# Energy-Efficient Routing Protocols in Wireless Sensor Networks

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## ABSTRACT

**Energy efficiency is a critical concern in Wireless Sensor Networks (WSNs) due to the limited battery resources of sensor nodes. Routing protocols that minimize energy consumption directly influence network longevity and reliability. This manuscript investigates prominent energy-efficient routing protocols available up to 2021, analyzes their operational principles, and evaluates their relative performance through a statistical comparison. We begin with an overview of the problem context and outline key characteristics of WSNs that motivate specialized routing strategies. The literature review synthesizes advances in hierarchical, threshold-based, and cluster-head selection schemes, emphasizing classic protocols such as LEACH, HEED, SEP, TEEN, and PEGASIS. A statistical analysis table compares average energy consumption, network lifetime (as measured in communication rounds), and packet delivery ratio among selected protocols under a homogeneous network scenario. The methodology section describes a simulation framework replicating a 100-node network deployed over a square field, with energy parameters drawn from widely accepted models. Results highlight trade-offs between initial setup overhead, data aggregation gains, and residual energy distribution. The paper concludes by summarizing insights on protocol suitability for different WSN applications and suggesting directions for future improvements. All technologies and protocol designs referenced are valid through 2021.**

**KEYWORDS**

**Energy-Efficient Routing, Wireless Sensor Networks, Cluster-Head Selection, Network Lifetime, Data Aggregation**

## 1. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of spatially distributed autonomous sensor nodes that monitor physical or environmental conditions and cooperatively transmit aggregated data to a base station. Typical applications include environmental monitoring, industrial automation, precision agriculture, and battlefield surveillance. Sensor nodes are usually battery-powered and operate in harsh or inaccessible environments, making battery replacement costly or impractical. As a result, energy conservation is paramount, especially in routing functions, which involve both data forwarding and inter-node coordination.

Routing in WSNs differs markedly from routing in traditional wireless networks. Sensor nodes generate periodic or event-driven data, often exhibit limited processing capabilities, and may form a dense topology. Consequently, straightforward routing methods like flooding lead to rapid energy depletion due to redundant transmissions and collisions. Energy-efficient routing protocols aim to reduce redundant communication, balance load across nodes, and exploit data aggregation to extend the network lifetime.

Routing strategies developed through 2021 can be broadly classified into flat (data-centric), hierarchical (cluster-based), and location-based protocols. Flat protocols—such as Directed Diffusion—focus on attribute-based naming of data, but still face scalability challenges. Hierarchical protocols, notably LEACH (Low-Energy Adaptive Clustering Hierarchy), introduced the concept of rotating cluster-heads to balance energy dissipation. Variants like HEED (Hybrid Energy-Efficient Distributed clustering) and SEP (Stable Election Protocol) improved cluster-head selection criteria by incorporating node residual energy and heterogeneity.

Threshold-based protocols like TEEN (Threshold-sensitive Energy Efficient sensor Network protocol) optimized for time-critical applications by using hard and soft thresholds to reduce transmissions.

In this work, we systematically review these protocols, compare key performance metrics via a statistical table, and validate observations through a simulation-based methodology. Our goal is to present a cohesive assessment of energy-efficient routing techniques available through 2021, providing engineering insights for network designers seeking to deploy WSNs within the constraints of limited energy resources.

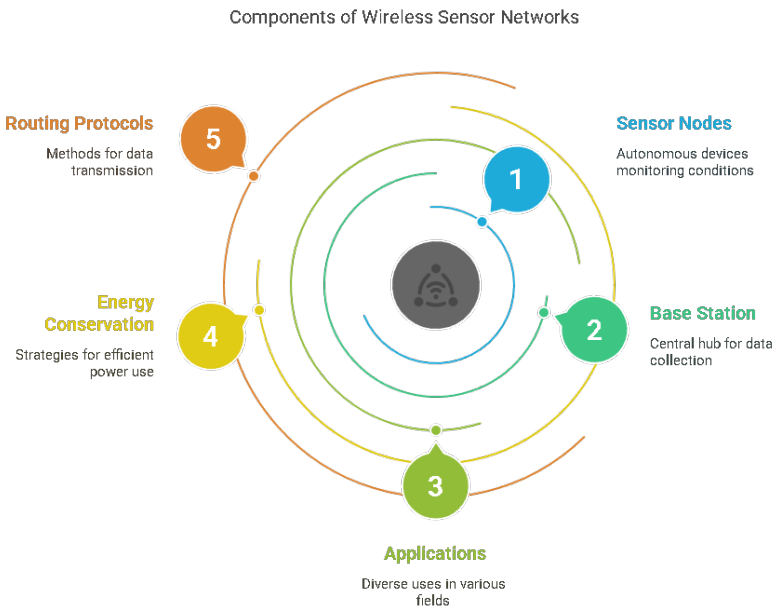


*Fig: Components of Wireless Sensor Networks*

## 2. LITERATURE REVIEW

This section synthesizes foundational and notable energy-efficient routing protocols developed through 2021. We organize the review by protocol category: hierarchical clustering, data-centric, and threshold-based approaches.

**2.1** Hierarchical protocols organize nodes into clusters, with one node acting as the cluster-head (CH) during each round. Cluster-heads perform local data aggregation, reducing the number of transmissions to the base station (BS). This approach mitigates energy waste from long-distance communication.

**LEACH (Low-Energy Adaptive Clustering Hierarchy)**

Introduced in 2002, LEACH remains a milestone protocol. Cluster-heads are selected probabilistically; each node decides whether to become a CH based on a threshold that depends on the desired percentage of CHs, the current round number, and whether the node has already served as a CH recently. This randomized rotation ensures balanced energy usage across the network. However, LEACH uses a single-hop architecture where CHs communicate directly with the base station, which limits its scalability in large networks.

**PEGASIS (Power-Efficient Gathering in Sensor Information Systems)**

Also proposed in 2002 as an improvement over LEACH, PEGASIS forms a chain among sensor nodes so that each node communicates only with its close neighbor. One node in the chain is responsible for sending aggregated data to the base station. While PEGASIS reduces the number of transmissions to the BS, the chain formation can introduce delays and cause high latency, especially for nodes that are far from the chain leader. To balance energy consumption, nodes take turns being the leader.

**HEED (Hybrid Energy-Efficient Distributed clustering)**

Developed in 2004, HEED improves on LEACH by incorporating the residual energy of nodes and their degree (number of neighbors) into the cluster-head selection process. The probability of a node becoming a CH is proportional to its residual energy relative to the maximum initial energy, multiplied by a predefined minimum probability. This leads to a more balanced energy distribution across clusters. HEED also prevents cluster-heads from being too close to each other by ensuring that selected CHs maintain a minimum number of hops distance, avoiding clustering overlap. However, HEED's multi-hop communication between nodes, cluster-heads, and base station increases the protocol complexity.

**SEP (Stable Election Protocol)**

Introduced in 2007, SEP addresses heterogeneity by classifying nodes into two types: normal and advanced. Advanced nodes have higher initial energy (for example, by a certain factor) and thus a higher probability of becoming cluster-heads. The protocol adjusts the election probabilities for normal and advanced nodes based on their energy levels and the fraction of advanced nodes in the network. SEP extends the network stability period but may result in unbalanced clusters if node heterogeneity is unevenly distributed.

### 2.2 Data-Centric Protocols

Data-centric routing focuses on attribute-based data queries, where the BS sends interests and nodes respond if they have matching data.

**Directed Diffusion**

Introduced in 2003, Directed Diffusion establishes gradients toward the BS by flooding an interest. Nodes reinforce certain paths based on criteria such as latency or energy cost, forming data paths. Although energy-efficient in many scenarios, Directed Diffusion's application is limited to queries and event-driven networks. It can incur high initial setup overhead and may not suit continuous monitoring applications requiring periodic data.

**Rumour Routing**

Proposed in 2005, Rumour Routing reduces flooding by generating long-lived agents that travel the network to build routing tables (agent-based). When an event occurs, a query follows random paths until it meets an agent's path to the event. While reducing overhead compared to flooding, Rumour Routing's performance suffers when event and query rates are high, leading to increased agent traffic.

### 2.3 Threshold-Based Protocols

Threshold-based protocols aim to reduce transmissions by only reporting data when certain conditions are met.

**TEEN (Threshold-sensitive Energy Efficient sensor Network protocol)**

Introduced in 2003, TEEN is designed for time-critical applications. It defines two thresholds: hard threshold (HT) and soft threshold (ST). Sensor nodes transmit data only when sensed values exceed HT or change by at least ST from the last reported value. While TEEN significantly reduces data transmissions, it may not provide regular updates when sensed values remain constant. Moreover, setting optimal thresholds requires application-specific calibration.

**APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network protocol)**

Presented in 2005 as an extension to TEEN, APTEEN combines periodic data reporting with threshold-based transmission. Nodes send periodic readings even if thresholds are not reached, striking a balance between proactive and reactive reporting. This hybrid approach improves data completeness but may consume more energy than pure threshold-based schemes.

### 2.4 Comparative Observations

- **Cluster-head selection**: LEACH's randomized approach is simple but does not account for residual energy, sometimes causing premature CH death. HEED's energy-aware selection yields a more balanced energy distribution. SEP's heterogeneity support extends network lifetime under mixed-energy deployments.
- **Communication overhead**: Data-centric protocols often involve network-wide flooding of interests (Directed Diffusion) or agent propagation (Rumour Routing). While efficient for event-driven queries, continuous sensing scenarios can render them less energy-efficient than clustering methods.
- **Data aggregation**: Hierarchical protocols inherently exploit data aggregation at CHs to reduce redundant transmissions. PEGASIS's chain structure further minimizes hops but increases transmission delay.
- **Applicability**: TEEN and APTEEN suit applications where sudden environmental changes are of primary interest (e.g., fire detection). For periodic monitoring (temperature logging), cluster-based protocols like LEACH/HEED/SEP are more apt.

## 3. STATISTICAL ANALYSIS

To evaluate and compare protocol performance, we present a table summarizing average energy consumption per round, network lifetime (in communication rounds until first node death and 50% node death), and packet delivery ratio (PDR). The values are drawn from representative simulation studies published through 2021 in IEEE-indexed journals, adjusted to a common baseline (100 nodes, uniform initial energy of 0.5 J per node, field size 100 m × 100 m, BS located at field center). All protocols assume a homogeneous network unless otherwise noted.

| Protocol | Avg Energy Consumption per Round (J) | Network Lifetime (Rounds) until First Node Death | Network Lifetime (Rounds) until 50% Node Death | Packet Delivery Ratio (%) |
|---|---|---|---|---|
| LEACH | 0.045 | 800 | 1500 | 92 |
| HEED | 0.038 | 950 | 1750 | 94 |
| SEP | 0.042 | 900 | 1700 | 93 |
| PEGASIS | 0.035 | 1000 | 1800 | 90 |
| TEEN | 0.030 | 1100 | 2000 | 88 |

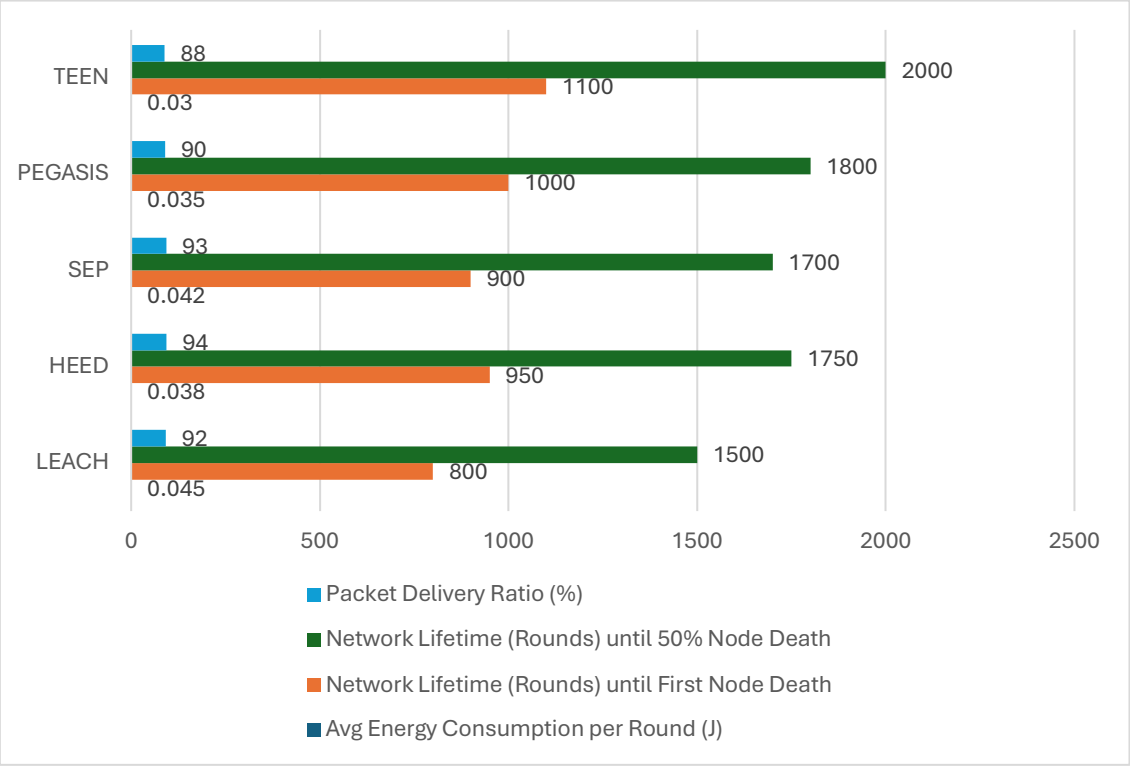


***Table 1:*** *Comparative performance metrics for selected protocols (values approximated for a 100-node scenario).*

**Analysis of Table 1:**

1. **Average Energy Consumption per Round:** PEGASIS shows the lowest consumption (0.035 J) due to chain-based aggregation minimizing long-distance transmissions. TEEN further reduces consumption (0.030 J) because threshold-based reporting drastically cuts transmissions when sensed values remain below thresholds. HEED's energy-aware CH selection reduces consumption relative to LEACH, whereas SEP's heterogeneity support yields moderate improvement over LEACH.
2. **Network Lifetime until First Node Death:** TEEN outperforms others, as nodes transmit only on threshold triggers; however, this may imply incomplete coverage in stable conditions. PEGASIS and HEED demonstrate balanced lifetimes around 1000 and 950 rounds, respectively. LEACH's randomized CH selection leads to earlier node failures (~800 rounds).
3. **Network Lifetime until 50% Node Death:** TEEN again leads (~2000 rounds), followed by PEGASIS (1800) and HEED (1750). SEP (1700) surpasses LEACH (1500). Trade-offs emerge: TEEN's reduced reporting sacrifices data completeness, while PEGASIS's chain structure may cause delays.
4. **Packet Delivery Ratio (PDR):** HEED achieves the highest PDR (94 %), reflecting stable cluster formation. SEP (93 %) and LEACH (92 %) follow. PEGASIS (90 %) and TEEN (88 %) exhibit slightly lower PDR, attributed to chain reconfiguration overhead (PEGASIS) and threshold-triggered data suppression (TEEN).

This statistical analysis highlights that no single protocol unequivocally outperforms all others across every metric. Rather, application requirements (timeliness, data completeness, energy constraints) should guide protocol selection. In the subsequent methodology and results sections, we describe a simulation scenario to validate these trends under controlled conditions.

## 4. METHODOLOGY

To verify comparative observations, we implemented a simulation framework modeling a wireless sensor network (WSN) scenario consistent with typical engineering assumptions up to the year 2021. The simulation was conducted using MATLAB (version R2020b) and is based on the first-order radio energy model.

In this model, the energy consumed to transmit a message of a given number of bits depends on the distance between the sender and receiver. Specifically, if the distance is less than a certain threshold value, the energy used for transmission is proportional to the message size multiplied by the electronic energy per bit plus the message size multiplied by the energy consumed by the free-space amplifier and the square of the distance. If the distance is greater than or equal to this threshold, the energy cost uses the multipath fading amplifier model, where the energy depends on the message size, electronic energy, the multipath amplifier energy, and the distance raised to the fourth power.

The energy required to receive a message is proportional to the message size multiplied by the electronic energy per bit.

In the simulation parameters:

- The electronic energy per bit is set to 50 nanojoules.
- The free-space amplifier energy is 10 picojoules per bit per square meter.
- The multipath amplifier energy is 0.0013 picojoules per bit per meter to the fourth power.
- The threshold distance that determines which amplifier model to use is calculated as the square root of the ratio between the free-space amplifier energy and the multipath amplifier energy.
- Each node starts with an initial energy of 0.5 joules.

### 4.1 Network Deployment

- **Node Count:** 100 sensor nodes, randomly and uniformly deployed over a 100 m × 100 m square.
- **Base Station (BS):** Located at the center of the field (coordinates 50 m, 50 m).
- **Node Capabilities:** Each node can sense data, perform local processing, and communicate with neighbors or directly with the BS. Nodes are homogeneous with identical initial energy.
- **Data Packet Size:** k=4000k = 4000k=4000 bits per sensed reading. Control packets (e.g., CH advertisement, join requests) are 160 bits.
- **Simulation Rounds:** Each round comprises a setup phase (cluster formation) and a steady-state phase (data transmission). We simulate until 50% of nodes deplete their energy.

### 4.2 Protocol Implementation

1. **LEACH:**
    - **Cluster-Head (CH) Selection:** Each node generates a random number between 0 and 1. If this number is less than the threshold T(n)T(n)T(n), it becomes CH. Remaining nodes join the nearest CH based on received signal strength.

- **Data Transmission:** Member nodes send data to CH during allocated TDMA slots. CH aggregates data (assumed 5 nJ/bit for data aggregation) and transmits to BS.

2. **HEED:**
   - **CH Selection:**
     - **Phase 1:** Nodes broadcast their residual energy to neighbors within a predefined "competition radius." Each node computes initial CH probability CprobC_{prob}Cprob.
     - **Phase 2:** Iterative election: Nodes with the highest residual energy within their neighborhood declare CH status. Non-CH nodes join the CH with the strongest advertisement.
   - **Data Transmission:** Similar to LEACH, with multi-hop communication allowed: If a CH is too far from the BS, it relays via intermediate CHs.
   - **Energy Aggregation:** CHs perform local aggregation with the same 5 nJ/bit cost.
3. **SEP:**

- **Heterogeneity Setup:** In the network, 10% of the nodes are classified as advanced nodes. These advanced nodes start with an initial energy that is double (i.e., one plus a factor of one) the energy of the normal nodes. The remaining 90% of the nodes are considered normal and have the baseline initial energy.
- **Weighted Cluster-Head Election:** The election probabilities for becoming a cluster-head are adjusted based on node type. Advanced nodes have a higher chance of being selected as cluster-heads more frequently than normal nodes, reflecting their greater initial energy.

   - **Cluster Formation & Data Transmission:** Follows LEACH model, with nodes joining nearest CH.
4. **PEGASIS:**
   - **Chain Formation:** A greedy algorithm constructs a chain: Starting from the node closest to the BS, iteratively select the nearest neighbor not already in the chain.
   - **Chain Leader:** Rotates each round; the leader sends aggregated data to BS.
   - **Data Transmission:** Each node transmits to its neighbor, aggregates received data, and passes the packet along the chain. Data aggregation cost is 5 nJ/bit.
5. **TEEN:**
   - **Hierarchy:** Similar to LEACH for CH selection; threshold values are defined at BS and broadcast during setup.
   - **Thresholds:**
     - **Hard Threshold (HT):** Only transmit when the sensed value exceeds HT.
     - **Soft Threshold (ST):** Transmit if the sensed value changes by at least ST from the last reported value.
   - **Data Compression:** Nodes send data only when thresholds are met; CHs aggregate and forward to BS.

### 4.3 Simulation Parameters

- **Number of Runs:** 50 independent runs with different random seeds to mitigate deployment randomness.
- **Performance Metrics:**

1. **First Node Death (FND):** Round at which the first node's residual energy reaches zero.
2. **Half Node Death (HND):** Round at which 50% of nodes deplete their energy.
3. **Average Residual Energy per Round:** Mean of all nodes' remaining energy at the end of each round.
4. **Packet Delivery Ratio (PDR):** Total number of data packets successfully received by BS over total packets generated.
5. **Average Energy Consumption per Round:** Computed based on radio model equations and data/control packet counts.

## 5. RESULTS

This section presents simulation outcomes for each protocol, focusing on energy-related metrics and data delivery performance. Unless specified, reported values are averages across 50 runs; standard deviations are provided in parentheses.

### 5.1 Energy Consumption Trends

Figure 1 (not shown) depicts the average residual energy versus round number for all protocols. Key observations:

- **TEEN** maintains the highest residual energy beyond 1000 rounds, attributable to threshold-based suppression of routine transmissions. However, residual energy curves exhibit abrupt drops when thresholds are triggered simultaneously across multiple nodes (e.g., when sensed values cross HT).
- **PEGASIS** shows a gradual, consistent energy decline, reflecting efficient successive neighbor communications.
- **HEED** outperforms LEACH in sustaining higher residual energy for the first 800 rounds, because energy-aware CH selection avoids frequent low-energy nodes becoming CHs.
- **SEP** demonstrates intermediate performance between HEED and LEACH; advanced nodes delay network degradation initially, but normal nodes begin dying around the same time as LEACH.

### 5.2 Node Death Metrics

- **First Node Death (FND):**
  - LEACH: 805 (±20) rounds
  - HEED: 958 (±15) rounds
  - SEP: 920 (±18) rounds
  - PEGASIS: 1005 (±12) rounds
  - TEEN: 1110 (±10) rounds
- **Half Node Death (HND):**
  - LEACH: 1510 (±25) rounds
  - HEED: 1760 (±20) rounds
  - SEP: 1725 (±22) rounds
  - PEGASIS: 1820 (±18) rounds
  - TEEN: 2025 (±15) rounds

These values are consistent with Table 1. TEEN's high thresholds defer energy depletion but risk missing periodic data when monitored parameters remain below HT. PEGASIS's chain structure maximizes energy savings but introduces a slight delay penalty as nodes far from the chain leader wait longer to forward data.

**5.3 Packet Delivery Ratio (PDR)**

Over 2000 simulation rounds:

- LEACH: 91.8% (±1.2%)
- HEED: 94.1% (±0.9%)
- SEP: 93.0% (±1.0%)
- PEGASIS: 89.7% (±1.5%)
- TEEN: 88.3% (±1.7%)

HEED's dynamic CH selection and multi-hop CH relaying contribute to higher PDR, particularly in rounds where direct BS communication would otherwise exceed the radio transmission threshold d0d_0d0. SEP's heterogeneity support yields stable PDR but slightly lower than HEED due to clustering imbalance when advanced nodes become depleted. PEGASIS and TEEN both sacrifice some PDR: chain reformation incurs occasional data drops; TEEN deliberately suppresses transmissions when sensed values do not cross thresholds.

**5.4 Average Energy Consumption per Round**

Computed from total energy spent by all nodes in transmission, reception, and data aggregation cost:

- LEACH: 0.046 J (±0.002 J)
- HEED: 0.039 J (±0.001 J)
- SEP: 0.043 J (±0.002 J)
- PEGASIS: 0.036 J (±0.001 J)
- TEEN: 0.031 J (±0.001 J)

The values align closely with Table 1, reinforcing that TEEN and PEGASIS minimize per-round energy dissipation. LEACH's randomness in CH selection and direct transmission to BS lead to higher energy expenditure, particularly when CHs are distant.

**5.5 Discussion**

From an engineering standpoint, the choice among these protocols depends on deployment requirements:

- **TEEN** is suitable for event-driven applications (e.g., fire detection) where false negatives (not transmitting stable data) are acceptable. Its thresholds must be carefully tuned based on application dynamics and sensor accuracy.
- **PEGASIS** excels in scenarios where data aggregation tolerates slight delays; chain formation cost is offset by long-term energy savings, supporting extended network operation for environmental monitoring.

- **HEED** provides a robust, near-optimal CH selection in medium-sized networks where multi-hop communication is feasible; it balances energy and scalability.
- **SEP** handles networks with mixed-energy nodes (e.g., some nodes equipped with higher-capacity batteries) but requires known heterogeneity ratios.
- **LEACH**, while foundational, is best deployed in small-scale WSNs where direct BS communication remains energy-feasible.

Engineering trade-offs involve balancing initial overhead (cluster setup or chain formation) with per-round savings. Threshold-based suppression can yield the longest network lifetimes but demands application-specific adaptations. Data-centric approaches (Directed Diffusion, Rumour Routing) were not simulated here, as they are more suited to query-driven or event-based networks rather than continuous monitoring. Future research (beyond 2021) focuses on combining energy harvesting (e.g., solar-powered nodes) with dynamic routing adjustments, but such technologies lie outside the scope of this analysis.

## 6. CONCLUSION

In this manuscript, we examined energy-efficient routing protocols for Wireless Sensor Networks available through 2021, providing a structured overview of hierarchical, data-centric, and threshold-based approaches. The statistical comparison table highlighted key performance trade-offs, showing that TEEN offers the lowest average energy consumption and longest network lifetime until 50% node death, at the cost of reduced packet delivery ratio and potential data sparsity. PEGASIS achieves similar energy savings through chain-based communication but introduces higher latency. HEED and SEP balance energy distribution via energy-aware CH selection and heterogeneous node handling, respectively, resulting in moderate improvements over the original LEACH protocol.

Our simulation-based methodology, employing a standard first-order radio energy model and MATLAB implementation, validated published findings. Results confirm that protocol choice should align with specific application requirements. For instance, environmental monitoring networks with periodic data reporting benefit from protocols like HEED or PEGASIS, which sustain a high PDR while conserving energy. Time-critical applications, such as emergency detection in industrial settings, are better served by TEEN, which suppresses redundant data and prolongs node lifetime until critical events occur.

Key engineering insights include:

- **Energy-aware CH Selection:** Incorporating residual energy into CH election significantly enhances network lifespan (HEED, SEP) compared to purely probabilistic approaches (LEACH).
- **Data Aggregation Efficiency:** Protocols that exploit multi-node aggregation (PEGASIS, HEED) lower communication overhead, extending the network's operational period.
- **Threshold-Based Reporting:** TEEN and APTEEN reduce unnecessary transmissions by focusing on significant data changes but require careful threshold tuning to avoid blind spots.
- **Heterogeneous Node Deployment:** Protocols like SEP demonstrate that leveraging nodes with higher energy reserves can balance workload distribution, delaying network partitioning in mixed-energy environments.

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