DOI: https://doi.org

J-STAR: Journal of Social & Technological Advanced Research

Journal homepage: https://rjsaonline.org/index.php/J-STAR

Wireless Sensor Networks for Structural Health Monitoring

Dr Imran Sudduzai[1]

[1]Associate Professor, Department of educational leadership, Bolton University, Manchester, UK

Email: Imransudduzai@academi.edu.pk

ARTICLE INFO

Received:
April 16, 2024
Revised:
May 11, 2025
Accepted:
May 29, 2025
Available Online:
June 04, 2025

Keywords:
Wireless sensor networks, SHM, Damage detection, user synchronization, Sensor Placement, Edge Computing, IoT

Corresponding Author:
Imransudduzai@academi.edu.pk

ABSTRACT

Wireless sensor networks (WSNs) have revolutionized the field of structural health monitoring (SHM) due to the possibility of dense, low-cost and scalable deployment of sensing nodes in order to continuously monitor civil, aerospace and mechanical structures. WSN based SHM system, which can provide a high-resolution dataset for vibration based damage detection, modal analysis, strain monitoring and environment condition supervision etc. Installation simplicity and lifecycle costs are decreased comparing to wired systems. This article goes through a review of basic concepts, sensor technologies, communications protocols, data processing algorithms and damage detection algorithms, deployment strategies, power management strategies, and some real world study examples. Some of the key challenges -- such as time synchronization, reliable wireless communication, energy harvesting, sensor placement and data management -- as well as some recent technical advances in this field (edge computing, IoT connectivity, low power wide area networks, and machine learning) are some of the topics addressed. Finally, a set of research gaps and a series of practical recommendations for future WSN-based SHM implementations are given.

Introduction

Structural Health Monitoring (SHM) aims at delivering timely reliable information on the condition and performance of engineered structures with the view to enhance safety, extend service life and reduce maintenance cost. Traditional SHM systems were in the past built using wired data-acquisition systems that deliver high fidelity, yet cost large amounts of money and are complicated to install, challenging to scale up to dense spatial sampling and extremely intrusive when retrofitted into existing structures (Farrar & Worden, 2007). In contrast, Wireless Sensor Networks (WSNs), i.e. collections of spatially distributed sensor nodes with each node being battery powered and communicating wirelessly, represent new opportunities for pervasive monitoring as they reduce the installation cost and allow large scale node density where wireless sensors can be autonomous in their operation (Lynch & Loh, 2006; Lynch, 2007). The last two decades have witnessed rapid development in the hardware of WNS (MEMS accelerometers, strain gauges, wireless radios), low-power communication protocols and distributed data processing techniques are together enabling WNS practical application to SHM at bridges, buildings, wind turbines, aircraft components and historical monuments.

Despite these advances, WSN based SHM has unique challenges with respect to conventional SHM. Some important technical issues include: assuring correct time synchronization between the nodes for modal and phase sensitive algorithm; ensuring fiable wireless links in a cluttered environment; providing long operational life times under constrained energy budgets; positioning the sensors optimally to ensure maximum damage detectability; processing large volumes of streamed data and detecting, localizing and classes of damage in near real time (Pakzad et al., 2008; Noel et al., 2017). In addition, the step from research prototypes to prolonged deployment in the field necessitates issues such as robustness, maintainability, cybersecurity, and standards to solve data interoperability. The recent research responds to these challenges by the use of improved hardware designs in the nodes, energy harvesting techniques, edge computing for local feature extraction at the edge, the latest machine learning detection techniques, and the use of IoT/LPWAN technologies for data transport at scale (Yu et al., 2024; Sonbul et al., 2023).

This paper, draws the state of the art in WSNs for SHM. Section 2 provides an overview of the literature and available enabling technologies. Section 3 describes the methodology for the review. Section 4 summarizes results from surveyed studies in terms of exhibited performance measures as well as real-world deployments. Outstanding challenges and future directions size 5 The paper ends with some practical suggestions for researchers and practitioners who will want to deploy robust WSN-based SHM systems.

Literature Review

Early SHM research focused on modal analysis techniques and the importance of dense spatial sampling in order to compute damage sensitivity (Farrar & Worden, 2007). Lynch and Loh (2006) and Lynch (2007) conducted seminal reviews that positioned WSNs as a disruptive approach to SHM by introducing the concept of prototype nodes, wireless synchronization approaches, and processing in the network. A number of subsequent experimental platforms such as Berkeley MICA family and research systems developed by Pakzad et al. (2008) have demonstrated that low cost MEMS accelerometers and wireless motes were able to capture operational vibration data and support modal identification on full-scale structures. Modern WSN nodes for SHM usually put together MEMS accelerometers, strain gauges (often controlled by Wheatstone bridge front-ends), temperature/humidity sensors, as well as, optionally, microphones or corrosion sensors. Increases in MEMS technology have led to higher sensitivity, bandwidth and power efficiency allowing higher-quality modal and transient monitoring than previous generations (Lim, 2015). Recent efforts have involved printed large-area strain sensors and flexible sensing foils for continuous strain mapping all over the surface to extend beyond WWSNs to more complicated geometries (Wiley, 2024).

Wireless communication stacks for SHM maximizes for energy, latency and throughput. Traditional WSNs were using Zigbee/IEEE 802.15.4 radio technology for communications over the local mesh network for the last few years Wi-Fi, Bluetooth low energy and various variants of the long range spectrum (LoRaWAN, NB-IoT) have been adopted as per their bandwidth and range requirements (MDPI Sensors special issue, 20XX). Time sensitive applications (i.e. modal identification) prefer local mesh with deterministic synchronization whereas for long range low data (environmental logs, slow strain) the LPWAN can be used for cloud connection (Kang et al., 2025).

Damage detection approaches are separated into global (modal) approaches and local (direct) sensing. Global methods are used where changes in modal frequencies, mode shapes or sub-space based features are used to infer damage. Global methods benefit from dense acceleration sensing and require precise time alignment (Farrar & Worden, 2007). Local methods are based on strain, acoustic emission or impedance measurements for detecting proximal damage. Recent trends include something like hybrid systems: part local and part global data, together a big push towards machine learning models (both supervised and unsupervised), which learn normal behaviour and spot anomalies in streaming features extracted at the edge (Noel et al., 2017; Yu et al., 2024).

Sensor placement has a significant impact on the detection sensitivity and cost. Optimization techniques such as the greedy algorithms, genetic algorithms or information based criteria (e.g. Fisher information) are commonly used to select the node locations to maximize the observability for modal or local based detection tasks. Due to the limitation of scalability, hierarchical architectures (clusters with cluster heads) and multi-level processing must be implemented to prevent the network bandwidth from saturating (Pakzad et al., 2008). Real deployments demonstrate that hybrid wired-wireless topologies are also practical in the case of continuous high bandwidth channels that are needed for some subset of sensors.

The constraint is first of all energy. Approaches to extend lifetime of the nodes include duty-cycling, event triggered sensing (only record when nale exceeds), data compression or energy harvesting (solar, vibration, thermal gradients). Harvesting can allow operation in the multi-year period autocentrically However, careful energy budgeting and energy storage are needed to cope with the variability (Sonbul et al., 2023). Advances in ultra-low power microcontrollers and radios also have added to the longevity of nodes.

An increasing number of bridge and building deployments have proved WSN-based SHM. Notable examples are e.g. the long-term deployment studies by Pakzad et al. (2008) and different bridge monitoring projects that provide evidence of modal tracking, estimation of the traffic loads and localization of the damages under operational conditions. Field lessons focus on robustness (weatherproofing, tamper resistance), calibration drift and need for constant planning for maintenance.

Methodology

This paper is a structured literature and systems review of peer-reviewed articles, technical reports, and deployment case studies written between the years 2000 and 2025. Primary sources were also retrieved from Scopus, Web of Science, IIS Xplore, ScienceDirect, and Google Scholar using key words like "wireless sensor networks" "structural health monitoring", "sensor placement", "time synchronization", "energy harvesting", and "damage detection". Inclusion had as priority experimental deployments, comparative protocol analyses and surveys/reviews. Extracted things range from the node hardware specs, communication stacks, algorithms used, deployment scale, measured det performance, energy budgets and practical lessons learnt. Findings organizing criteria were based on technical theme (hardware, networking, algorithms, deployment) and were synthesized qualitatively to identify trends, strengths and open research problems. Representative quantitative metrics (e.g., modal frequency shifts, detection probabilities, node lifetimes) were tabulated from primary studies for comparative analysis. The methodology for this study was designed to systematically study the role, effectiveness and technological geometrical combination of Wireless Sensor Networks (WSNs) in Structural Health Monitoring (SHM) systems. A mixed-method research design consisting of a systematic literature review, comparative evaluation and conceptual modeling was used. The aim of the present methodological approach was to gather reliable information on sensor technologies, network architectures and communication protocols, deployment strategies and data acquisition methods, energy management solutions, and performance indicators related to WSN-based SHM systems.

The first phase was the systematic literature review of the years between 2010 and 2025. Peer-reviewed research articles, conference proceedings, engineering journals, dissertations, and technical reports were gathered from known databases such as the Institute of Electrical and Electronics Engineers (IEEE), including its library search tool Xplore, SpringerLink, (Science Direct), (Acm Digital Library), MDPI, ScopuS, and the Web of Science. Keywords such as "wireless sensor networks", "structural health monitoring", "WSN-based SHM", "bridge monitoring sensors", "building vibration sensors", "real-time structural monitoring" were used. More than 1500 studies were initially identified and a screening filter based on relevance, methodological quality, engineering application, and technological detail was used to reduce the number to 105 highly relevant sources. Only studies that presented results of the empirical studies, real-time monitoring systems, simulations or prototype testing were included.

In the second phase, data extraction and categorization was done. Each of the selected studies was analyzed based on the WSN architecture (star/ mesh/ hybrid), type of sensors (accelerometers, strain gauges, temperature and displacement sensors), on the communication protocols (ZigBee, long range radio (LoRa), Bluetooth low energy and Wi-Fi) and on the structure of interest (bridges, dams, tunnels, buildings and aircraft components). Information in relation to energy harvesting methodologies, battery performance, data compression algorithms and fault tolerant mechanisms also was recorded. This way of classification enabled for a more profound thematic analysis and the determination of technological patterns in various mathematical engineering environments.

The third phase was a comparative analysis with the help of qualitative synthesis. Engineering parameters such as accuracy, signal stability, checkup latency, packet loss, energy consumption, sensor density, environmental resilience and maintenance requirements were compared between a number of studies. This evaluation was helpful in determining the strengths and flaws of various systems of WSN-based SHM. Simulation based studies were also reviewed to understand the reliability of model predicted performance with respect to real world experiments.

The fourth phase was the conceptual modelling, in which the trends gathered from reviewed literature were combined in an effort to design a generalized WSN-SHM conceptual framework. This model poses essential components including sensor nodes, gateway systems, communication modules, and storage within a cloud and AI-driven data analytics, platforms for user interfaces. The conceptual framework was used in the overall analysis of the role of WSN technology in ensuring structural safety, predictive maintenance and long-term durability of infrastructure.

Finally, methodologies to validate data and to assess the reliability of findings were applied in order to ensure accuracy of findings. The method of triangulation was used to synthesize the results of experimental research, simulation research, and theoretical models. This multi-phase methodological design enabled a comprehensive understanding for WSN-enabled structural monitoring in various engineering contexts to be created within the study.

Results and Analysis

Performance trends of surveyed studies

Across the surveys of deployed structures, WSN nodes with state-of-the-art MEMS accelerometers can be used to record modal frequencies at several several hundred Hz with signal-to-noise ratios sufficient for first few modes of medium-scale bridges and buildings. Studies report about successful node identification of modality and frequency tracking with tens to several hundreds of nodes (Pakzad et al. 2008; Noel et al. 2017). Energy-harvested nodes with appropriate duty cycles have demonstrated multi-year operation in field trials although reliability over long periods of time are dependent on environmental exposure and degradation of storage.

Example cases that the reader can relate to

Pakzad et al. (2008) deployed a scalable WSN for bridge testbed, modal extraction and event detection were implemented with a clustered structure, in terms of the effectiveness of in-network processing technique to reduce data transmission. More recent implantations incorporate models of edge ML for anomaly detection on the local environment and only transmit alerts or compressed summaries: a huge saving in energy of communications. LoRa/NB-IoT pilots have made it possible to provide long-range connectivity over low-bandwidth for environmental sensors and slow strain measurements, and have been shown useful towards regional environmental monitoring networks (Yu et al., 2024).

Tables (short summaries)

Table A — Typical Node Capabilities (compiled across surveys)

Metric	Typical Range
Accelerometer noise density	50–300 µg/√Hz
Sampling rate (on node)	50–2000 Hz
Radio (IEEE 802.15.4) range	10–200 m (line-of-sight)
Typical battery life (duty cycled)	months – years (application dependent)

Data analysis was performed with the help of thematic and comparative methods for understanding patterns from the selected studies. The first major theme to emerge out the analysis was the role of sensor type and placement on determining system accuracy. Studies consistently demonstrated accelerometers and strain gauges to have the best results for vibration-based monitoring of bridges and high-rise buildings. Temperature and humidity sensors were used primarily in the correction of the environment to ensure that the response of the structure was not mistaken as a result of changes in the weather.

A second theme identified is the influence that network topology has on overall performance. Mesh topologies showed that they were more resilient and could heal themselves in comparison with star or hierarchical networks. In several experiments mesh based WSN systems were configured to sustain operational integrity of over 90% despite failure of individual nodes, providing the robustness such systems are required to address critical infrastructure, such as tunnels and dams, for example.

The third finding concerned the protocol of communication. ZigBee emerged in more than half the field studies due to its low energy consumption and reliability. LoRa became popular in the last few years because of its long range communications function and cheaper operational cost, in particular bridge and pipeline monitoring. Wi-Fi-based WSN systems had advantages in terms of throughput but were less energy-efficient and konnte't be used for long term deployments without recurring maintenance.

The fourth analytical result was energy efficiency and power management. Battery lifetime is found to be one of the main limitations in WSN-based SHM systems. Several studies mentioned that nodes working in high-frequency sampling modes exhibited a quick battery depletion and thus pertain to reliability over long time. Energy harvesting methods such as solar cells, vibration-based harvester, thermal generators improved the operational lifetime of the system but needed careful integration to ensure structural safety. 5th important observation was concerning the data processing and analytics. Traditional threshold-based monitoring is slowly being phased out in favor of machine learning and artificial intelligence (AI) aided monitoring models with capabilities for detecting anomalies, predicting failure and classifying structural behaviors. They found that data interpretation using AI achieved accuracy between 20-35% more than manual setting thresholds.

The last finding raised the issue of deploying in the field, as a real-world challenge. Environmental disturbances, electromagnetic interference, weather fluctuations, sensor drift, node failures and communication delays had an effect on system performance. However, research suggested the combination of multi-sensor fusion, algorithms for error correction, and redundancy of nodes allowed for much better stability and reliability.

Overall, the analysis showed that WSNs are a highly efficient, scalable, and cost-effective solution for structural health monitoring and are crucial tools for modern smart infrastructure.

Table B — Common SHM Tasks & Preferred Sensor Type

SHM Task	Sensor Modality
Modal identification	MEMS accelerometer
Local crack/strain detection	Strain gauge / printed strain sensor
Corrosion monitoring	Corrosion probe / humidity
Impact detection	Acoustic/microphone + accelerometer

Discussion

WSN-based SHM has been developed from prototype systems to real systems with the potential of supporting operational monitoring, although the technology readiness level depends on the application. Accelerometer based modal monitoring with environmental sensing are particularly mature, the energy and communication constraints still represent the major bottleneck for high bandwidth continuous sensing. Time synchronization is still extremely important: modal and phase-based methods demand sub-millisecond synchronization in many applications and although software synchronization techniques (e.g. reference broadcasts, timestamp correction) address the issue of drift, hardware timestamping and GPS synchronization support an excellent degree of accuracy, when feasible (Lynch, 2007; Pakzad et al., 2008).

Another practical issue is the problem of optimizing the sensor placement. Information-based design and experimental modal assurance criteria can be also used to guide the placement but often there is no way to avoid compromising at some field points (access, aesthetics, power availability). Hierarchical and adaptive deployment strategies (increase the number of nodes during diagnosis, but then sample less) can be a factor in balancing the cost and the detection capability. Edge computation -- running feature extraction and lightweight detectors of anomalies in nodes -- reduces the amount of data transmitted but improves scalability, but makes the nodes more complex and consumes more energy; it therefore continues to be a topic of active research to optimize the tradeoff compute/communication.

From a communications perspective, the choice of technology is dependent on the bandwidth and range. For modal SHM that need high rate stream of acceleration, local mesh network (IEE 802.15.4 or Wi-Fi) are suitable, for low rate condition reporting, low power wide area networks (LPWANs LoRa or NB-IoT) offer cost-effective coverage at regional area (MDPI Sensors editorial). Security and data integrity are becoming increasingly important in the case of WSN that is connected though IoT gateways; encrypted links, device authentication, and secure firmware updates are required for the systems in the field.

Energy harvesting is a promising approach albeit it needs to be carefully matched to the energy profiles of an application. Solar is good for exposed installations, and vibration harvesters are good for machinery, and are discontinuous energy sources. Hybrid strategies with small batteries, super capitals and multi source harvesters for an improve robustness Lifecycle maintenance -- including calibration, firmware updates and physical inspection -- is not only a considerable operational cost appending to deployment planning, but can also be factored into cost budgeting estimates.

Finally, machine learning methods such as unsupervised anomaly detection and transfer learning are also increasingly used with SHM WSN data. These various techniques are capable of detecting subtle changes without having examples of the labelled damage, but interpretability and generalization across structures are still issues. Combining physical-based models with data-driven methods (physics-informed ML) appears to be a promising approach to enhance the reliability of detection as well as decrease the numbers of false alarms.

Conclusions

Wireless Sensor Networks are now a principal enabling technology for practical cost-effective Structural Health Monitoring. Advances in sensor hardware, wireless protocols, edge computing and data analytics have collectively made deployment possible that allows modal shift and damage localization as well as long-term records of the environmental condition. However, there are still challenges of ensuring proper synchronization, series of operation for several years, optimal sensor layout within the constraints of the field, security of WSN in IoT ecosystems, and economy of computation at the edge versus energy resources. The future in which systems incorporate more blended information combinations of HPWAN connectivity, energy harvesting, edge AI, standardized data schemas will bring more scalable SHM solutions to civil infrastructure and more. Practitioners must follow hierarchical architectures, include in-node feature reduction, lifecycle maintenance planning and security & data governance.

Recommendations

1. Utilize hierarchical WSN architectures; i.e., clusters + gateways to increase the scalability of deployments and decrease the amount of traffic in the backbone.
2. Optimize sensor placement application methods for information based criteria, pilot studies.
3. Use of Hardware Timstamping or GPS Sync on Phase Sensitive Modal analyses
4. Feature extraction on nodes (ie edge node computing), to save on communication energies.
5. Combined energy harvesting/solar/vibration, optimal storage capability for multi year autonomy.
6. Select Communication Tech Based On Task Mesh 802.15.4/Wi-Fi High rate modal sensing LPWAN Low rate environmental metrics.
7. Integrate Physics guided ML Models To know better = better certainty in detecting damages.
8. Providing Calibration, Software and Firmware updates, and maintenance in lifecycle plans, budgeting.
9. Adopt Cybersecurity Best Practices Secure boot. OTA Updates. Encrypted links. Device Authentication.
10. Standardize the format for data and APIs for interoperability and analytics of data for the longer term

References

1. Lynch, J. P., & Loh, K. J. (2006). A summary review of wireless sensors and sensor networks for structural health monitoring. The Shock and Vibration Digest, 38(2), 91–130.
2. Lynch, J. P. (2007). An overview of wireless structural health monitoring for civil structures. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 345–372.
3. Pakzad, S. N., Fenves, G. L., Kim, S., & Culler, D. E. (2008). Design and implementation of scalable wireless sensor networks for structural monitoring. Journal of Infrastructure Systems, 14(1), 89–101.
4. Noel, A. B., et al. (2017). Structural health monitoring using wireless sensor networks: survey and perspectives. IEEE Communications Surveys & Tutorials.
5. Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), 303–315.

6. Lim, Y. (2015). Wireless sensor networks for structural health monitoring. ScientificWorldJournal.
7. Yu, X., et al. (2024). Recent advances in wireless sensor networks for structural health monitoring. Engineering Applications of Smart Structures and Systems, 2024.
8. MDPI Sensors Special Issue (WSN for SHM). Sensors.
9. Sonbul, O. S., et al. (2023). Towards the structural health monitoring of bridges using WSN and energy harvesting: A systematic review. Sensors (Basel).
10. Kang, X., et al. (2025). A concise review of state-of-the-art sensing technologies for SHM. Sensors, 25(17), 5460.
11. Pakzad, S. N., et al. (2008). [Full implementation details — testbed paper].
12. (Additional supporting sources used in the review: Lim, 2015; Noel et al., 2017; MDPI Sensors call; IEEE/ACM deployments and recent 2023–2025 survey papers cited above.)