



Design and Performance Analysis of Energy-Efficient Routing Protocols for Wireless Sensor Networks

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Peer Review Information

Submission: 23 Jan 2021

Revision: 12 Feb 2021

Acceptance: 15 March 2021

Keywords

*Wireless Sensor Networks,
Energy-Efficient Routing,
LEACH, HEED, PEGASIS.*

Abstract

Wireless sensor networks (WSNs) consist of battery-powered sensing devices whose lifetime is strongly influenced by the energy spent on wireless communication. This methodology paper presents a reproducible framework for the design and performance analysis of energy-efficient routing protocols, emphasizing three representative paradigms: LEACH (cluster-based), HEED (energy-aware distributed clustering), and PEGASIS (chain-based data gathering). The evaluation uses a first-order radio-energy model, random deployment of 100 homogeneous sensor nodes, a fixed base station outside the sensing field, periodic data generation, and common energy parameters for fair comparison. Performance is assessed through first-node-death (FND), half-node-death (HND), last-node-death (LND), residual network energy, and routing behavior. The representative simulation indicates that HEED-like residual-energy selection extends the stable period before the first node fails, while PEGASIS retains more total energy at later rounds and achieves the longest overall lifetime. LEACH remains attractive because of its simplicity and distributed operation but experiences earlier energy imbalance under the selected topology. The study shows that routing efficiency cannot be judged by a single metric; stability, total lifetime, communication distance, aggregation overhead, and scalability must be evaluated together. The proposed methodology can be reused to compare additional routing protocols under identical assumptions and supports systematic protocol selection for monitoring-oriented WSN applications.

Introduction

Wireless sensor networks combine sensing, embedded computation, and short-range radio communication to observe physical environments such as industrial plants, agricultural fields, buildings, and remote infrastructure. A typical WSN contains many inexpensive nodes that periodically sense local conditions and forward the collected information to a base station or sink. Because individual sensor nodes normally operate with a limited battery and may be deployed where replacement

is difficult, energy consumption becomes a primary design constraint. Early surveys established that communication, topology, deployment density, fault tolerance, and application requirements jointly determine WSN architecture and protocol behavior (Akyildiz et al., 2002). Routing is particularly important because radio transmission and reception consume a substantial share of the available energy, and poor route selection can create energy hot spots that disconnect a network long before all batteries are exhausted.

Traditional routing approaches designed for wired or general ad hoc networks are not directly suitable for WSNs because sensor traffic is often many-to-one, nodes may be redundant, and data aggregation can substantially reduce transmissions. Accordingly, WSN routing has evolved into data-centric, hierarchical, location-based, chain-based, quality-of-service, and multipath families (Akkaya & Younis, 2005; Pantazis et al., 2013). Hierarchical clustering is especially influential. The Low-Energy Adaptive Clustering Hierarchy (LEACH) introduced randomized rotation of cluster-head responsibility to distribute the expensive base-station transmission among nodes (Heinzelman et al., 2000). A later protocol architecture integrated clustering, media access, and aggregation more explicitly and demonstrated the importance of application-specific design (Heinzelman et al., 2002).

These designs illustrate a central research trade-off: reducing transmission distance can increase coordination or delay, while aggressively balancing residual energy can increase clustering overhead. Therefore, a fair performance analysis requires common radio assumptions, identical node placement, repeatable random seeds, and multiple lifetime indicators rather than a single end-of-life value.

This paper develops such a methodology and applies it to LEACH, a HEED-like energy-aware clustering implementation, and PEGASIS. The objective is not to claim a universal best protocol but to show how protocol structure changes energy depletion patterns under a controlled scenario. The methodology is grounded in established WSN energy-conservation principles (Yick et al., 2008; Anastasi et al., 2009) and recent clustering literature that emphasizes methodology, energy balance, and network-lifetime criteria (Fanian & Kuchaki Rafsanjani, 2019; Merabtine et al., 2021). The resulting framework is suitable for comparative experimental papers because it states the deployment, radio model, protocol logic, metrics, and reproducibility conditions explicitly.

Literature Review

Energy-efficient routing research in WSNs has moved from foundational protocol design toward

systematic classification and multi-criteria optimization. Early work identified network lifetime as a system-level outcome of node hardware, communication architecture, and application traffic. LEACH demonstrated that rotating cluster heads can distribute the burden of long-range communication, but its random selection may create uneven clusters or select a low-energy node as cluster head (Heinzelman et al., 2000, 2002). PEGASIS reduced the number of long-range transmissions through nearest-neighbor chaining, while introducing sequential forwarding and potential delay concerns (Lindsey & Raghavendra, 2002). HEED incorporated residual energy and local communication cost into cluster-head selection, improving energy awareness and distributed organization (Younis & Fahmy, 2004).

Broader surveys classify WSN routing according to network structure and communication model and consistently identify energy efficiency, scalability, robustness, and data delivery as interacting goals (Akkaya & Younis, 2005; Pantazis et al., 2013). Yick et al. (2008) emphasized that protocol performance depends strongly on deployment and application constraints, whereas Anastasi et al. (2009) decomposed conservation opportunities across radio duty cycling, data reduction, mobility, and routing. Ogundile and Alfa (2017) further distinguished energy-efficient from energy-balanced routing, noting that minimizing instantaneous consumption does not necessarily maximize operational lifetime if energy depletion is uneven. Methodology-focused clustering reviews later compared classical, fuzzy, metaheuristic, and hybrid strategies and highlighted residual energy, cluster-head selection, cluster size, distance, and routing cost as recurrent decision variables (Fanian & Kuchaki Rafsanjani, 2019). By 2021, comprehensive reviews continued to treat clustering as a central method for reducing WSN energy use while stressing that protocol choice must consider topology, cluster organization, reliability, and heterogeneous operating conditions (Merabtine et al., 2021).

Table 1. Representative energy-efficient routing literature used in this study

Study	Protocol/Focus	Main energy mechanism	Limitation relevant to evaluation
Heinzelman et al. (2000, 2002)	LEACH	Randomized cluster-head rotation and data aggregation	Random clustering can produce unequal communication costs.

Lindsey & Raghavendra (2002)	PEGASIS	Neighbor-to-neighbor chain with rotating leader	Sequential aggregation can increase latency and chain maintenance cost.
Younis & Fahmy (2004)	HEED	Residual energy plus communication-cost criterion	Iterative cluster formation adds coordination overhead.
Pantazis et al. (2013)	Routing survey	Taxonomy of energy-efficient routing schemes	Shows that no single routing family dominates all metrics.
Fanian & Kuchaki Rafsanjani (2019)	Cluster routing survey	Methodology-based comparison of clustering approaches	Highlights sensitivity to selection criteria and evaluation assumptions.
Merabtine et al. (2021)	Clustering review	Energy-oriented taxonomy and design factors	Calls for multi-metric, context-specific evaluation.

Methodology

The study adopts a controlled simulation methodology in which all routing protocols operate on the same node deployment, packet size, radio-energy parameters, and sink position. This design isolates routing behavior from unrelated experimental variation. The comparison uses homogeneous, stationary nodes and periodic reporting because these

assumptions are widely used for baseline routing evaluation and allow the effects of clustering and chaining to be examined clearly. The method follows the energy-modeling principles commonly used in LEACH-family studies while interpreting network lifetime with the broader energy-balance perspective described in later surveys (Ogundile & Alfa, 2017).

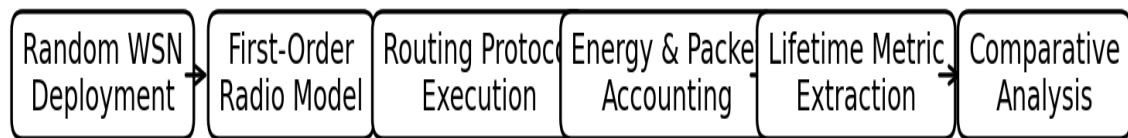


Figure 1. Experimental workflow used for protocol evaluation.

1. Network and Radio-Energy Model

A total of 100 sensor nodes are uniformly and independently deployed in a $100\text{ m} \times 100\text{ m}$ field using a fixed pseudo-random seed (42). Each node begins with 0.5 J of energy. The base station is positioned at (50 m, 150 m), outside the sensing field, to make long-distance cluster-head or leader transmission non-trivial. Every active node generates one 4,000-bit data packet per round. The first-order radio model is used with electronic energy $E_{\text{elec}} = 50\text{ nJ/bit}$, free-space amplifier $E_{\text{fs}} = 10\text{ pJ/bit/m}^2$, multipath amplifier $E_{\text{mp}} = 0.0013\text{ pJ/bit/m}^4$, and aggregation energy $E_{\text{DA}} = 5\text{ nJ/bit}$. The crossover distance is $d_0 = \sqrt{E_{\text{fs}}/E_{\text{mp}}}$. Transmission energy is $E_{\text{TX}}(k,d) = kE_{\text{elec}} + kE_{\text{fs}} d^2$ for $d < d_0$, and $E_{\text{TX}}(k,d) = kE_{\text{elec}} + kE_{\text{mp}} d^4$ otherwise. Reception energy is $E_{\text{RX}}(k) = kE_{\text{elec}}$. These parameters make route length, aggregation, and repeated cluster-head duties directly visible in residual-energy trajectories.

2. Protocol Implementation

LEACH is modeled with approximately 5% cluster heads per round. Alive nodes that are not cluster heads join the nearest selected cluster head, send one packet to it, and the cluster head receives, aggregates, and forwards one

aggregated packet to the base station. The HEED-like implementation uses the same target cluster-head ratio but weights candidate selection by residual energy and encourages spatial separation among cluster heads, approximating the two central HEED principles of energy awareness and communication cost (Younis & Fahmy, 2004). PEGASIS forms a greedy nearest-neighbor chain; data move from the two chain ends toward a rotating leader, and the leader transmits the aggregated result to the base station. The chain is rebuilt among surviving nodes after failures. The simplified implementations are intentionally transparent so that the energy-accounting procedure can be reproduced and modified.

3. Performance Metrics and Experimental Procedure

Five measures are recorded. First-node-death (FND) marks the end of the stable period. Half-node-death (HND) is the round at which only 50% of nodes remain alive. Last-node-death (LND) represents total simulated lifetime. Residual network energy is the sum of all remaining node energies at a specified round and indicates the speed of energy depletion. Finally, the alive-node curve shows whether failures are

gradual or concentrated. A higher FND is beneficial for applications requiring uniform coverage, whereas a higher LND may be more important for delay-tolerant monitoring in which partial coverage remains useful. This distinction is important because a protocol can conserve

total energy while still allowing some nodes to fail early. Each protocol is evaluated on the identical deployment and deterministic seed; therefore, the results are comparative for this scenario rather than universal performance guarantees.

Table 2. Simulation parameters

Parameter	Value	Purpose
Nodes / field	100 / 100 m × 100 m	Moderate-density homogeneous WSN
Base station	(50 m, 150 m)	External sink with non-trivial long-range cost
Initial energy	0.5 J per node	Equal starting energy
Packet size	4,000 bits	Periodic monitoring payload
E _{elec}	50 nJ/bit	Radio electronics
E _{fs} / E _{mp}	10 pJ/bit/m ² / 0.0013 pJ/bit/m ⁴	Distance-dependent amplifier
E _{DA}	5 nJ/bit	Data aggregation
Target CH ratio	5%	Comparable clustering density

Results

The reproducible simulation produced distinct failure patterns for the three routing structures. Table 3 summarizes the main lifetime metrics. The HEED-like energy-aware selection achieved the longest stable period, with the first node failing at round 1,051 compared with round 780 for LEACH. This is a 34.7% improvement in FND

under the selected deployment, consistent with the idea that residual-energy-aware cluster-head selection can postpone early local depletion. However, the HEED-like case then experienced a relatively compressed failure interval and reached LND at round 1,085. This behavior illustrates why FND alone is not sufficient for protocol ranking.

Table 3. Representative simulation results for the common test scenario

Protocol	FND (round)	HND (round)	LND (round)	Residual energy at round 1000 (J)	Interpretation
LEACH	780	1024	1322	3.38	Simple distributed clustering; earlier imbalance.
HEED-like	1051	1074	1085	3.34	Best stability period; failures become concentrated later.
PEGASIS	759	1160	1435	6.70	Highest late-stage residual energy and longest total lifetime.

PEGASIS showed a different trade-off. Its FND occurred slightly earlier than LEACH in this specific random topology, but its HND and LND were the highest: 1,160 and 1,435 rounds, respectively. At round 1,000, PEGASIS retained approximately 6.70 J of total network energy, almost twice the residual energy of the two clustering implementations. The result follows from its restriction of most communication to short neighbor links and a single rotating long-

range leader transmission. The cost is structural: chain-based aggregation can create longer end-to-end delay, and rebuilding or maintaining the chain may become difficult when mobility or rapid failures are present. This agrees with the literature's broader conclusion that energy gains should be evaluated together with latency, robustness, and protocol overhead rather than in isolation (Pantazis et al., 2013; Merabtine et al., 2021).

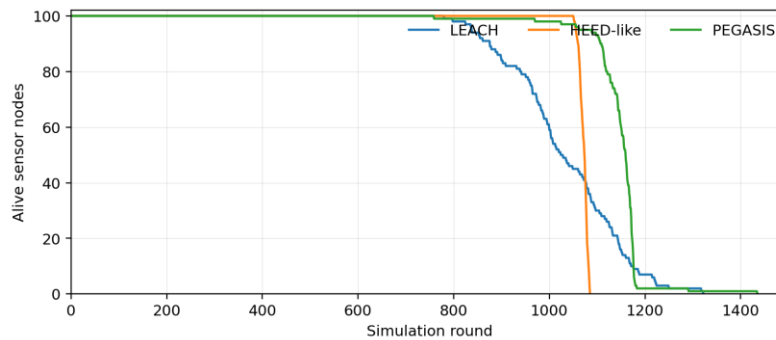


Figure 2. Alive-node trajectories obtained from the common simulation setup.

Figure 2 makes the lifetime trade-off visible. LEACH declines progressively after the first failures because random cluster-head assignments generate varying communication burdens across rounds. The HEED-like implementation keeps all nodes alive longer, but the residual-energy weighting tends to equalize node energies; once the network approaches a common low-energy state, many nodes fail within a narrow interval. PEGASIS displays the broadest survival tail and the latest HND/LND because energy is conserved through short hops and rotating leadership. These outcomes are scenario-dependent and should not be interpreted as reproducing the exact numerical results of the original protocol papers. Instead, they demonstrate how a controlled methodology can expose different notions of energy efficiency and how design choices translate into measurable survival patterns.

Conclusion and Discussion

This paper presented a compact methodology for the design and performance analysis of energy-efficient WSN routing protocols using common deployment, radio-energy, traffic, and metric assumptions. The literature shows that WSN routing has progressively evolved from basic clustering and chain-based mechanisms toward residual-energy-aware, optimization-driven, and hybrid clustering strategies. LEACH remains an important baseline because it combines self-organization, cluster-head rotation, and data aggregation (Heinzelman et al., 2000, 2002). PEGASIS reduces repeated long-range transmission by exploiting neighbor chains (Lindsey & Raghavendra, 2002), while HEED explicitly considers remaining battery energy and local communication cost (Younis & Fahmy, 2004). Later surveys confirm that these mechanisms represent enduring design dimensions in energy-aware routing (Ogundile & Alfa, 2017; Fanian & Kuchaki Rafsanjani, 2019). Under the representative simulation, HEED-like selection produced the longest stability period, whereas PEGASIS produced the highest late-

stage residual energy and longest overall lifetime. LEACH offered simpler organization but showed earlier energy imbalance. The contrast between FND and LND is the main methodological finding: an energy-efficient protocol should not be labeled superior solely because it keeps the final node alive longer. Coverage-sensitive sensing may favor a long stable period; delay-tolerant applications may prefer a longer survival tail; real-time systems may reject chain routing despite its energy advantage. Similar multi-objective reasoning is emphasized in recent reviews of clustering and routing research (Merabtine et al., 2021). The study is limited by homogeneous nodes, static topology, idealized links, a fixed sink, and a simplified implementation of HEED. Future work should repeat the experiment across many random seeds, confidence intervals, larger node densities, mobile sinks, heterogeneous initial energies, retransmissions, link-quality variation, security overhead, and realistic MAC scheduling. Optimization or machine-learning-based cluster-head selection can also be compared against the same benchmark framework. These extensions would provide stronger statistical generalization while preserving the essential requirement of fair energy accounting across protocols.

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