Sensors and Materials, Vol. 38, No. 1 (2026) 349–362
MYU Tokyo

S & M 4303

Communication Protocol and Network Deployment Design for Wireless Sensor Network

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(Received June 5, 2025; accepted January 21, 2026)

Keywords: wireless sensor network, hierarchical protocol, LEACH, structural health monitoring, energy consumption optimization

A wireless sensor network design is tailored for the structural health monitoring of large-scale civil infrastructure in this study. To address the challenge of power management in remote deployments, we integrated advanced sensor technology with a hierarchical network architecture. In the experiment, we implemented an improved low-energy adaptive clustering hierarchy (LEACH) protocol to enhance data fidelity and operational longevity. The protocol requires high-precision sensor integration, including ADXL202E accelerometers with a thermal sensitivity of 2 mg/°C for real-time drift compensation. The results demonstrate that the improved LEACH protocol extends the network lifetime to 394 rounds, a 23% improvement over traditional schemes. Furthermore, the design achieves a 42% reduction in energy imbalance among nodes, effectively preventing the premature failure of critical hotspot sensors. The results contribute a scalable, high-fidelity solution for long-term structural monitoring by harmonizing sensor-level calibration with network-level energy optimization.

1. Introduction

The integration of wireless sensor networks (WSNs) into structural health monitoring (SHM) has contributed to the integrity of civil infrastructure.(1) However, the operational efficiency of the system largely depends on the synergy among sensor hardware, network topological structures, and communication protocols.(2) Different from general-purpose networks, WSNs for SHM must facilitate high-fidelity data collection from sensors, such as accelerometers and strain gauges, while operating under severe energy constraints.

The most critical challenge facing WSNs is the network's power management.(3) Since sensor nodes in the WSN are deployed in remote locations on large-scale structures such as bridge pylons or high-rise frameworks, battery replacement might be impractical.(4) Therefore, extending the operational lifetime of the network through energy-efficient protocols is essential. While standard protocols such as sensor protocols for information via negotiation (SPIN)(5) and

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https://doi.org/10.18494/SAM5782

ISSN 0914-4935
https://myukk.org/

low-energy adaptive clustering hierarchy (LEACH) have been proposed, their performance varies depending on the demands of the sensing environment and data collection frequency for monitoring.

When compared with fiber-optic monitoring systems (FOMSs), WSNs offer distinct advantages in terms of ease of use and deployment flexibility. While FOMSs provide high precision, long-term stability without battery requirements, and immunity to electromagnetic interference, their applications are limited by high installation costs and the difficulties in large-scale deployment. In contrast, WSNs allow for rapid, cost-effective deployment across extensive areas without the need for physical interconnects, making them highly effective for the dynamic monitoring needs of civil infrastructure, provided that challenges such as energy consumption are addressed.[6]

In this study, we optimize sensor technology and network architecture by analyzing and designing a two-layer topological structure (comprising a main base station and subnets) tailored for the spatial distribution of sensors in SHM applications. A hierarchical communication protocol is designed on the basis of the International Organization for Standardization's seven-layer model, ensuring robust data transmission from the physical sensor layer to the application layer.[7] The developed modular software architecture provides an approach for the flexible integration of different sensors and the system's scalability and reliability. The architecture also provides a solution for long-term, low-power structural monitoring that maintains high data integrity across the network based on the hierarchical coordination of sensor nodes.

2. WSN Protocols

Various communication methods are adopted in the WSN, but they suffer from information explosion, partial overlap, and inefficient resource allocation, causing transmission delays and unsatisfactory real-time performance. Therefore, appropriate routing protocols are required for effective and efficient communication. The protocols are categorized into planar and hierarchical routing protocols, depending on the architecture based on network topology.

2.1 Planar routing protocols

In planar routing, all nodes maintain equal status, and routes are generated through local operations and feedback. While simple and scalable, these protocols cannot optimize resource management and respond slowly to dynamic changes.

Despite their effectiveness, planar networks require nodes to continuously monitor communication channels, resulting in high power consumption. For large-scale SHM, maintaining communication within local areas is essential to prevent the degradation of transmission capacity.[8] Routing algorithms are classified into proactive, reactive, and geographical approaches. In proactive protocols, all nodes maintain routing tables between source and destination addresses regardless of immediate need. In reactive protocols, route discovery is initiated only when data transmission is required; once established, the route information is retained temporarily. Although reactive routing reduces table size to approximately the scale of the network, route discovery introduces significant delays, making it unsuitable for real-time applications.

Most distributed routing algorithms in ad hoc mobile networks are based on planar structures such as mesh networks, whether proactive or reactive. Because ad hoc networks lack hierarchy, each node functions as a relay and shares equal responsibility. In fully distributed systems, nodes not actively transmitting must still monitor the channel to act as relays, leading to substantial energy consumption. A star–mesh hybrid topology offers a more efficient alternative, enabling intelligent routing that improves connectivity, reduces delay, and enhances overall performance.

Given the limited storage capacity of sensor nodes, reactive routing provides a compact solution for sensor network applications. By transmitting information to a small number of nodes designated as data concentration stations, the delay associated with reactive routing can be mitigated. Each concentration station aggregates communication within its local area, thereby supporting scalability. However, as the size of an ad hoc network increases, the transmission capacity of individual nodes decreases because the average path length between source and destination grows proportionally. To counteract this decline, communication should remain localized, ensuring that the average number of hops per packet is less than the total number of relays in the network. Representative data-centric planar protocols include the following.

2.1.1 SPIN

SPIN employs a negotiation mechanism, such as Advertisement (ADV), Request (REQ), and DATA packets,(5) to prevent implosion and overlap by transmitting metadata instead of raw data.(9) As the first data-centric adaptive routing protocol, SPIN effectively addresses problems such as information explosion and resource waste inherent in traditional flooding and gossiping approaches through this negotiation mechanism.(9) Nodes negotiate by exchanging metadata, which describes the attributes of the collected data rather than the data itself. Because metadata is significantly smaller than raw sensor data, its transmission consumes less energy. Before transmitting or receiving data, each node evaluates its available energy. If a node is at a low energy level, it suspends certain operations, such as acting as a router or forwarding data, to conserve resources. SPIN defines three packet types: ADV, REQ, and DATA. ADV packets are used to broadcast the availability of new data.(10) When a node has data to transmit, it first broadcasts an ADV packet containing metadata. Neighboring nodes that wish to receive the data respond with a REQ packet, after which the transmitting node sends the corresponding DATA packet. DATA packets contain the actual sensed information, accompanied by metadata headers.

The most widely used version of SPIN is SPINPoint-to-Point (SPIN-PP). In this protocol, a sensor node broadcasts an ADV packet to its neighbors before sending a DATA packet. If a neighbor node accepts the data, it replies with a REQ packet, prompting the sender to transmit the DATA packet. Through successive exchanges, DATA packets can be relayed to distant sink nodes. However, in SPINPP, ADV packets are broadcast indiscriminately to all neighbors without considering their energy constraints. Consequently, nodes might be unwilling or unable to forward new data, leading to transmission failures and the formation of data blind spots, which hinder information collection across the network.(11)

2.1.2 Directed diffusion (DD)

DD represents a milestone in data-centric routing, in which the sink broadcasts an interest and nodes establish gradients to determine the optimal path.[10,11] The DD protocol is designed for wireless sensor networks.[12] Its principle is that sensor nodes are identified by attribute values, and data propagation paths are established through interactions between nodes and their neighbors. To process queries, DD introduces the concept of gradient variables, which quantify the degree of match between a node and the query conditions during diffusion (Fig. 1). A higher gradient value indicates a greater likelihood of obtaining relevant data along that path, thereby enabling the construction of an optimized route between the source and destination nodes.[11]

2.1.3 Additional variants

Other planar protocols include hierarchical reliable energy-efficient multipath routing (HREEMR) for energy-efficient fault recovery,[12] sequential assignment routing (security-aware ad hoc routing, SAR) for the quality of service awareness,[13] and a small minimum-energy communication network (SMECN) for location-based energy minimization.[14] The HREEMR protocol is an improved design of the DD algorithm. It uses multipath technology to achieve energy-efficient fault recovery. The SAR protocol is the first routing protocol with QoS awareness. It adopts a routing table-driven multipath approach to obtain the energy conservation and robustness of the network. SMECN is a routing protocol based on node location information. It reduces the energy consumed for transmitting data by constructing a subnet with the minimum energy attribute and can be well applied in sensor networks where topological changes are not very frequent. In the above planar routing, each node has the same responsibility to obtain routing information and forward messages.[15]

2.2 Hierarchical and cluster-based protocols

Hierarchical routing protocols organize the network into clusters, each comprising a cluster head and multiple member nodes. This structure enables data fusion at the cluster head, thereby reducing the volume of information transmitted to the base station. In such protocols, cluster heads at lower levels function as members within higher-level clusters, creating a multitiered

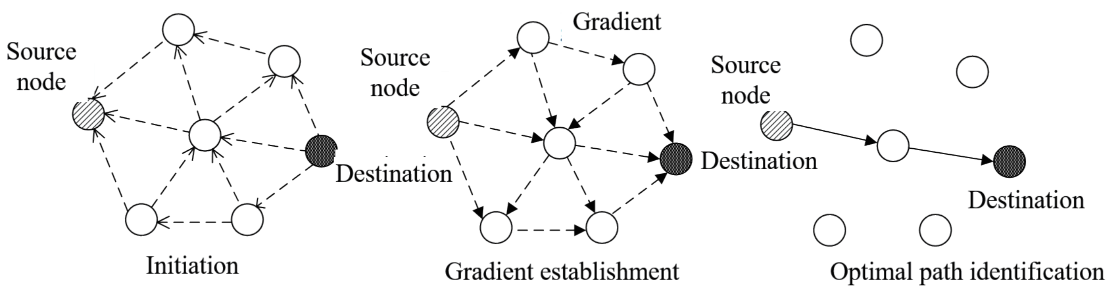


Fig. 1. Routing using DD protocol (drawn in this study).

hierarchy. Cluster heads are responsible for not only aggregating and processing data within their clusters but also forwarding information between clusters.

Cluster formation is determined by node energy levels and proximity to the cluster head. To prolong network lifetime, cluster heads must be periodically reselected. The hierarchical approach simplifies management, allows rapid adaptation to system changes, and supports high-quality communication services. However, these benefits are compromised by the increased overhead associated with cluster maintenance.

2.2.1 LEACH

LEACH is the first multicluster protocol to use the randomized rotation of cluster heads to distribute energy loads.[15] The basic idea of LEACH is to randomly and cyclically select cluster-head nodes to evenly distribute the energy load of the entire network to each sensor node to achieve the purpose of reducing the energy consumption of the network and increasing the overall survival time of the network. Compared with general routing protocols based on a planar structure and static routing protocols based on a multicluster structure, LEACH can extend the network survival time by 15%.

2.2.2 Power-efficient gathering in sensor information system (PEGASIS)

PEGASIS is a chain-based enhancement of LEACH that employs a greedy algorithm to ensure that each node communicates only with its nearest neighbor.[16] In PEGASIS, nodes transmit test signals with decreasing energy to identify their closest adjacent nodes, thereby establishing positional relationships across the network. On the basis of these relationships, each node determines its cluster membership, while the cluster leader optimizes the link to the sink node. The chain is constructed prior to each communication round using a greedy algorithm, beginning with the node farthest from the base station. Because the nodes already included in the chain cannot be revisited, the distance between successive neighbors gradually increases. If a node fails, the chain is reconstructed to maintain connectivity. To prevent excessive energy consumption by nodes located far from their neighbors, a threshold is introduced to restrict such nodes from serving as cluster leaders. This threshold can be adjusted during chain reconstruction to ensure balanced energy usage and sustained network performance.

2.2.3 Threshold-sensitive energy-efficient sensor network protocol (TEEN)

TEEN is a threshold-based routing protocol designed for reactive applications, where data is transmitted only when a specific physical threshold is exceeded.[17] TEEN is tailored for reactive applications and introduces two types of threshold to regulate data transmission: a hard threshold, which specifies the absolute value of a sensed parameter that must be reached before transmission, and a soft threshold, which defines the minimum change in the sensed value that triggers reporting. By appropriately configuring these thresholds, TEEN significantly reduces communication overhead and conserves energy. Younis and Akkaya proposed a three-layer routing protocol that differs from LEACH by requiring users to predefine clusters before network deployment, including the identification of cluster-head nodes and the location of member nodes.(18) Within each cluster, nodes operate in sensing, forwarding, sensing and forwarding, or sleeping. Cluster heads, unconstrained by energy limitations, monitor the energy status of member nodes, manage their operational states, and employ a cost function to select the minimum-cost communication path. Simulation results demonstrate that this protocol achieves efficient energy utilization, high throughput, and low communication delay.

The performance indicators of these various routing protocols are presented in Table 1.

3. Methodology

3.1 Network structure and deployment

In this study, we implemented a LEACH protocol tailored for SHM. The protocol organizes network activity into rounds, each comprising two phases: an initialization phase, during which clusters are formed and cluster heads are selected, and a stable operation phase, during which sensor nodes collect and transmit data to their respective cluster heads for aggregation and delivery to the base station. This network consists of a main base station and multiple subnets in a hierarchical structure. Each subnet includes a secondary base station (cluster-head node) and multiple sensor nodes. The number of nodes within each subnet must be sufficient to meet the requirements of vibration monitoring. The topology of the WSN is illustrated in Fig. 2.

In the initialization, cluster heads are selected by generating a random number between 0 and 1. If the number is larger than the threshold $T(n)$, the node becomes a cluster head for the current round. The threshold is defined as follows.

$$T(n) = \begin{cases} \dfrac{p}{1 - p \times \left(r \times \operatorname{mod} \dfrac{1}{p} \right)} & (\text{if } n \in G) \\ 0 & (\text{otherwise}) \end{cases} \tag{1}$$

Table 1
Performance indicators of routing protocols.

Protocol	Routing	Data-centric routing	Existence of optimal path	Robustness	Scalability
SPIN	On-demand	Yes	No	Bad	Good
DD	On-demand	Yes	Yes	Good	Good
HREEMR	On-demand	Yes	No	Good	Good
SMENCE	On-demand	No	Yes	Good	Good
SAR	On-demand	No	Yes	Good	Good
LEACH	Initiative	No	No	Good	Good
TEEN	Initiative	Yes	No	Good	Good
PEGASIS	Initiative	No	No	Good	Good

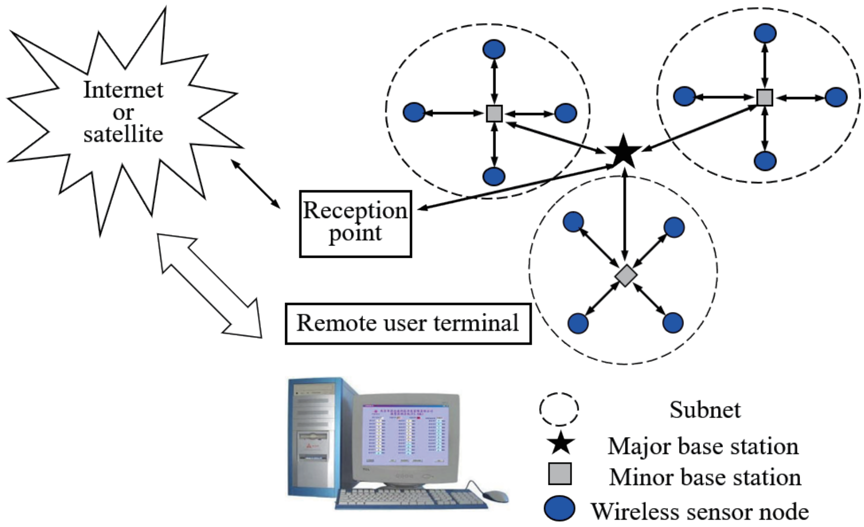


Fig. 2. (Color online) Topology of WSN in this study.

Here, p is the desired percentage of cluster heads, r is the current round, and G is the set of nodes that are cluster heads in the last $1/p$ rounds. When $r = 0$, each node has a probability p of being selected as a cluster head. Nodes that have served as cluster heads in the previous r rounds are excluded from serving again during the subsequent $[1/(p-r)]$ rounds, increasing the likelihood that other nodes assume the cluster head role. After $1/p$ rounds, all nodes regain the probability p of becoming cluster heads, and the cycle repeats. Once cluster heads are selected, they broadcast this information to all nodes with equal transmission energy using the carrier sense multiple access-medium access control protocol.

Each cluster head then communicates with its members using the time division multiple access (TDMA) method defined in the medium access control protocol. After repeated stable operation, reinitialization occurs to rotate the role of cluster heads, thereby balancing energy consumption and extending system lifetime. The LEACH model assumes a symmetric communication channel, meaning that under a given signal-to-noise ratio, the energy required to transmit data from node A to node B equals that from node B to node A. Nodes continuously monitor physical phenomena and transmit data at a constant rate. A round consists of initialization and stable operation, with the stable phase typically lasting longer to minimize overhead.

Once clusters are formed, data transmission begins in the stable operation phase. Nodes transmit monitoring data to the cluster head during their assigned time slots with minimal energy consumption, while entering the sleep mode during idle periods to conserve power. Cluster heads aggregate the collected data and forward the aggregated information to the main base station. Given the long distance to the base station, this approach reduces communication traffic and optimizes energy usage. After a certain period, the network reenters the initialization phase, and new cluster heads are selected.

3.2 Software design

The software architecture of the WSN adopts a modular design, embedding firmware in the sensor nodes and upper-layer management software in the base station (a PC interfaced with a wireless transceiver). The software processes packaged data and executes a handshake protocol to locate the target node. The node firmware remains in a listening state upon a successful handshake, decodes the command, and executes the corresponding sensing or transmission task.

3.3 Node embedded software

The embedded firmware integrates the following modules to ensure autonomous operation and high data fidelity.

- Acceleration sensor calibration module: The duty cycle output of the ADXL202E accelerometer is calibrated at 0 g. While the theoretical 0 g output is a 50% duty cycle, sensors are susceptible to thermal drift. During initialization, the WSN establishes a 0 g baseline at 20 °C. Using the sensor's thermal sensitivity (2 mg/°C), the software adjusts the readings on the basis of real-time ambient temperature data to maintain measurement accuracy.
- Data preprocessing module: Digital filtering is applied to raw sensor signals to eliminate redundant information. By real-time processing at the edge, the wireless transmission load is reduced to prevent data bottlenecks.
- Communication management module: The framing and deframing of data packets are conducted. Outgoing data is encapsulated into a defined frame format, while incoming commands are unpacked for instruction execution.
- Energy management module: To maximize the lifespan of battery-powered nodes, the software switches the wireless transceiver to a low-power idle state between transmissions and places the microprocessor in a deep-sleep mode during periods of inactivity.
- Acquisition and data fusion module: The system acquires acceleration via pulse-width modulation decoding using microprocessor counters, while temperature and strain signals are sampled via analog-to-digital converter channels. Data fusion is used to correlate acceleration with temperature to compensate for drift, while strain data undergoes arithmetic mean filtering to enhance signal-to-noise ratios.
- Node identification module: In this module, each node is assigned a unique ID corresponding to its spatial position within the monitored structure. These identifiers are initialized at deployment but remain reconfigurable via the management software.

3.4 Human–machine interface

The upper-layer software provides a graphical user interface for the following functions of administration and data visualization.

- Serial communication and management: The base station's serial port is monitored in real time, decoding incoming frames from the sensor nodes and issuing global or node-specific control commands.

- Visualization and alarms: Sensor data is rendered through real-time waveforms or tabular displays. The WSN incorporates threshold-based monitoring, triggering automated alarms if structural parameters exceed safety limits.(19)
- Advanced data processing: Structural damage identification algorithms are run for data processing. Secondary data fusion is performed across multiple sensor nodes to evaluate the overall structural integrity.
- Database integration: Processed datasets are archived in a large-scale database management system. This supports longitudinal analysis and historical queries, with remote access enabled via the Internet for decentralized monitoring.

3.5 Algorithm and protocol implementation

The microprocessor calibrates the 0 g offset of the ADXL202E acceleration sensor by measuring the time interval of its output signal. The algorithm initiates a counter upon detecting the rising edge at the input/output port and stops the counter at the falling edge. To reduce stochastic error and enhance measurement stability, multiple intervals are recorded and averaged. This process establishes a reliable baseline for accurate acceleration calibration, as illustrated in Fig. 3.

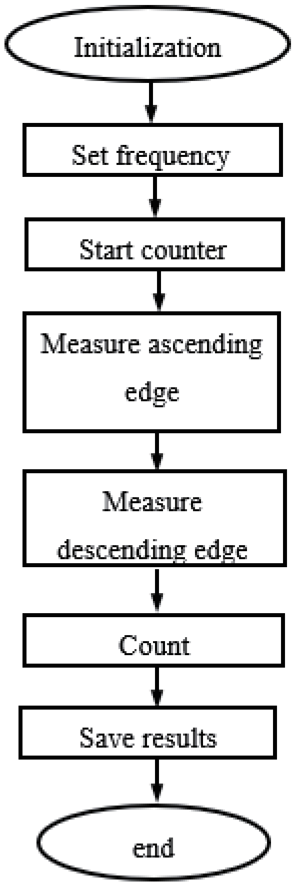
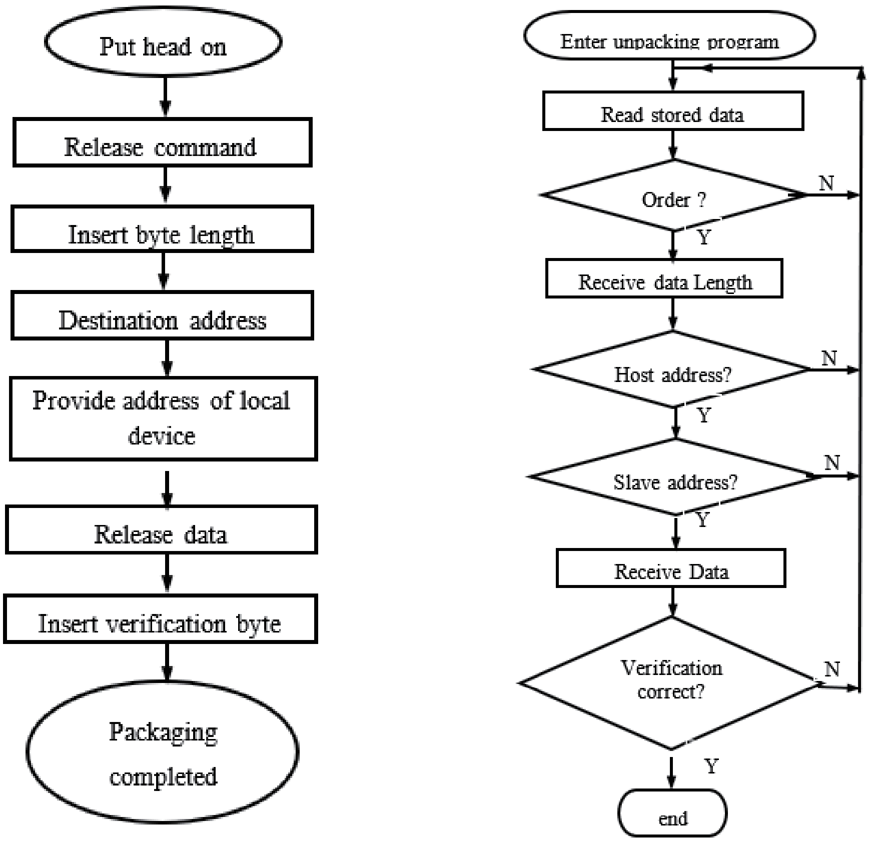


Fig. 3. Calibration workflow of acceleration sensor.

To ensure data integrity, the system employs a structured framing protocol, as shown in Fig. 4(a). In the unpacking process, the software verifies the command type, data length, and both source and host addresses. A checksum validation is then performed to confirm packet integrity. Only data packets that successfully pass all verification steps are accepted for further processing, thereby enhancing the reliability and robustness of the monitoring network [Fig. 4(b)].

4. Results and Discussion

After cluster formation, nodes select the cluster they wish to join on the basis of the strength of the received signal and notify the corresponding cluster head, which must remain in a receptive state during this process. Using the TDMA mechanism, each cluster head allocates dedicated communication time slots to its members. Once clusters are established, the network enters the stable operation phase. During this phase, sensor nodes continuously collect monitoring data and transmit them to the cluster head with minimal energy consumption during their assigned slots. In nontransmission periods, nodes enter the sleep or shutdown mode to conserve energy. Cluster heads aggregate the collected data and forward the aggregated information to the main base station. Because the base station is located at a considerable distance, direct communication consumes significant energy; therefore, this hierarchical



(a) (b)

Fig. 4. Data packaging and unpacking process diagrams. (a) Packaging algorithm. (b) Unpacking algorithm

approach reduces traffic and optimizes energy efficiency. After a certain period, the network reenters the initialization phase, and new cluster heads are selected to balance energy consumption across nodes.

The improved LEACH protocol extends the network lifetime from 320 rounds in traditional schemes to 394 rounds, representing a 23% improvement, through dynamic cluster-head election and energy-aware mechanisms. It also reduces energy imbalance by 42%, effectively preventing the premature failure of hotspot nodes (Fig. 5). Within each region, nodes transmit data to their cluster head, which then forwards the aggregated information to the base station. In practice, the transmission process combines single-hop and multihop routing: communication within a cluster follows a single-hop protocol, whereas intercluster communication employs multihop routing (Fig. 6).

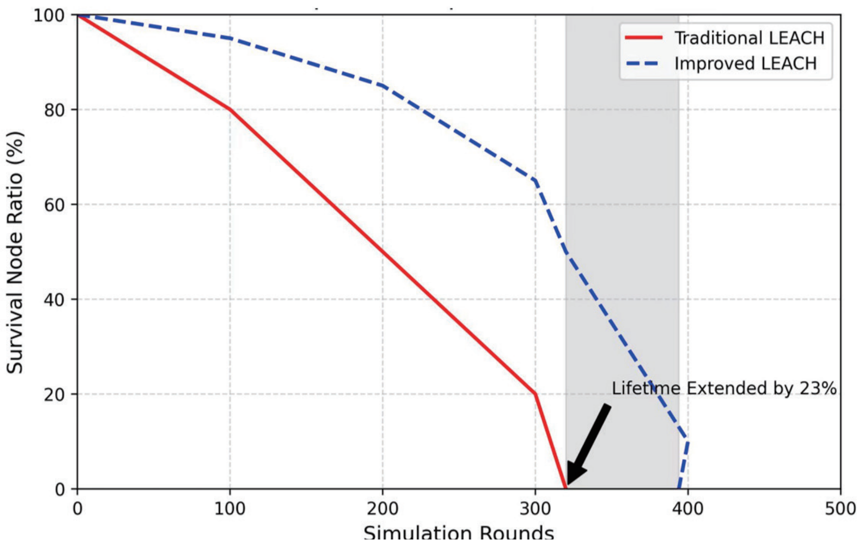


Fig. 5. (Color online) Network lifetime comparison: improved LEACH and traditional LEACH.

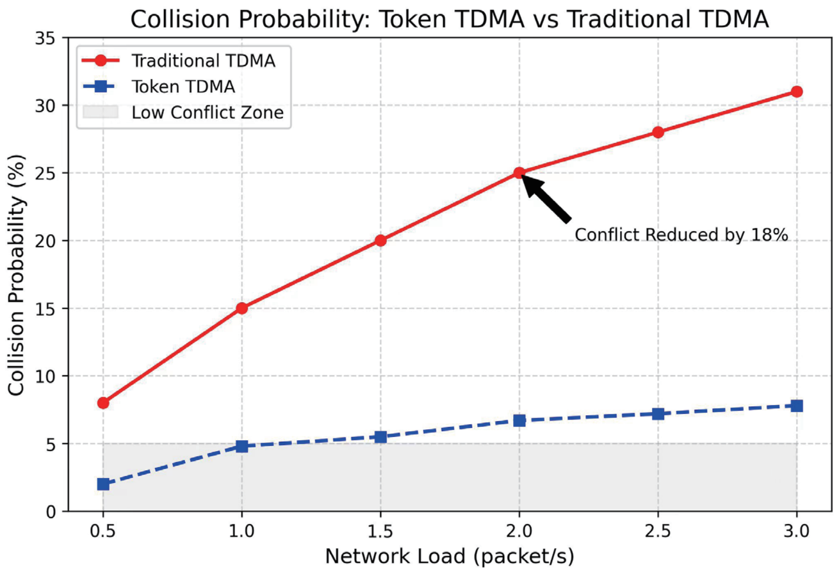


Fig. 6. (Color online) Collision comparison: token TDMA and traditional TDMA.

To enhance reliability, a token-based TDMA mechanism is integrated to dynamically allocate time slots under various loads. This reduces the collision probability from 15% in traditional TDMA schemes to below 5%, ensuring stable performance during continuous vibration monitoring in SHM applications.[18] Additionally, a hop-by-hop error recovery technique, supported by intermediate node buffering and verification, achieves an end-to-end packet loss rate below 1.5% and a packet delivery ratio of 98.5%, thereby meeting the stringent requirements of real-time monitoring.[20]

The network architecture includes main and secondary base stations, each equipped with a computer and a wireless transceiver module. The main base station does not directly communicate with sensor nodes; instead, it manages the operation of secondary base stations. These secondary stations control wireless sensors, process collected data, and relay information to the main base station. Sensor nodes monitor structural parameters such as vibration, strain, and temperature, and transmit data through the secondary base stations. When monitored parameters exceed predefined thresholds, the nodes issue alarms to ensure the timely detection of abnormal structural conditions.[21] To ensure the high-fidelity data required by sensors, a hop-by-hop error recovery technique is employed. By utilizing intermediate node buffering and verification, the system achieves a packet delivery ratio (PDR) of 98.5% and maintains an end-to-end packet loss rate below 1.5%.[20]

5. Conclusions

For the integration of sensor technology and network deployment for SHM applications, a specialized node-embedded software module was developed to enable the real-time calibration of accelerometers. By establishing a 0 g baseline at 20 °C and compensating for thermal drift at 2 mg/°C, the system ensures high-fidelity data collection under various environmental conditions. The LEACH protocol was optimized for hierarchical data transmission, employing single-hop communication within clusters and multihop routing for intercluster data delivery. The optimized protocol extended operational life from 320 to 394 rounds, representing a 23% efficiency gain. Energy imbalance across the network was also reduced by 42%, significantly improving the reliability of the sensing grid. Compared with standard planar or static multicluster structures, the hierarchical approach extended the overall survival time by at least 15%. The modular software architecture and structured framing protocols ensured data integrity through checksum validation and real-time edge-level preprocessing, thereby reducing wireless transmission loads and preventing data bottlenecks.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Project No. 61473329), the Fujian Provincial Natural Science Foundation of China (Project No. 2021J011235]), and the phased research results of the provincial major research project on education and teaching reform of undergraduate colleges and universities in Fujian Province [Project title: Research on Three Innovation Education Projects of Internet of Things Engineering (Project No. fbjg202101018)].

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