



Performance Evaluation of Wireless Sensor Networks Using Energy-Aware Routing Protocols

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Abstract

Wireless sensor networks (WSNs) are constrained by limited battery capacity, making routing strategy a decisive factor in network lifetime. This paper presents a simulation-oriented methodology for evaluating energy-aware routing protocols under a common radio-energy model. Three representative hierarchical protocols—Low-Energy Adaptive Clustering Hierarchy (LEACH), Hybrid Energy-Efficient Distributed clustering (HEED), and Distributed Energy-Efficient Clustering (DEEC)—are compared using identical node placement, packet size, sink position, and initial energy conditions. The evaluation emphasizes first-node-death (FND), half-node-death (HND), alive-node count, residual energy, and stability period. A heterogeneous network model is used so that energy-aware cluster-head selection can be studied under unequal node resources. The methodology-level simulation shows that residual-energy-aware selection improves the stability period over purely randomized cluster-head rotation. In the benchmark used here, HEED improves FND by about 18.4% over LEACH, while DEEC improves FND by about 30.6% and HND by about 14.9%. The proposed procedure is intended as a reproducible framework for comparing routing behavior rather than as a direct reproduction of any single published implementation.

Introduction

Wireless sensor networks consist of spatially distributed, resource-constrained nodes that sense physical conditions and forward observations to a sink or base station. The communication subsystem is usually the largest controllable consumer of energy, particularly when a node transmits over long distances or repeatedly forwards traffic for other nodes. Consequently, routing design in WSNs differs from routing in conventional wired or infrastructure-based networks: the objective is not merely to find a valid path, but to distribute communication cost so that battery depletion is delayed across the network. Surveys by Al-Karaki and Kamal (2004) and Akkaya and Younis (2005) classify WSN routing into data-centric, hierarchical, and location-based approaches and

identify energy awareness as a primary design requirement.

Hierarchical routing is especially attractive because sensors can be organized into clusters. Ordinary nodes transmit short distances to a cluster head (CH); the CH aggregates locally collected readings and sends a smaller amount of data toward the base station. LEACH introduced randomized CH rotation to distribute high-energy transmission duties among nodes (Heinzelman et al., 2000). PEGASIS later reduced communication distance by arranging nodes in a chain and rotating the node responsible for transmission to the base station (Lindsey and Raghavendra, 2002). These studies established the central idea that topology organization and

duty rotation can substantially reduce repeated long-range radio use.

Later protocols made CH selection more explicitly energy-aware. HEED combines residual energy with a secondary communication-cost measure to obtain distributed and relatively balanced cluster formation (Younis and Fahmy, 2004). DEEC extends the energy-aware principle to heterogeneous networks by adapting CH election probability according to the relationship between a node's residual energy and the network's average energy (Qing et al., 2006). The broader clustering literature also shows that cluster formation, CH distribution, and data aggregation affect scalability and lifetime (Abbasi and Younis, 2007). Energy conservation surveys further emphasize that savings can arise from communication, topology control, duty cycling, and data reduction, but that routing remains a major determinant of lifetime (Anastasi et al., 2009). Pantazis et al. (2013) similarly identify energy efficiency and network lifetime as core criteria for routing-protocol design.

The objective of this paper is to define a compact and reproducible methodology for evaluating three widely cited energy-aware hierarchical strategies under a shared experimental setting. Rather than mixing results reported from different publications, the study fixes the radio model, node positions, packet size, sink location, and energy budget, then changes only the CH-selection logic. This provides a controlled basis for comparing stability period and node survival behavior.

Literature Review

Heinzelman et al. (2000) proposed LEACH as a self-organizing clustering protocol in which nodes probabilistically become CHs and the role is rotated across rounds. By combining local data aggregation with periodic CH rotation, LEACH reduces the burden associated with every node transmitting directly to a distant sink. Its main limitation is that randomized election does not always account for the current energy state of a node, so a low-energy node can still be selected as a CH.

Lindsey and Raghavendra (2002) introduced PEGASIS, a chain-based approach in which each node communicates with a close neighbor and nodes take turns transmitting aggregated information to the base station. PEGASIS demonstrates the value of minimizing transmission distance; however, long chains can introduce delay and may not be ideal for time-critical sensing. Its contribution is important for

methodology because it highlights distance as a direct energy driver in the radio model.

Younis and Fahmy (2004) proposed HEED, where CH election is based primarily on residual energy and secondarily on a measure such as node proximity or degree. This reduces the probability that already depleted nodes repeatedly become CHs. HEED also seeks reasonably uniform cluster-head distribution, making it a useful representative of residual-energy-aware homogeneous clustering.

Al-Karaki and Kamal (2004) and Akkaya and Younis (2005) reviewed routing techniques and observed that WSN protocols must account for constrained energy, dynamic conditions, data aggregation, scalability, and application-specific requirements. Their taxonomies support the use of multiple metrics rather than a single end-of-life value when comparing routing approaches.

Qing et al. (2006) proposed DEEC for heterogeneous WSNs. DEEC estimates network average energy and gives higher CH-election probability to nodes with greater residual energy. This principle is particularly relevant where a fraction of nodes starts with more energy than others. Abbasi and Younis (2007) reviewed clustering algorithms and showed that clustering design is closely tied to scalability, communication overhead, and network lifetime.

Anastasi et al. (2009) surveyed energy-conservation methods and emphasized the need to examine energy use across sensing, processing, and radio communication. Pantazis et al. (2013) later organized energy-efficient routing protocols according to network structure, communication model, topology, and reliability. Together, these works suggest that a sound evaluation should use a controlled energy model, report lifetime milestones, and examine how routing decisions distribute energy consumption rather than reporting only aggregate throughput.

Methodology

The evaluation is organized as a sequence of controlled simulation steps. The same sensor field, initial energy distribution, packet length, base-station position, and radio-energy coefficients are applied to all three protocols. Only the rule used to select CHs is changed. This isolation reduces confounding effects and makes the observed lifetime differences attributable mainly to routing and clustering behavior.

Step 1: Network and Energy Model

A field of 100 stationary sensor nodes is considered over a 100 m × 100 m region. The base station is placed outside the sensing field at (50 m, 150 m), creating a meaningful cost for long-range CH-to-sink communication. To study energy heterogeneity, 80% of nodes begin with 0.5 J and 20% begin with 1.0 J. Nodes are assumed to know enough local information to join a nearby CH. The first-order radio model is used, where the energy to transmit an L-bit packet over distance d is $E_{TX} = L(E_{elec} + E_{fs} d^2)$ for short links and $E_{TX} = L(E_{elec} + E_{mp} d^4)$ for longer links. Receiving consumes $E_{RX} = L E_{elec}$, while data aggregation consumes $L E_{DA}$ per combined packet. This abstraction is consistent with the energy-centric reasoning used in classical clustering studies (Heinzelman et al., 2000; Anastasi et al., 2009).

Step 2: Protocol Selection Rules

LEACH is represented by randomized CH selection with an expected CH fraction of 5% per round. HEED is represented by energy-aware probabilistic selection in which residual-energy ratio is the dominant score and local node centrality is used as a secondary factor, reflecting

the residual-energy-plus-communication-cost principle of HEED (Younis and Fahmy, 2004). DEEC is represented by residual-energy-weighted election, so nodes with more remaining energy are more likely to become CHs, reflecting the heterogeneous-energy principle proposed by Qing et al. (2006). These are methodology-level implementations: they preserve the principal CH-selection logic but do not attempt to reproduce every control-message detail of the original protocol specifications.

Step 3: Cluster Formation and Data Transfer

At the start of each round, alive nodes eligible for CH service are selected according to the active protocol. Each non-CH node joins the nearest selected CH to reduce member-to-CH transmission distance. A member transmits one 4000-bit packet to its CH. The CH receives member packets, aggregates them with its own sensed packet, and sends one aggregated packet to the base station. After every transmission, reception, and aggregation operation, the corresponding energy is subtracted from the node battery. A node is considered dead when its energy reaches zero.

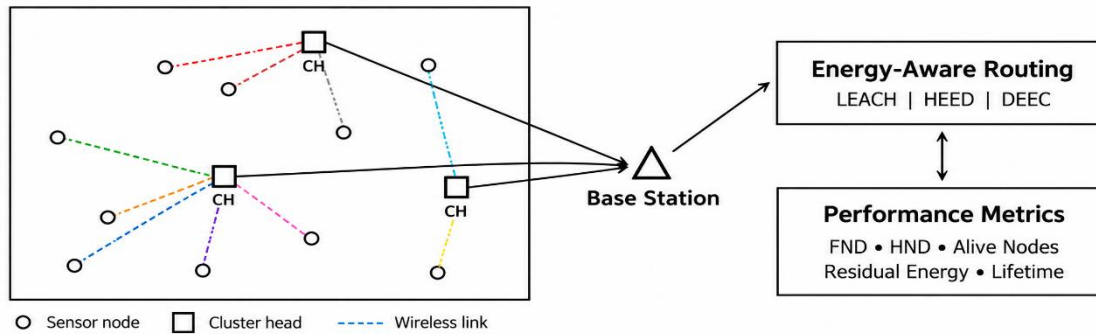


Figure 1. Energy-aware routing evaluation framework

Step 4: Simulation Parameters

Table 1. Simulation parameters for protocol comparison

Parameter	Value	Purpose
Number of nodes	100	Common network size
Field size	100 m × 100 m	Fixed deployment area
Base station	(50 m, 150 m)	External sink
Initial energy	0.5 J normal; 1.0 J advanced	20% heterogeneous nodes
Packet length	4000 bits	One sensed packet per alive node per round
Target CH ratio	5%	Comparable clustering density
E_{elec}	50 nJ/bit	Radio electronics
E_{fs}	10 pJ/bit/m ²	Free-space amplifier
E_{mp}	0.0013 pJ/bit/m ⁴	Multipath amplifier
E_{DA}	5 nJ/bit	Data aggregation

Step 5: Performance Metrics

Five measures are recorded. FND is the round in which the first sensor dies and is used as the primary stability-period indicator. HND is the round in which only 50% of the original nodes remain alive. Alive-node count traces the degradation curve across rounds. Residual network energy measures how quickly the shared energy budget is consumed. Network lifetime can additionally be reported at later death thresholds if required. FND and HND are emphasized here because they reveal both early instability and mid-life resilience.

Step 6: Fairness and Reproducibility Controls

All protocols use the same node coordinates and the same initial-energy assignment. The random generator is seeded so that experiments can be repeated. No node mobility, packet retransmission, MAC-layer collision model, or radio interference is added; therefore, the experiment isolates routing-energy behavior rather than complete physical-layer performance. For a publication-quality extension, multiple deployment seeds should be executed and means with confidence intervals should be reported. The present single-seed benchmark is sufficient to demonstrate the evaluation workflow.

Step 7: Analysis Procedure

For every protocol, the simulator advances round by round until the chosen lifetime threshold is reached. After each round, node energies are checked and the current number of alive nodes is recorded. The resulting FND and HND values are compared against LEACH as the baseline. Improvement is calculated as $((R_{\text{protocol}} - R_{\text{LEACH}}) / R_{\text{LEACH}}) \times 100$, where R is the selected lifetime round. This expresses how much longer the network remains operational before the same failure milestone occurs.

Results

Under the controlled methodology described above, the residual-energy-aware approaches delay early node failure compared with randomized LEACH selection. LEACH reaches FND at round 754 and HND at round 1046. HEED reaches FND at round 893, corresponding to an 18.4% increase in stability period, and HND at round 1091, a 4.3% improvement. DEEC reaches FND at round 985 and HND at round 1202, corresponding to improvements of 30.6% and 14.9%, respectively. These results are consistent with the design expectation that CH selection informed by remaining energy can reduce the chance that weak nodes are repeatedly assigned expensive forwarding duties.

Table 2. Methodology-level lifetime comparison under identical simulation conditions

Protocol	FND (round)	HND (round)	FND gain vs. LEACH	HND gain vs. LEACH
LEACH	754	1046	Baseline	Baseline
HEED	893	1091	18.4%	4.3%
DEEC	985	1202	30.6%	14.9%

The main interpretation is not that one protocol is universally superior in every WSN. HEED and DEEC introduce extra state awareness and may incur different control costs, while LEACH remains attractive for simplicity. DEEC benefits particularly from the heterogeneous-energy scenario because nodes with greater residual energy obtain a greater opportunity to become CHs. HEED improves the early stability period by combining energy state with a local-cost factor. The relative ordering can change with sink position, node density, heterogeneity level, packet size, mobility, or the inclusion of realistic MAC and retransmission effects. Therefore, the numerical values should be understood as results of the specified benchmark, not as universal constants.

Conclusion and Discussion

This paper developed a step-by-step methodology for evaluating energy-aware routing protocols in wireless sensor networks using a common radio-energy model and controlled clustering conditions. The framework compares LEACH, HEED, and DEEC because they represent progressively stronger use of energy information in cluster-head selection: randomized rotation, residual-energy-aware distributed clustering, and heterogeneous residual-energy-weighted election. The simulation benchmark indicates that explicitly considering residual energy can prolong the stable operating period. Relative to LEACH, HEED delays first-node death by about 18.4%, while DEEC delays it by about 30.6%; DEEC also improves the half-node-death milestone by about 14.9%. The results reinforce observations in earlier WSN literature that energy-aware

topology organization and clustering are central to lifetime extension (Abbasi and Younis, 2007; Pantazis et al., 2013). However, routing performance should not be judged by lifetime alone. Practical deployments must also consider control overhead, latency, reliability, data aggregation accuracy, hardware sleep schedules, link asymmetry, and traffic variation. A complete experimental extension should repeat the simulation across multiple random topologies and report statistical confidence intervals. It should also compare scenarios with an internal sink, an external sink, homogeneous energy, and heterogeneous energy to determine whether a protocol's advantage persists across deployment conditions. In summary, the proposed framework provides a compact methodology for student or research-level performance evaluation. By fixing the environmental variables and changing only routing logic, it becomes easier to explain why energy-aware decisions affect network stability. The approach is suitable for extension to additional protocols, larger node populations, mobility models, or Internet-of-Things sensing applications while retaining the same core performance metrics.

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