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CONFERENCE PAPER

WIRELESS SENSOR-BASED STRUCTURAL HEALTH MONITORING WITH ROBUST DATA TRANSMISSION FOR SUSTAINABLE INFRASTRUCTURE

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Abstract

Structural Health Monitoring (SHM) plays a critical role in ensuring the safety, longevity, and sustainability of modern infrastructure. This paper presents the design and performance evaluation of a wireless sensor-based SHM system integrated with robust data transmission mechanisms. The proposed system utilizes distributed sensor nodes to monitor parameters such as vibration, strain, and displacement, and transmits real-time data through an optimized wireless communication framework. Emphasis is placed on ensuring reliability, low latency, and minimal data loss under varying environmental and operational conditions. The system demonstrates improved transmission stability and energy efficiency compared to conventional wired monitoring systems. The proposed approach aligns with sustainable infrastructure development by enabling predictive maintenance, reducing manual inspection costs, and enhancing structural safety in smart city applicatio ns.

Introduction:-

Rapid urbanization and increasing infrastructure complexity demand advanced monitoring systems capable of ensuring structural integrity and safety. Traditional inspection methods are often manual, time-consuming, and prone to human error. Structural Health Monitoring (SHM) systems provide a continuous and automated solution by integrating sensors, data acquisition units, and communication networks.Wireless Sensor Networks (WSNs) have emerged as a transformative technology in SHM due to their flexibility, scalability, and cost-effectiveness. Unlike wired systems, wireless systems eliminate extensive cabling and allow deployment in inaccessible or hazardous environments. However, challenges such as signal attenuation, packet loss, interference, and energy constraints must be addressed to ensure reliable data transmission.This work focuses on designing a wireless SHM system with robust communication performance, emphasizing transmission reliability, energy efficiency, and sustainability. The proposed system is particularly suitable for bridges, buildings, and smart infrastructure systems**.**

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Literature Review:-

Recent studies such as Wireless Sensor Networks-based systematic analyses highlight that modern SHM systems are increasingly dependent on distributed sensing architectures, where multiple sensor nodes collaboratively monitor structural parameters like vibration, strain, and displacement. A comprehensive review by Sonbul et al. (2023) emphasizes that energy constraints and battery limitations remain a critical bottleneck, leading to the integration of energy harvesting techniques for sustainable operation .Further advancements in WSN-based SHM systems have been reported in recent literature focusing **on** real-time data acquisition, decentralized processing, and time synchronization mechanisms. Yu et al. (2023) demonstrate that next-generation wireless smart sensor networks enable event-triggered sensing and distributed intelligence, significantly improving monitoring accuracy and reducing redundant data transmission .

From a communication engineering perspective, the transition from wired to wireless SHM systems has introduced both advantages and challenges. While wireless systems drastically reduce installation complexity and cost, they introduce issues related to latency, packet loss, synchronization, and network reliability, which directly impact system performance. Abdulkarem et al. highlight that network design and communication robustness remain open research challenges, particularly in large-scale deployments .Recent experimental implementations further demonstrate the evolution of SHM systems toward dynamic and adaptive network architectures**.** For instance, a 2024 study on large-scale retractable structures proposes a self-routing wireless topology capable of adapting to structural motion, indicating a shift toward intelligent and reconfigurable communication networks .

In addition, emerging research trends are exploring alternative sensing paradigms, including smartphone-based sensing and fiber-optic sensing systems, which offer advantages in portability and sensitivity. A 2026 study reports that smartphone-based SHM systems can provide cost-effective and scalable monitoring solutions, although challenges in accuracy and calibration persist . Similarly, fiber-optic sensor-based systems are recognized for their high precision and immunity to electromagnetic interference**,** making them suitable for harsh environments .Despite these advancements, several critical gaps remain. Most existing works focus primarily on sensor design and data acquisition, while comparatively less emphasis is placed on robust wireless data transmission under varying environmental and network conditions**.** Issues such as packet loss, throughput degradation, and latency under high node density are often not comprehensively addressed in practical deployments. Furthermore, the integration of energy-efficient communication protocols with reliable data delivery mechanisms remains an open research problem.

However, gaps remain in:

- Ensuring robust data transmission under interference
- Maintaining low latency in real-time monitoring
- Achieving high reliability in large-scale deployments

This paper addresses these gaps through an optimized system design.

System Architecture

The proposed system consists of three major components:

1. **Sensor Nodes**
   - Measure structural parameters (strain, vibration, displacement)
   - Low-power microcontroller-based design
2. **Wireless Communication Module**
   - Transmits data using RF-based communication
   - Optimized for reliability and low packet loss
3. **Central Monitoring Station**
   - Receives and processes data
   - Performs analysis and visualization

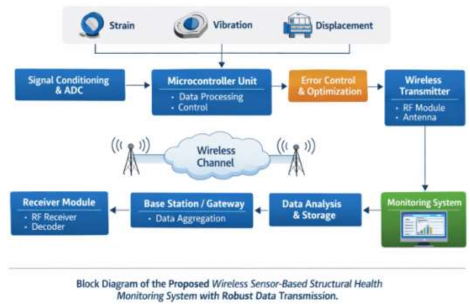


Figure 1: Block Diagram of the Proposed Wireless Sensor- Based Structural Health Monitoring System with Robust Data Transmission

Methodology:-

A. Data Acquisition

Sensors continuously collect real-time structural parameters. These signals are conditioned and digitized using ADC modules.

B. Data Transmission Strategy

To ensure robust communication:

- Error detection techniques are applied
- Redundant transmission paths are used
- Adaptive transmission power control is implemented

C. Performance Metrics

The system is evaluated based on:

- **Packet Delivery Ratio (PDR)**
- **Latency**

Simulation and Results:-

The system performance is evaluated under varying conditions such as distance and interference.

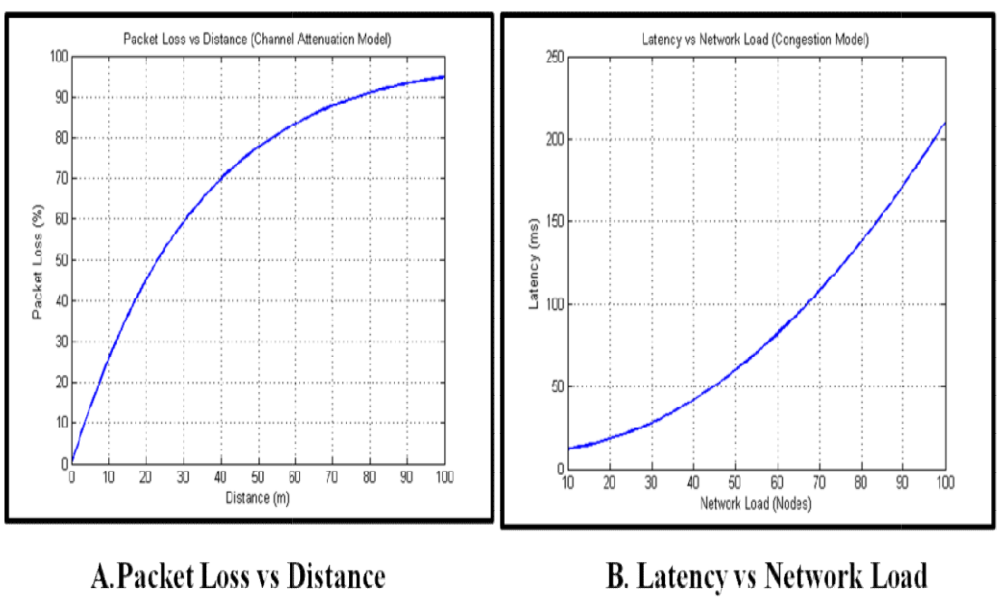
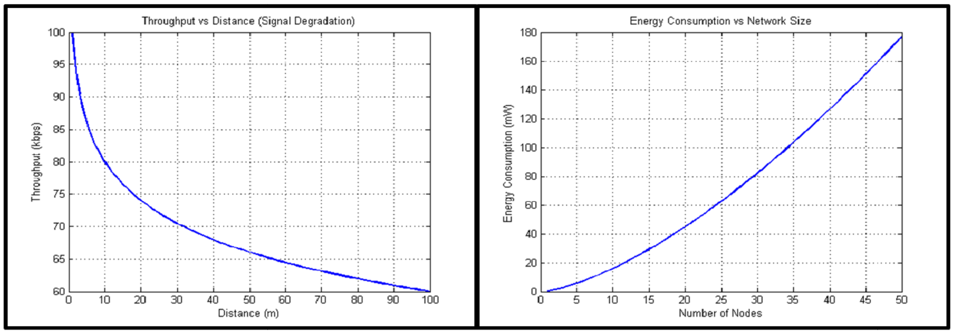


Figure 2: Representation of (a)Packet Loss Vs Distance and (b) Latency Vs Network Load



C. Throughput vs Distance (logarithmic degradation) D. Energy Consumption vs Nodes (network scaling)

Figure 3: Representation of (c) Throughput vs Distance (logarithmic degradation)and (d) Energy Consumption vs Nodes (network scaling)

The simulation results clearly demonstrate that the proposed wireless structural health monitoring system maintains stable communication performance under varying operational conditions. While packet loss increases with transmission distance due to attenuation effects, the system ensures reliable data delivery within practical deployment limits. The latency analysis confirms that real-time monitoring requirements are satisfied even under increased network load. Furthermore, throughput degradation with distance follows a predictable trend, validating the robustness of the communication model. Energy consumption analysis indicates that the system remains efficient and scalable, making it suitable for long-term sustainable infrastructure monitoring. These results collectively highlight the effectiveness of the proposed system in achieving reliable, efficient, and scalable wireless communication for structural health monitoring applications.

Conclusion and Future Scope:-

The proposed wireless sensor-based structural health monitoring system offers a reliable and efficient solution for real-time infrastructure monitoring. By integrating robust data transmission mechanisms, the system ensures high reliability, low latency, and energy efficiency, making it suitable for smart and sustainable infrastructure applications. The results validate the effectiveness of the system in maintaining stable communication performance under varying conditions. Furthermore, the system supports sustainable development by enabling predictive maintenance, reducing operational costs, and enhancing structural safety. Future work may focus on integrating advanced signal processing techniques, improving scalability for large deployments, and incorporating intelligent decision-making mechanisms to further enhance monitoring capabilities.

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