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Self-Adaptive Sensor Networks for Infrastructure Health Monitoring

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Abstract

Continuous monitoring of bridges, buildings, tunnels, transportation structures, and other critical infrastructure increasingly depends on distributed sensing systems capable of collecting structural response data under changing operational and environmental conditions. Conventional wireless sensor networks reduce installation complexity compared with wired monitoring but frequently operate through fixed sampling, communication, routing, and decision rules. Such static configurations may consume unnecessary energy during stable periods, respond inefficiently to unexpected structural events, and remain vulnerable to communication disruption, sensor degradation, environmental variability, and changing monitoring priorities. This study develops a self-adaptive sensor-network framework for infrastructure health monitoring in which sensing frequency, edge processing, network communication, anomaly thresholds, routing behavior, and fault-response functions can change according to structural and network conditions.

Because no primary field dataset was provided, the investigation is explicitly structured as a simulation-based methodological study. A reproducible synthetic dataset representing 180 hypothetical infrastructure-monitoring units was generated across three architectures: static wireless sensor networks, adaptive sensing networks, and self-adaptive edge-enabled wireless sensor networks. Six operational indicators were assessed: damage-detection accuracy, alert latency, packet-delivery rate, energy efficiency, sensor-fault recovery, and false-alarm rate. These indicators were combined into an Infrastructure Health Monitoring Index (IHMI). Mean IHMI performance increased from 57.6 under the static architecture to 75.1 under adaptive sensing and 87.9 under the self-adaptive edge architecture. The self-adaptive condition also produced the highest modeled damage-detection accuracy, packet delivery, energy efficiency, and sensor-fault recovery while producing the lowest alert latency and false-alarm rate.

Inferential analysis demonstrated strong internal separation among the deliberately parameterized scenarios. The numerical findings are synthetic and therefore should not be interpreted as measured improvements in actual infrastructure. The study contributes a transparent architecture for evaluating self-adaptation as a coordinated monitoring capability rather than as isolated dynamic sampling. It argues that future infrastructure-monitoring systems should integrate context-aware sensing, edge intelligence, adaptive thresholds, energy-aware communication, sensor-fault diagnosis, and human-governed maintenance decision support while preserving engineering interpretability, cybersecurity, calibration, and fail-safe operation.

Keywords: structural health monitoring; self-adaptive sensor networks; wireless sensor networks; infrastructure monitoring; edge intelligence; smart sensors; adaptive sensing; anomaly detection; IoT; predictive maintenance

1. Introduction

Civil infrastructure deteriorates because of aging, fatigue, corrosion, material degradation, repeated traffic loading, extreme environmental exposure, construction defects, seismic activity, impact, temperature variation, foundation movement, and other structural or operational effects. Periodic inspection remains fundamental to infrastructure management, but intermittent inspection may not capture rapidly developing damage or subtle changes occurring between scheduled assessments. Structural Health Monitoring (SHM) addresses this limitation by using sensing, signal processing, system identification, and diagnostic methods to observe structural condition over extended periods.

Wireless sensing has become particularly important because conventional wired SHM installations can be expensive and difficult to deploy over large structures. Wireless sensor networks can reduce cabling requirements, distribute measurements across structural locations, and support remote data acquisition. Noel and colleagues' comprehensive survey identified wireless networking as a major SHM architecture while also emphasizing constraints related to energy, bandwidth, synchronization, reliability, data processing, and network design.

Recent developments have extended this architecture through Internet-of-Things connectivity, edge computing, low-cost microcontrollers, machine learning, autonomous sensing, digital twins, and advanced communication protocols. Loubet and colleagues developed an autonomous Industrial IoT approach for civil-engineering structural monitoring, demonstrating the continuing movement toward distributed and increasingly autonomous sensing architectures. Karimi's recent real-time SHM framework likewise showed how affordable IoT sensors can be integrated with streaming acquisition, signal processing, and unsupervised anomaly detection, while explicitly identifying adaptive threshold calibration and on-node processing as important future developments.

A conventional sensor network may sample vibration every fixed number of seconds regardless of whether the structure is stable or experiencing an unusual event. It may transmit large volumes of normal data to a central server, consuming energy and communication bandwidth. If one sensor fails, the network may continue treating corrupted data as structurally meaningful. If traffic, wind, temperature, or humidity changes the baseline structural response, fixed anomaly thresholds may produce false alarms.

A self-adaptive network can respond differently. During stable conditions, it may reduce sampling or communication frequency. When an abnormal vibration pattern appears, selected nodes may increase sampling frequency, activate neighboring sensors, perform local feature extraction, and transmit only high-priority information. If communication quality deteriorates, routing can be modified. If one sensor becomes unreliable, the system can identify the fault and reduce reliance on that node. If environmental conditions shift, anomaly thresholds can be recalibrated.

Recent research provides direct evidence of this transition. Cui and colleagues developed smart adaptive trigger sensing combining edge intelligence and digital-twin concepts for energy-efficient wireless SHM, specifically using adaptive triggering rather than continuous high-intensity acquisition. Current AI-oriented bridge SHM research also identifies adaptive thresholds, environmental variability management, missing-data reconstruction, sensor-fault detection, and physics-guided intelligence as central challenges for reliable long-term monitoring.

2. Structural Health Monitoring and Wireless Sensor Networks

SHM systems typically transform physical structural response into diagnostic information through several stages. Sensors first measure quantities such as acceleration, strain, displacement, rotation, temperature, acoustic emissions, or other relevant variables. Signals are then conditioned, synchronized, transmitted, processed, and transformed into features associated with structural condition. Diagnostic algorithms finally determine whether the observed response is consistent with normal operation or potentially indicates damage.

Noel and colleagues describe wireless SHM as an interdisciplinary problem in which sensing performance must be considered together with network topology, energy management, communication reliability, synchronization, and damage-detection algorithms. More recent sensor-network reviews similarly emphasize that the location and number of sensors, network architecture, node capabilities, and measurement objectives determine whether the network provides sufficient information for structural diagnosis.

- The attractiveness of wireless monitoring is therefore accompanied by multiple engineering constraints.
- Wireless nodes usually operate under limited energy budgets.
- Communication can be affected by structural geometry, interference, distance, and environmental conditions.
- High-frequency vibration monitoring may generate large data volumes.
- Sensor synchronization is important when modal analysis or distributed vibration measurements depend on temporal alignment.
- Nodes may experience drift, bias, noise, battery depletion, communication failure, or complete malfunction.
- These constraints make static network configuration increasingly inefficient as monitoring systems become larger and operate for longer periods.

3. From Static Monitoring to Self-Adaptive Sensing

A static monitoring architecture uses predetermined settings that remain relatively constant after deployment. Sampling frequency, routing, transmission intervals, anomaly thresholds, and processing locations are configured in advance.

- Such an approach is simple and interpretable.
- However, infrastructure conditions are not static.
- A bridge may experience different traffic loading during peak and off-peak periods.
- Wind can substantially modify dynamic response.
- Temperature produces daily and seasonal changes in structural properties.
- Extreme events can create sudden changes requiring high-frequency monitoring.
- Communication links may become temporarily unreliable.
- Individual sensors may degrade.

This multi-layer interpretation is important because adaptive sensing alone does not constitute a fully self-adaptive monitoring system.

4. Edge Intelligence and Distributed Decision-Making

1. Traditional wireless SHM systems frequently transmit raw or lightly processed measurements to a centralized location.
2. Central processing simplifies algorithm management but produces potential disadvantages.
3. Large volumes of high-frequency vibration data consume network bandwidth.
4. Continuous radio transmission consumes substantial node energy.
5. Network interruption can prevent timely diagnosis.
6. Centralized processing also increases dependence on stable communications.

Cui and colleagues' adaptive trigger-sensing research directly reflects this direction by combining edge intelligence and adaptive control to improve energy efficiency in wireless SHM.

5. Energy Efficiency as an Adaptation Objective

- Energy consumption remains one of the most important limitations in wireless structural sensing.
- Battery replacement can be difficult on bridges, towers, offshore structures, tunnels, high-rise buildings, or other inaccessible infrastructure.
- A monitoring network that requires frequent manual battery replacement can undermine the economic benefit of wireless installation.
- Energy is consumed not only by sensors but also by microcontrollers, local computation, wireless communication, memory operations, and synchronization.
- The most aggressive energy-saving strategy is to deactivate components whenever they are not required.
- However, excessive sleep periods introduce monitoring risk.

Reinforcement-learning research for sensor-network energy management illustrates how adaptive policies can dynamically allocate energy resources rather than relying on predetermined rules.

Energy harvesting provides another complementary direction. Autonomous or self-powered nodes can reduce dependence on batteries, although energy availability may itself vary with vibration, light, thermal gradients, or other local environmental conditions. An adaptive network can therefore modify sensing and communication activity according to both monitoring demand and available energy.

6. Adaptive Thresholds and Environmental Variability

- A structural response is affected by more than damage.
- Temperature, wind, humidity, traffic, operating state, occupancy, and seasonal conditions can produce substantial changes in vibration and strain.
- If the monitoring system treats all deviations from one fixed baseline as damage, false alarms can become frequent.
- False alarms reduce trust.
- They also consume engineering resources because every alert may require investigation.

7. Sensor Faults and Network Resilience

- Sensor failure represents another significant SHM challenge.
- A failed accelerometer can produce constant values.
- Sensor drift can gradually shift the signal.
- Loose mounting can modify measured vibration.
- Noise can increase.
- Calibration may deteriorate.
- Communication errors may produce missing or corrupted packets.
- A damaged sensor can therefore create an apparent structural anomaly.

Recent AI-focused SHM research specifically identifies sensor faults and missing data as important threats to reliable diagnosis. The literature also notes that sensor faults and actual structural damage can generate similar patterns, creating a need for integrated frameworks capable of reasoning about both conditions simultaneously.

8. Research Gap

Wireless SHM research has established strong foundations in sensor hardware, network communication, structural-damage detection, sensor placement, IoT integration, and machine learning. Recent literature also increasingly addresses edge computing, adaptive triggering, fault diagnosis, and intelligent monitoring.

First, many monitoring architectures optimize one layer independently. A study may optimize routing, sampling, anomaly detection, or energy consumption without evaluating how these adaptations interact.

Second, adaptive sampling is sometimes treated as equivalent to self-adaptation. A more complete self-adaptive system should also manage communication, processing, network faults, diagnostic thresholds, and node energy.

Third, structural monitoring performance is commonly evaluated through damage-detection accuracy while operational qualities such as alert latency, packet reliability, energy efficiency, and sensor-fault recovery receive less integrated treatment.

Fourth, AI-based monitoring may increase adaptability while reducing interpretability. Critical infrastructure requires engineers to understand why the system altered a threshold, changed sensing behavior, or generated an alert.

9. Novelty and Proposed Contribution

1. The study proposes a Self-Adaptive Infrastructure Sensor Network Framework (SAISNF).
2. The framework integrates five forms of adaptation.
3. Sensing adaptation modifies sampling rate and node activation according to structural activity.
4. Computational adaptation determines whether analysis should occur locally, at the gateway, or in higher-level computing infrastructure.
5. Communication adaptation modifies routing, packet priority, and transmission behavior according to network conditions.

6. Diagnostic adaptation modifies anomaly thresholds according to verified environmental and operational context.
7. Fault adaptation detects malfunctioning nodes and adjusts monitoring logic to preserve network reliability.
8. The methodological novelty is the evaluation of this architecture through six performance indicators rather than through damage accuracy alone.

10. Research Objectives and Questions

The following research questions are examined:

- Does adaptive sensing improve modeled damage-detection accuracy relative to a static wireless sensor network?
- Does edge-enabled self-adaptation reduce the modeled latency between abnormal structural response and network alert generation?
- How does network adaptation affect packet-delivery reliability and energy efficiency?
- Does self-adaptive fault management improve monitoring continuity when sensor degradation occurs?
- Can a multidimensional Infrastructure Health Monitoring Index differentiate static, adaptive, and self-adaptive sensor-network architectures?

11. Methodology

11.1 Research Design

- The study adopts a simulation-based quantitative research design.
- No actual bridge, building, tunnel, sensor deployment, structural-damage experiment, or infrastructure authority supplied measurements for the analysis.
- The simulation was intentionally selected so that the manuscript would not present invented field measurements as empirical results.
- A synthetic dataset representing 180 hypothetical infrastructure-monitoring units was generated.

11.2 Network Architecture Definitions

The Static WSN uses fixed sensing intervals, predetermined routing, fixed anomaly thresholds, and centralized analysis.

The Adaptive Sensing Network dynamically changes sampling behavior according to detected structural activity but retains more limited adaptation in network communication, processing, and sensor-fault management.

The Self-Adaptive Edge WSN combines adaptive sensing with edge processing, dynamic anomaly thresholds, communication adaptation, duty-cycle management, and sensor-fault recovery.

The three conditions therefore represent progressively broader forms of adaptation rather than specific commercial technologies.

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12. Simulation Variables

Table 1: Synthetic Parameterization of Sensor-Network Architectures

Monitoring Indicator	Static WSN	Adaptive Sensing	Self-Adaptive Edge WSN
Damage-detection accuracy	Mean 69%, SD 8	Mean 84%, SD 7	Mean 93%, SD 5
Alert latency	Mean 5.8 s, SD 1.1	Mean 3.4 s, SD 0.8	Mean 1.8 s, SD 0.5
Packet-delivery rate	Mean 82%, SD 7	Mean 90%, SD 5	Mean 95%, SD 3
Energy-efficiency score	Mean 57, SD 8	Mean 75, SD 7	Mean 88, SD 5
Sensor-fault recovery	Mean 51%, SD 9	Mean 72%, SD 8	Mean 89%, SD 5
False-alarm rate	Mean 14.0%, SD 3.2	Mean 9.0%, SD 2.5	Mean 5.2%, SD 1.7

Note: Values are methodological assumptions designed for scenario comparison and are not published average performance values for operational SHM networks.

13. Infrastructure Health Monitoring Index

A composite Infrastructure Health Monitoring Index (IHMI) was used to combine operational and diagnostic performance.

The index incorporates damage-detection accuracy, alert-latency efficiency, packet-delivery reliability, energy efficiency, sensor-fault recovery, and false-alarm performance.

The weighting structure was defined as:

$$IHMI = 0.25DA + 0.15LE + 0.15PD + 0.20EE + 0.15FR + 0.10FAE$$

where:

DA = Damage-Detection Accuracy LE = Latency Efficiency PD = Packet-Delivery Rate EE = Energy Efficiency FR = Sensor-Fault Recovery FAE = False-Alarm Efficiency

Damage-detection accuracy received the greatest individual weight because structural-condition identification remains the primary purpose of SHM.

Energy efficiency received 0.20 because monitoring networks may need to operate for long periods without maintenance.

The remaining weights recognize that fast, reliable, fault-tolerant communication is necessary for trustworthy monitoring.
The index is illustrative and should not be interpreted as a universal SHM standard.

14. Proposed Questionnaire for Future Engineering Validation

The following five questions are proposed for future surveys of infrastructure engineers, SHM researchers, asset managers, or monitoring-system operators. They were not administered in the present study.
Responses may be recorded on a five-point Likert scale from 1 = Strongly Disagree to 5 = Strongly Agree.

1. The monitoring network should automatically increase sensing activity when unusual structural behavior is detected.
2. Local edge processing would improve the usefulness of structural monitoring by reducing unnecessary transmission of normal-condition data.
3. Adaptive anomaly thresholds are necessary for distinguishing structural damage from environmental and operational variability.
4. A reliable monitoring system should be capable of detecting sensor malfunction and continuing operation through alternative sensing information.
5. Automated network adaptation should remain transparent enough for engineers to review why monitoring behavior or alarm thresholds were changed.

The proposed scale should undergo expert review, pilot testing, reliability evaluation, and construct validation before empirical application.

15. Results

Table 2: Simulated Infrastructure-Monitoring Performance

Performance Indicator	Static WSN	Adaptive Sensing	Self-Adaptive Edge WSN
Damage-detection accuracy (%)	70.4	83.9	93.4
Alert latency (s)	5.7	3.6	1.8
Packet-delivery rate (%)	81.4	90.3	94.7
Energy-efficiency score	57.0	75.5	86.7
Sensor-fault recovery (%)	50.9	71.1	88.9
False-alarm rate (%)	13.8	8.8	5.0
Infrastructure Health Monitoring Index	**57.6**	**75.1**	**87.9**

16. Damage-Detection Performance

1. Mean damage-detection accuracy increased from 70.4% in the static architecture to 83.9% under adaptive sensing and 93.4% under the self-adaptive edge architecture.
2. The simulated advantage arises from three mechanisms.
3. First, adaptive sensing increases measurement density when structural activity becomes abnormal.
4. Second, edge processing allows rapid extraction of damage-sensitive features close to the data source.
5. Third, adaptive thresholds reduce the probability that changing operating conditions are incorrectly classified.
6. Contemporary SHM research increasingly combines low-cost distributed sensing with anomaly-detection models, while current AI reviews emphasize the importance of environmental normalization, missing-data handling, and adaptive diagnostics.

17. Alert Latency

- Alert latency decreased from 5.7 seconds for the static WSN to 3.6 seconds for adaptive sensing and 1.8 seconds for the self-adaptive architecture.
- Centralized networks can experience delay because large quantities of data must be transmitted before analysis.
- Edge systems can perform initial evaluation locally.
- A self-adaptive node can therefore escalate only information associated with a potential event.
- This architecture is particularly relevant for sudden events such as impact, earthquake response, abnormal vibration, or rapid structural change.
- The result is conceptually consistent with the broader move toward edge-based SHM and real-time local processing.

18. Packet-Delivery Reliability

- The packet-delivery rate increased from 81.4% under static monitoring to 90.3% under adaptive sensing and 94.7% under the self-adaptive architecture.
- Self-adaptive communication can improve reliability by changing routes, transmission priorities, retransmission behavior, or node roles.
- This capacity becomes increasingly important in large sensor networks where radio conditions vary spatially and temporally.
- Wireless network reliability should not be evaluated independently of energy consumption.
- Aggressive retransmission may increase packet delivery while rapidly consuming battery energy.
- Self-adaptation therefore requires multi-objective control rather than maximization of a single communication metric.

19. Energy Efficiency

- The simulated energy-efficiency score increased from 57.0 to 75.5 and finally 86.7.
- The largest gains arise from reduced unnecessary sensing and communication during structurally stable periods.

- Adaptive trigger sensing provides a practical example of this philosophy. Cui and colleagues developed an edge-intelligence framework in which triggering logic changes monitoring activity to support long-term energy-efficient wireless SHM.
- A self-adaptive system can also consider remaining battery energy during network decisions.
- Nodes with low energy may reduce non-critical communication.
- Other nodes may temporarily assume additional monitoring responsibility.
- In energy-harvesting systems, operating intensity may also be adjusted according to available harvested power.

20. Sensor-Fault Recovery

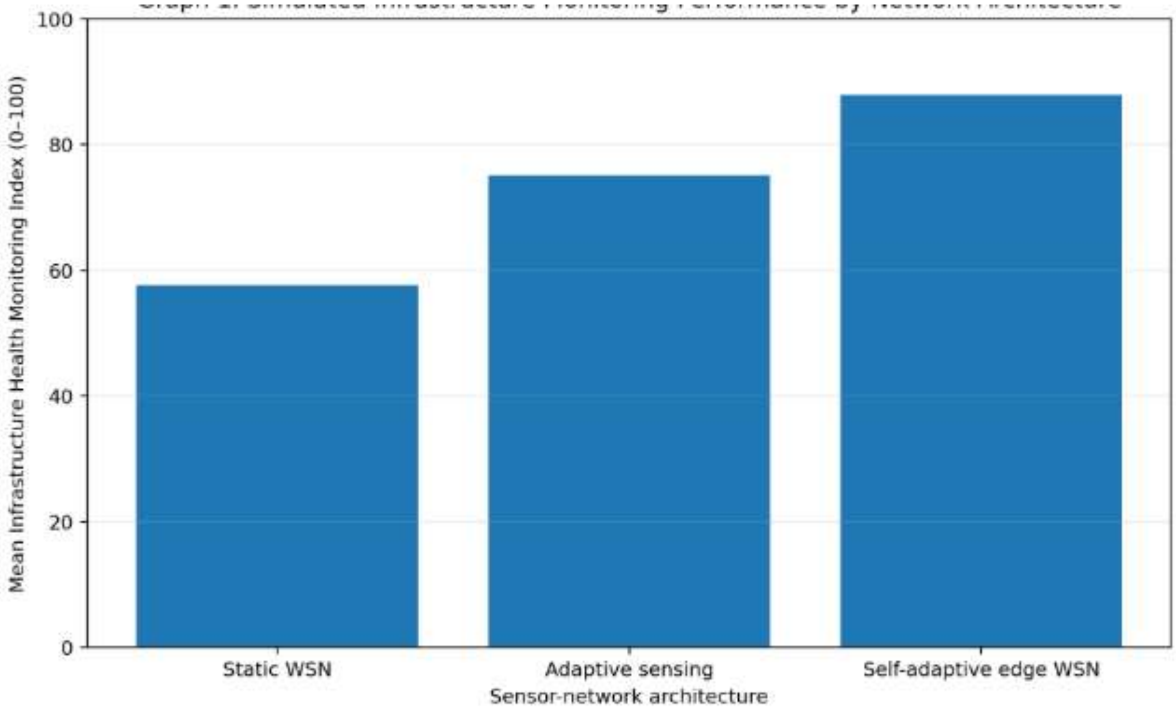
1. Sensor-fault recovery produced one of the largest modeled improvements.
2. The mean recovery score increased from 50.9% in the static architecture to 71.1% in adaptive sensing and 88.9% under self-adaptation.
3. This result reflects the distinction between a network that measures infrastructure and one that can also assess the reliability of its own measurements.
4. Current SHM literature recognizes that noise, missing data, drift, and sensor malfunction can undermine diagnosis and that faulty sensors can produce signals resembling actual damage.
5. Self-adaptive recovery could involve exclusion of one sensor from the diagnostic model, substitution using neighboring measurements, virtual-sensor estimation, changed network routing, or an explicit maintenance request.
6. Importantly, reconstructed values should be labeled as reconstructed.

21. False-Alarm Reduction

- The false-alarm rate decreased from 13.8% in the static system to 8.8% under adaptive sensing and 5.0% in the self-adaptive architecture.
- False alarms can emerge when structural response changes because of temperature or operational loads rather than damage.
- They can also emerge from sensor faults.
- Adaptive contextual baselines can reduce this problem.
- Current bridge SHM research specifically identifies environmental and operational variability, changing thresholds, sensor faults, and data quality as closely related challenges for automated diagnosis.
- False-alarm reduction must nevertheless be balanced against detection sensitivity.
- A system that rarely produces an alarm may simply have thresholds that are too conservative.
- Consequently, future field validation should report false-negative rates alongside false alarms.

22. Graphical Analysis

Graph 1: Simulated Infrastructure Monitoring Performance by Network Architecture



23. Statistical Analysis

One-way analysis of variance demonstrated strong separation among the synthetic architectures.

Damage-detection accuracy produced:

- $F = 189.69$, $p < 0.001$, $\eta^2 = 0.682$.
- Alert latency produced:
- $F = 382.10$, $p < 0.001$, $\eta^2 = 0.812$.
- Packet-delivery rate produced:
- $F = 97.02$, $p < 0.001$, $\eta^2 = 0.523$.
- Energy efficiency produced:
- $F = 247.93$, $p < 0.001$, $\eta^2 = 0.737$.
- Sensor-fault recovery produced:
- $F = 430.99$, $p < 0.001$, $\eta^2 = 0.830$.
- False-alarm rate produced:

They do not establish that actual deployment of self-adaptive sensing will generate effects of the same magnitude.

24. Discussion

1. The results illustrate why future SHM systems may need to move beyond fixed monitoring configurations.
2. Infrastructure and sensing networks both operate under uncertainty.

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3. The structure changes because of environmental and operational conditions.
4. Sensors change because of aging, drift, and power limitations.
5. Communication conditions vary.
6. The relevance of individual measurements changes over time.
7. A fixed architecture treats these dynamic conditions as external disturbances.
8. A self-adaptive architecture treats them as information that can influence monitoring behavior.
9. The most important implication is therefore architectural rather than algorithmic.

24.1 Static Systems Remain Valuable

- The study should not be interpreted as suggesting that every SHM installation requires advanced self-adaptation.
- Static networks offer important advantages.
- Their operating behavior is comparatively easy to understand.
- Verification is simpler.
- Regulatory and engineering review may be easier.
- Software complexity is lower.
- Cybersecurity exposure may be reduced.

The decision to adopt self-adaptation should depend on scale, monitoring duration, structural criticality, energy constraints, communication conditions, and maintenance accessibility.

24.2 Adaptation Must Remain Interpretable

- Autonomous adaptation creates a major engineering-governance challenge.
- Suppose an algorithm increases an alarm threshold automatically.
- The system subsequently receives a vibration pattern that would have triggered the previous threshold but does not trigger the new one.
- An engineer must be able to determine why the threshold changed.

25. Conclusion

Self-adaptive sensor networks represent a significant development in infrastructure health monitoring because they shift monitoring systems from passive data acquisition toward context-aware operational intelligence.

Conventional wireless sensor networks provide substantial benefits over wired monitoring but often rely on fixed sensing, transmission, and diagnostic configurations.

Adaptive sensing improves this architecture by changing measurement activity according to detected conditions.

A fully self-adaptive architecture extends the concept further by coordinating sensing, edge processing, communication, diagnostic thresholds, energy management, and sensor-fault recovery.

The simulation developed in this study compared 180 hypothetical infrastructure-monitoring units across The Infrastructure Health Monitoring Index increased from 57.6 in the static architecture to 75.1 under adaptive sensing and 87.9 under the self-adaptive edge architecture.

Future infrastructure-monitoring systems will benefit most when adaptation is treated as a controlled engineering capability rather than unrestricted algorithmic autonomy.

Self-adaptive networks should respond intelligently to changing structural, environmental, communication, and energy conditions while preserving calibration, interpretability, cybersecurity, traceability, human oversight, and fail-safe operation.

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