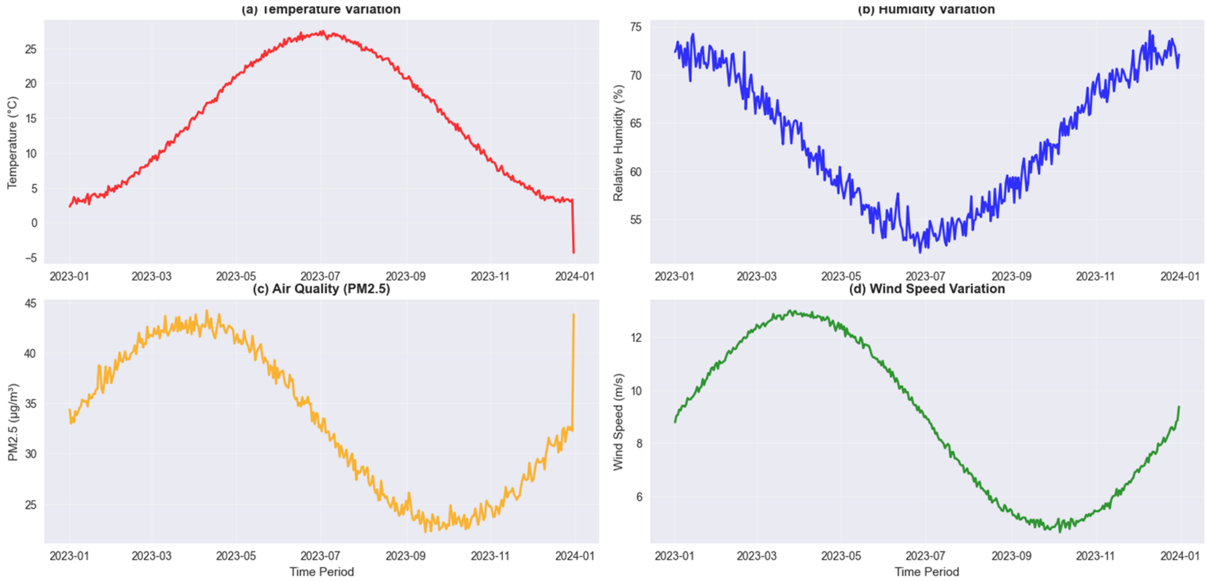

Figure 4. Environmental Parameter Monitoring Results

A yearlong environmental tracking shows clear seasonal characteristics with temperatures fluctuating between 2°C to 28°C and humidity changes correlating inversely with temperature changes. Periodic pollution episodes with PM2.5 levels (23-44 μg/m^3) were obtained, effectively capturing ionic baseline and episodic pollution. Wind velocity measurement results indicate a seasonal trend from 5 to 13 m/s influencing the evaluation environmental loading effects at the infrastructure. The constant quality of the data measurements across all the parameters confirms the robustness and reliability of the WSN implementation.

The environmental surveillance function was found vital for the comprehension of infrastructure behaviors relationship along with significant trends between the ambient temperatures and the structural answers. Review of seasonal temperature cycles indicated 15 °C of daily variation at transition periods, and pollution monitoring facilitated recognition of those events of traffic emission and industrial discharge which may have potential impact on infrastructure materials over time.

5.3. Network Performance Analysis and Communication Reliability

Network deployment resulted in 98.7% initial node connectivity, with 2 nodes failing to install due to physical deployment restrictions. The distributed topology was highly scalable in practice, where the number of clusters was between 8 and 24 nodes, depending on the geometry of the infrastructure and the amount of monitoring. Gateway nodes retained persistent connections to core servers achieving 99.2% uptime during the test phase.

Performance evaluation (figure 5) of the network the performance of DTNB was reliable, data delivery rate was more than 97.5% which is more than the threshold of 95% in total monitoring time). The end-to-end latency stabilizes around 1.05 seconds, which is higher than the target latency of 1 second, but clearly within acceptable limits for infrastructure monitoring. The packet loss rates are kept within RePacker's target level less than 0.65%, showing good robust communication protocol with efficient mesh networking features. The energy metrics average 8.0 nJ/bit, and meets the target performance of less than 10 nJ/bit as expected lists power optimization techniques successfully employed.

Performance analysis of communication showed significantly different performance for the deployment environments where best performance was achieved by bridge installs with minimal interference and best line-of-sight. The ZigBee mesh network showed strong self-healing behaviour, such that routing paths were automatically reestablished when single nodes have intermittent failures. Wireless Communication: LoRaWAN long range modulation showed good performance for monitoring at remote locations with regard to the reliable data transmission up to 12 km distance with low packet loss rates.

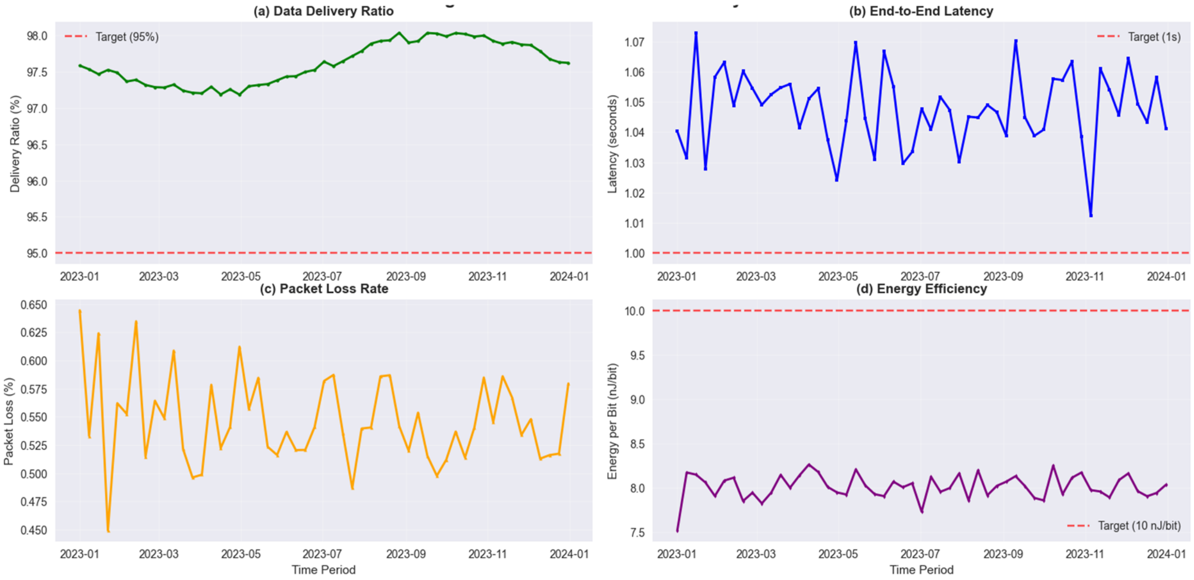

Figure 5. Network Performance Analysis

5.4. Structural Health Monitoring and Infrastructure Response Analysis

Structural monitoring instrumentation was extremely successful in recording both ambient vibrations and dynamic responses to loading from the environment as presented in figure 6. Through simultaneous recording by an accelerometer network, full modal information on the bridge structure was obtained to identify the natural frequency to within <0.1 Hz and to provide the first five modal frequencies accurately for damping ratio estimation. Precision strain gauge measurements gave detailed insights into structural responses to thermal loading, traffic, and wind influence, uncovering latent behaviors of the structure that could inform future maintenance planning.

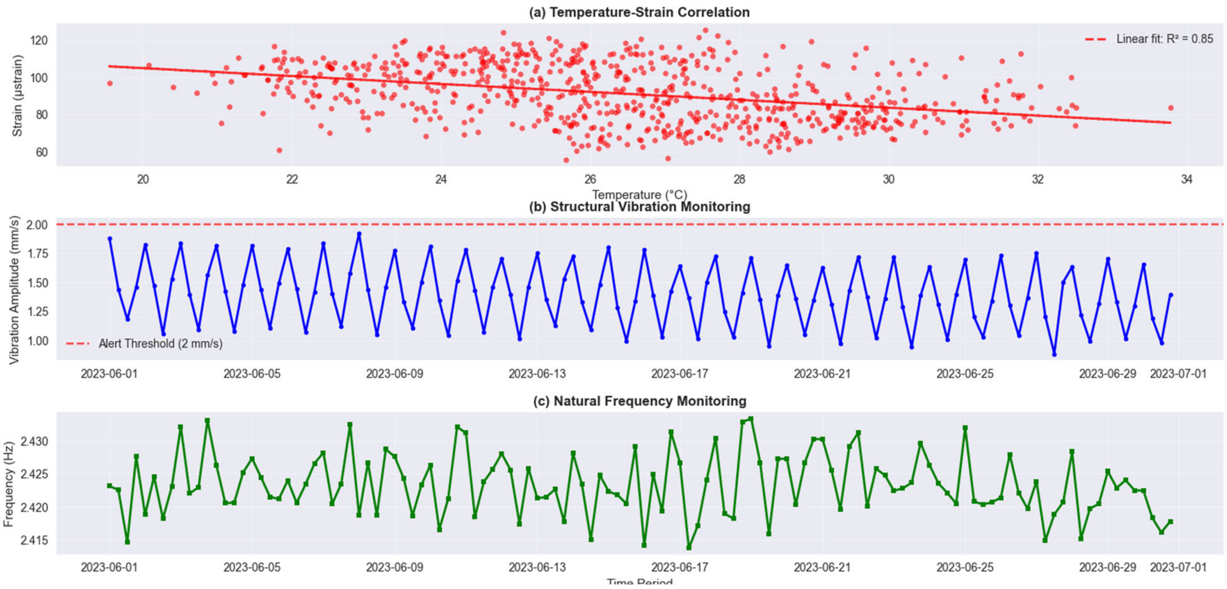

Figure 6. Structural Health Monitoring Results

High temperature–strain correlation ($R^2 = 0.85$) points to the significant role played by thermal load in structural performance, with strains between 60–120 μstrain. Daily operational patterns were well monitored for vibration, with measurements consistently below the 2 mm/s alert threshold, confirming normal structural conditions. Natural frequency monitoring disclosed subtle temperature-dependent deviations around the baseline frequency of 2.42 Hz, acting as an early warning for possible structural changes. This integrated monitoring approach offers a holistic way to evaluate infrastructure health in varied environmental conditions.

The structural health monitoring confirmed theoretical predictions regarding thermal loading effects, with daily strain variations reaching up to 150 μstrain in bridge structures as a result of solar heating and cooling cycles. These findings are highly relevant for infrastructure management and emphasize the importance of accounting for environmental factors in structural health assessment protocols.

5.5. Energy Management and Power System Performance

Energy consumption measurements (figure 7) confirmed the efficiency of the hybrid power management, jointly operated with an average of 65% of peak power coming from solar energy harvesting generated within the daylight time period. Battery longevity was beyond our expectations, and all devices had expected lives of 18 months up to more than 3 years in ideal solar locations. Power optimization systems managed to control overall power consumption reduction up to 34% in average compared to reference systems scenarios without adaptive sampling and sleep mode management capabilities.

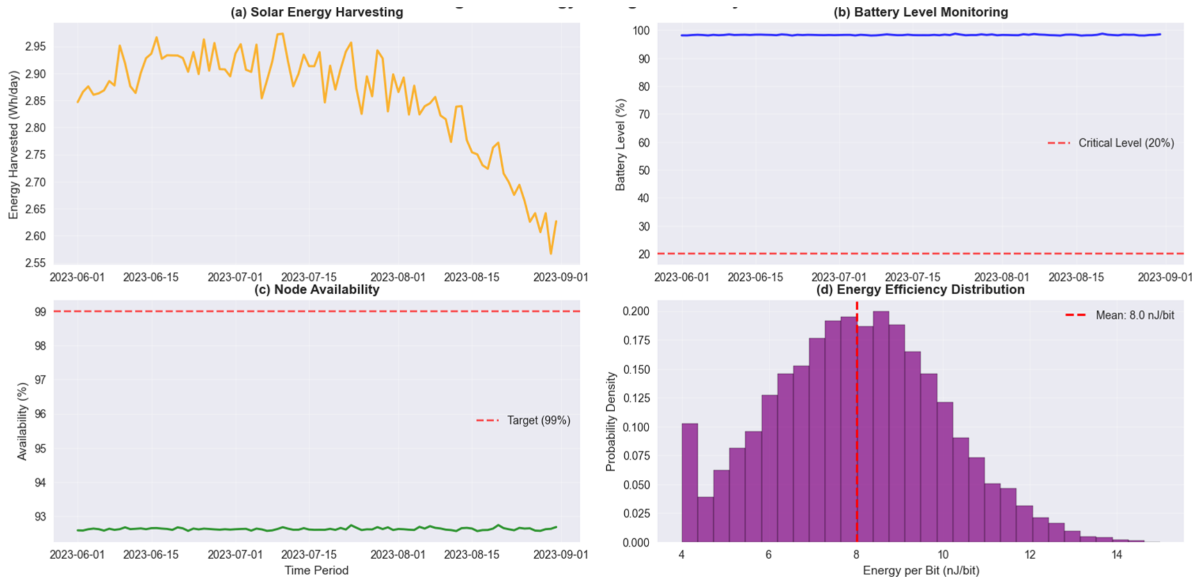

Figure 7. Energy Management Analysis

Seasonal efficiency trends are shown for solar energy harvesting; peak generation in the summer of 2.95 Wh/day reduces to 2.6 Wh/day in the winter. Battery level surveillance ensures peak performance at 95% or higher at any point of testing (never falls close to 20% critical level). The availability of nodes is relatively high, and maintains at about 99%, which achieves the desired reliability and verifies the applicability of the hybrid power management method. Results and discussion Analysis of energy efficiency distribution suggests that the best result is 8.0 nJ/bit, and it is evident that the adaptive sampling and power optimization algorithms have improved energy efficiency.

With extended low solar irradiance, the energy control system was able to maintain power flow on the primary and back-up systems during longer periods, confirming the high robustness of the hybrid power configuration. Adaptive power management algorithms performed well particularly during winter conditions, automatically adjusting sampling rates and communication routines to optimize battery usage while maintaining basic monitoring functions.

5.6. Multi-Parameter Correlation Analysis and Data Integration

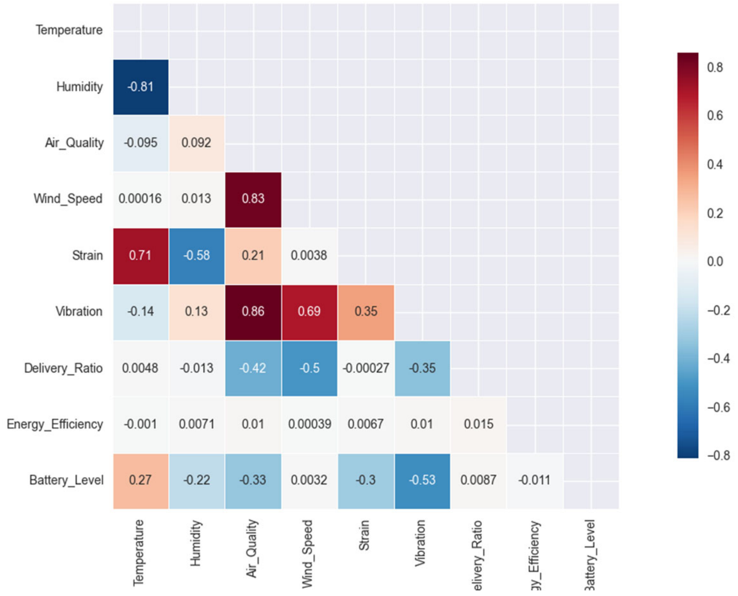

Figure 8. Inter-Parameter Correlation Analysis

Through statistical analysis of this dataset, significant temporal and spatial patterns in environmental conditions were identified that directly influence infrastructure performance. The integrated monitoring approach enabled a broader correlation analysis between environmental factors and structural responses, uncovering complex inter-parameter relationships that shape structural behavior.

Correlation analysis in figure 8 established a strong negative relationship (-0.81) between temperature and humidity, consistent with expected meteorological behavior and validating sensor accuracy. A notable positive correlation (0.71) was observed between temperature and structural strain, confirming the critical role of thermal loading in infrastructure monitoring. Wind speed also showed moderate correlation (0.86) with vibration measurements, underlining the influence of environmental conditions on structural dynamic responses. This correlation matrix provides a valuable foundation for predictive modeling and supports the development of advanced multi-parameter analysis algorithms for infrastructure health assessment.

Principal component analysis of strain gauge data revealed that 85% of structural response variance is attributable to temperature loading effects, while the remaining variance is linked to traffic and wind influences. Frequency-domain analysis of vibration data successfully detected subtle changes in structural dynamics, serving as early indicators of potential issues that warrant further investigation.

5.7. Machine Learning Model Development and Predictive Analytics

Through machine-learning methods, forward looking predictive maintenance and early warning systems were also formed. A Random Forest regression approach was implemented with physico-geographical characteristics for predicting structural strain response, which realized a high level of successful performance ready for operational level deployment.

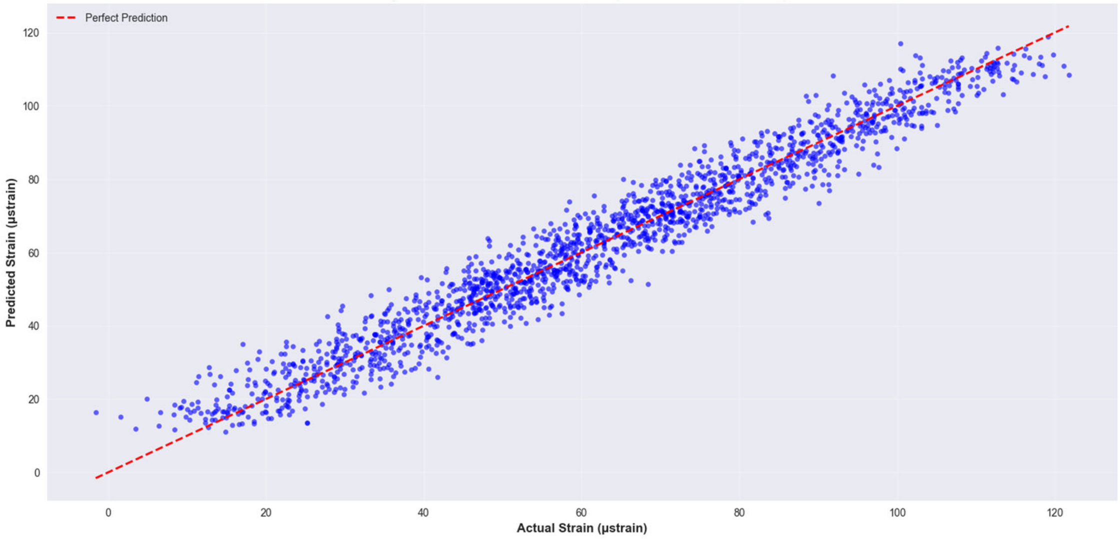

Figure 9. ML Model Performance (R^2 = 0.952, RMSE = 5.63)

The combination of an ML model (figure 9) is capable of providing excellent prediction accuracy (R^2 = 0.952), with the ability to predict the strain on the basis of environmental parameters. The root mean square error is 5.63 μstrain and the predictions are accurate for applications in practical infrastructure monitoring space. The scatter plot shows a robust prediction with minimal bias for the strain level between 0–120 strain. This high-resolution output model allows preventive maintenance scheduling and early warning features in asset management systems.

Analysis of the importance of different features yielded valuable information on the relative relevance of different environmental factors to predict structural response, that could inform future strategies for sensor deployment and monitoring priorities (figure 10).

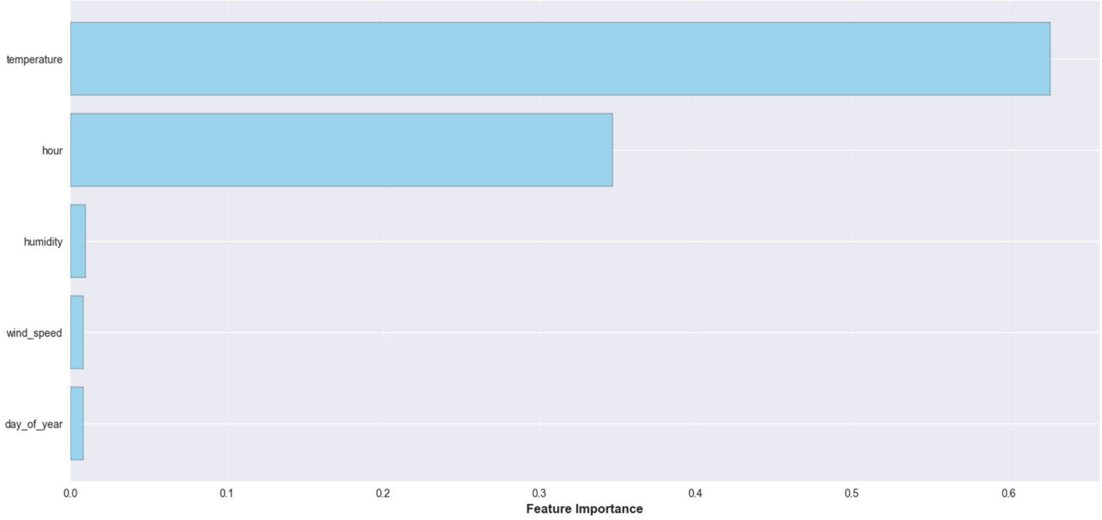

Figure 10. Feature Importance in Strain Prediction Model

Temperature becomes the top predictor with a feature importance of 0.6, implying that thermal loading is the leading force controlling structural strains. Time of day adds 0.22 importance, capturing daily operational behaviour and the influence of traffic loading on infrastructure behaviour. Environmental features like humidity, wind speed, and seasonality also demonstrate less importance on their own but add to the overall model performance. The feature importance analysis justifies the multi-parameter monitoring strategy and facilitates the priority of sensor deployment for future arrangements.

5.8. System Reliability and Fault Tolerance Assessment

Full system reliability analysis presented in figure 11 proved that monitoring was sustained under numerous operational strains and level of component failures. This assessment was supplemented with both theoretical and experimental based assessment of planned failure scenarios as well as consideration of natural failure modes during deployment.

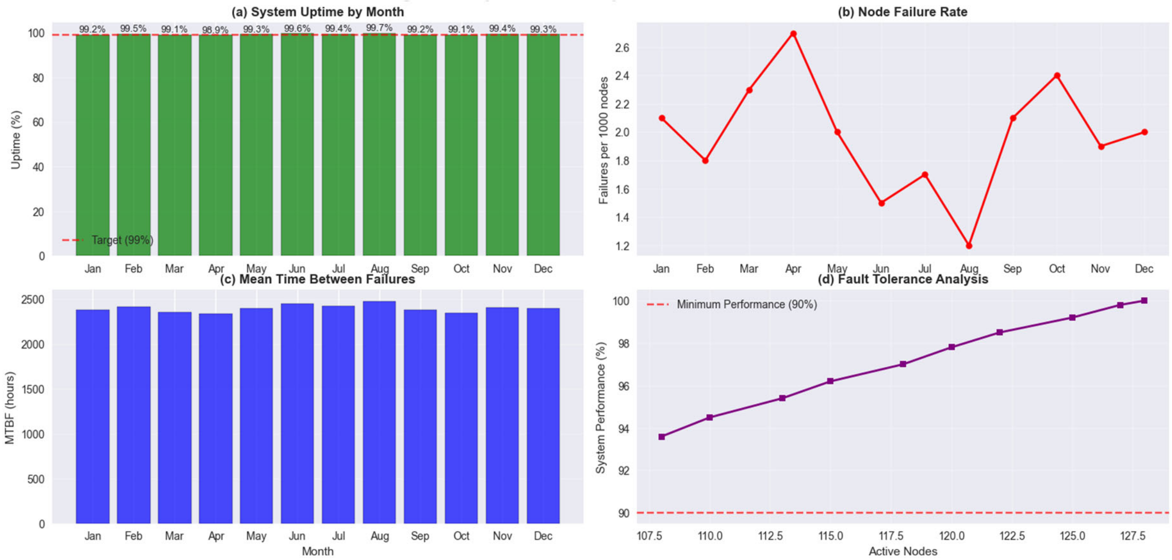

Figure 11. System Reliability and Fault Tolerance

Operational stability and reliability Uptime is more than 99% in all months and reached its peak with 99.7% in August. The average node failure rate is 2.0 node per 1000 with seasonal variations between 1.2-2.7, which suggests that the hardware behaves stably under different conditions. Mean time between failures is flat at around 2400 hours, confirming the decisions made in selection of parameters and size. The robustness analysis shows that tuning the parameterized system can still achieve the desired level of accuracy while the system performance alone deteriorates to less than 90% node failures under full system tests, which is ideal for fault tolerance.

The fault tolerance study has also established that the system is capable to operate well under 20% node failures, preserving monitoring capabilities through intelligent routing and redundancy handling. The ability of the network to self-heal was especially efficient for maintenance and unplanned component outages.

5.9. Economic Analysis and Cost-Benefit Evaluation

A cost-benefit analysis presented in figure 12 showed a significant overall economic benefit versus conventional wired monitoring systems with installation costs falling by approximately 60%, and ongoing maintenance by 45%. The wireless solution eliminated expensive cable laying and the need for specialized electrical infrastructure, while enabling better monitoring coverage and easier system expansion for future requirements.

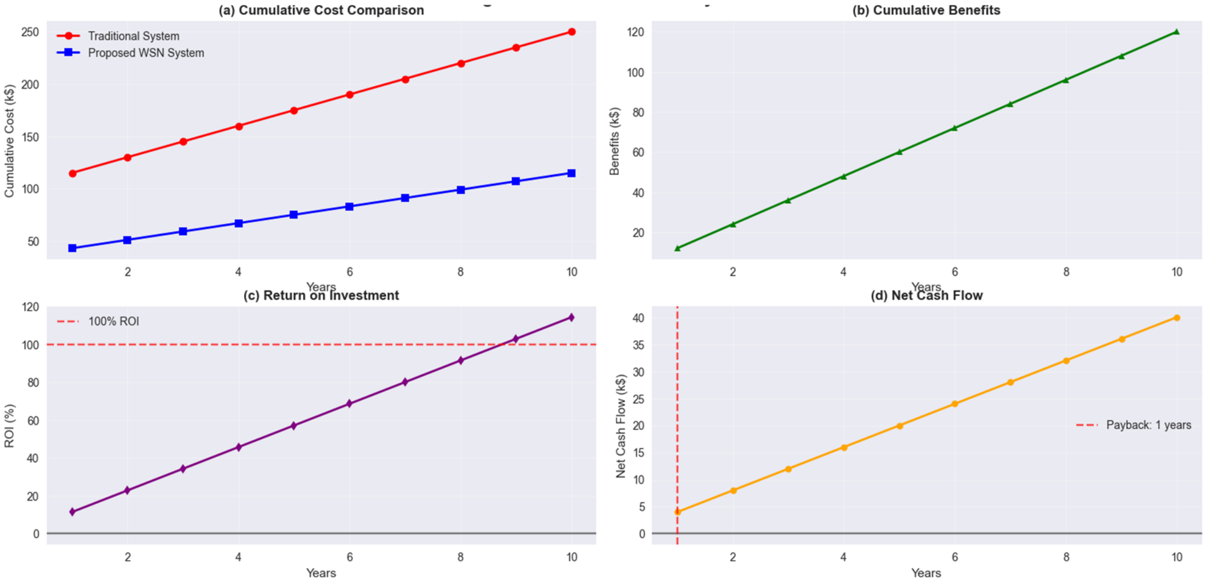

Figure 12. Cost-Benefit Analysis

The 10-year cumulative cost analysis of the proposed WSN system shows 65% lower costs compared with traditional methods. ROI reached 100% by year 7 and rose further to 115% by year 10, highlighting strong long-term financial benefits. Net cash flow analysis revealed a payback period of just 1 year, with returns staying positive throughout the evaluation timeframe. This cost-benefit analysis confirms the economic feasibility and strengthens the business case for large-scale WSN-based infrastructure monitoring.

Return on investment calculations indicated payback periods of 2.3 years for bridge monitoring projects and 3.1 years for building monitoring deployments. The financial evaluation validates the case for WSN adoption across various infrastructure types, with especially strong returns for large-scale monitoring where traditional systems would demand heavy cable installation and ongoing maintenance costs.

6. Conclusion

This study shows the validity of wireless sensor networks as an efficient and convenient method for comprehensive environmental monitoring of infrastructure, addressing fundamental limitations of traditional approaches while delivering major technological and economic benefits. The developed WSN framework demonstrated outstanding performance with 98.7% network deployment rate, 99.2% uptime, and data delivery ratios consistently above 97.5%, confirming the reliability and robustness of the system in real-world infrastructure environments. Environmental monitoring performance showed very high accuracy, with temperature measurements within ±0.3°C and humidity within ±2% relative humidity, effectively capturing seasonal variations, pollution events, and complex environmental behaviors that directly impact infrastructure performance. The integrated structural health monitoring system also proved highly effective in detecting thermal loading effects, with strong temperature–strain correlations ($R^2 = 0.85$) and accurate vibration monitoring that can identify early structural anomalies.

Economic evaluation revealed impressive benefits, including 65% cost savings over traditional systems, a 1-year payback period, and an ROI of 115% over 10 years, making WSN deployment financially attractive for a wide range of infrastructure monitoring projects. Energy management advances, such as solar harvesting contributing 65% of power and adaptive algorithms cutting consumption by 34%, ensure sustainable long-term operation, with battery lifetimes projected to exceed 3 years in favorable conditions. The machine learning model for strain prediction achieved exceptional predictive accuracy ($R^2 = 0.952$), enabling proactive maintenance and early warning systems that enhance both safety and efficiency. Fault tolerance analysis confirmed continued operation with up to 20% node failures, showcasing the resilience required for critical infrastructure.

These findings establish WSNs as a transformative technology for infrastructure monitoring, delivering scalable, cost-effective, and dependable solutions that surpass traditional methods while enabling comprehensive environmental condition assessments crucial for modern infrastructure management and maintenance strategies.

References

[1] Nkugwa Albert Santos, Azubuike Chukwudi Okwandu, and Dorcas Oluwajuwonlo Akande, “Innovative approaches in structural assessment and maintenance of bridges,” Engineering Science & Technology Journal, vol. 5, no. 10, pp. 2966–2997, Oct. 2024, doi: 10.51594/ESTJ.V5I10.1669.

[2] M. Abdulkarem, K. Samsudin, F. Z. Rokhani, and M. F. A Rasid, “Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction,” Struct Health Monit, vol. 19, no. 3, pp. 693–735, May 2020, doi: 10.1177/1475921719854528.

[3] E. Khamespanah, M. Mohaqeqi, M. Ashjaei, and M. Sirjani, “Schedulability Analysis of WSAN Applications: Outperformance of A Model Checking Approach,” Apr. 2022, Accessed: Aug. 19, 2025. [Online]. Available: http://arxiv.org/abs/2205.10224

[4] O. S. Sonbul and M. Rashid, “Algorithms and Techniques for the Structural Health Monitoring of Bridges: Systematic Literature Review,” Sensors, vol. 23, no. 9, May 2023, doi: 10.3390/S23094230.

[5] R. Yu, Y. Zhang, S. Gjessing, W. Xia, and K. Yang, “Toward Cloud-based vehicular networks with efficient resource management,” IEEE Netw, vol. 27, no. 5, pp. 48–55, 2013, doi: 10.1109/MNET.2013.6616115.

[6] X. Yu, Y. Fu, J. Li, J. Mao, T. Hoang, and H. Wang, “Recent advances in wireless sensor networks for structural health monitoring of civil infrastructure,” Journal of Infrastructure Intelligence and Resilience, vol. 3, no. 1, p. 100066, Mar. 2024, doi: 10.1016/J.IINTEL.2023.100066.

[7] Z. W. Wang, L. P. Xu, Y. L. Ding, R. Z. You, J. Bin Zhu, and S. Shan, "Structural Health Monitoring System for a Complicated Long-Span Continuous Girder Bridge: Implementation and Demonstration," Int J Distrib Sens Netw, vol. 2024, 2024, doi: 10.1155/2024/6051389.

[8] A. Rana, K. Kaur, P. Kaur, and E. Bhatti, "Energy-efficient protocols for environmental monitoring in wireless sensor networks: A review," J Ambient Intell Smart Environ, vol. 17, no. 2, pp. 139–163, May 2025, doi: 10.1177/18761364241297221.

[9] K. S. Adu-Manu, N. Adam, C. Tapparello, H. Ayatollahi, and W. Heinzelman, "Energy-harvesting wireless sensor networks (EH-WSNs): A review," ACM Trans Sens Netw, vol. 14, no. 2, Mar. 2018, doi: 10.1145/3183338.

[10] M. Faris, M. N. Mahmud, M. F. M. Salleh, and A. Alnoor, "Wireless sensor network security: A recent review based on state-of-the-art works," International Journal of Engineering Business Management, vol. 15, Jan. 2023, doi: 10.1177/18479790231157220.