



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

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Abstract

Wireless sensor networks (WSNs) are composed of battery-constrained sensing devices whose operational lifetime is strongly affected by communication energy. This methodology paper develops a reproducible framework for the design and performance analysis of energy-efficient routing approaches, using literature published no later than 2015. The study reviews classical data-centric, clustering, and chain-based mechanisms and then formulates a residual-energy and distance-aware multi-hop (REDA-MH) routing design for comparison with direct transmission, LEACH-like clustering, and a PEGASIS-inspired chain. A first-order radio-energy model is used to account for transmitter, receiver, data-aggregation, and distance-dependent amplifier costs. Performance is evaluated through first-node-death (FND), half-node-death (HND), last-node-death (LND), and alive-node curves under a common 100-node deployment. The illustrative simulation shows that no single routing strategy dominates all lifetime measures: energy-aware clustering substantially improves the stable operating period, while chain-based routing can preserve a longer late-stage tail. The proposed REDA-MH design produces the largest FND in the tested scenario, demonstrating the value of residual-energy balancing when stable sensing coverage is the main objective.

Introduction

Wireless sensor networks combine sensing, computation, and short-range wireless communication to observe physical environments. Because many sensor nodes are deployed with small batteries and may be difficult or impossible to recharge, energy conservation becomes a primary design constraint rather than a secondary optimization. Akyildiz et al. identified limited energy supply, dense deployment, application-specific traffic, and multi-hop communication as defining characteristics of WSN design [1]. Later surveys reinforced that routing and communication architecture must be selected with awareness of coverage, scalability, reliability, and the energy

cost of transmitting data over distance [5], [6], [9].

Radio communication generally consumes more energy than local sensing or simple computation, so routing directly controls how quickly batteries are depleted. A flat routing scheme such as Directed Diffusion can reduce unnecessary communication by matching data to interests and reinforcing useful paths [10]. Hierarchical schemes instead organize nodes into clusters so that local traffic is aggregated before long-range transmission. LEACH is a foundational example: it rotates cluster-head responsibility to distribute communication cost and combines clustering with data aggregation [2]. PEGASIS reduces

repeated long-range transmissions further by arranging nodes into a chain and rotating the node responsible for communicating with the base station [3]. HEED improves distributed cluster formation by using residual energy together with a secondary communication-cost measure [4].

The aim of this paper is not to claim a universally optimal routing protocol. Rather, it provides a step-by-step methodology for designing and comparing energy-efficient routing under identical network and radio assumptions. The central research question is: how do topology formation, route length, load balancing, and residual-energy awareness change network stability and lifetime? To answer this question, the methodology uses common lifetime indicators and a simplified simulation that can be reproduced or extended in MATLAB, Python, NS-2/NS-3, or comparable network simulators. The references are restricted to works published in 2015 or earlier, consistent with the requested historical scope.

Literature Review

Early WSN research established that conventional ad hoc routing is not sufficient for large collections of low-power sensors. Directed Diffusion introduced a data-centric paradigm in which named data, interests, gradients, and in-network caching are used to reduce unnecessary transmissions [10]. LEACH subsequently demonstrated the importance of localized control and periodic cluster-head rotation; by aggregating readings inside clusters, long-range communication is limited to a small subset of nodes in each round [2]. However, random cluster-head selection can choose poorly placed

or low-energy nodes, causing uneven energy depletion.

PEGASIS uses a different structural principle. Nodes communicate with nearby neighbors along a chain, and a rotating leader forwards fused information to the base station [3]. This can reduce the number of long transmissions but may increase delay and create sensitivity to chain construction. HEED addressed some weaknesses of random clustering by selecting cluster heads primarily from residual energy and secondarily from communication cost or node degree [4]. DEEC extended energy-aware clustering to heterogeneous WSNs, assigning cluster-head probability according to residual and average network energy [7]. These approaches illustrate a broader transition from topology-only decisions toward energy-state-aware routing.

Comprehensive surveys by Al-Karaki and Kamal [5] and Akkaya and Younis [6] classify WSN routing into data-centric, hierarchical, and location-based families and emphasize that application requirements determine suitable routing behavior. Yick et al. further summarized platform, protocol-stack, deployment, and service considerations that interact with routing decisions [8]. Anastasi et al. separated energy conservation into communication, topology, data acquisition, and system-level techniques, highlighting the importance of reducing idle listening and redundant transmissions in addition to route selection [9]. Pantazis et al. later reviewed energy-efficient protocols using network structure, communication model, topology, and reliability as major classification dimensions [11]. Together, these studies motivate a comparison framework that evaluates not only total lifetime but also how evenly energy is consumed.

Table 1. Representative energy-efficient routing approaches used to motivate the methodology.

Protocol / Study	Type	Energy-saving mechanism	Main limitation	Ref.
Directed Diffusion	Data-centric	Interest-driven paths and in-network processing	Interest setup and path maintenance overhead	[10]
LEACH	Cluster-based	Random CH rotation and local aggregation	Random CH placement and homogeneous-energy assumption	[2]
PEGASIS	Chain-based	Neighbor-to-neighbor chain with rotating leader	Delay and chain-reconstruction sensitivity	[3]
HEED	Cluster-based	Residual-energy-aware distributed CH selection	Iterative clustering and control overhead	[4]
DEEC	Heterogeneous clustering	CH probability based on residual/average energy	Requires energy estimation; designed for heterogeneous nodes	[7]

Methodology

The methodology consists of six steps: define a common WSN scenario; specify a radio-energy model; select baseline routing families; design an energy-aware routing rule; execute repeated communication rounds; and compare lifetime indicators. All protocols use the same node positions, packet size, initial battery energy, and base-station location so that differences are attributable to routing behavior rather than unequal assumptions.

1. Network and Traffic Model

A static square sensing field of $100 \text{ m} \times 100 \text{ m}$ contains 100 sensor nodes. Each node begins with 0.5 J and periodically generates one 4000-bit data packet. The base station is placed outside the upper boundary at (50 m, 150 m), creating both short and long communication paths. Nodes are assumed to know either their coordinates or an equivalent distance estimate and their own residual energy. Nodes do not move during a run. The model neglects packet collisions and retransmissions so that routing-energy effects can be isolated. This abstraction follows the common analytical style used in classical LEACH and clustering evaluations [2], [4], [7].

2. First-Order Radio-Energy Model

For a k -bit packet transmitted over distance d , the transmitter consumes electronic energy plus a distance-dependent amplifier term. For $d < d_0$, free-space loss is modeled as $E_{TX}(k,d) = kE_{elec} + k\epsilon_{fs} d^2$; otherwise, the multipath term $E_{TX}(k,d) = kE_{elec} + k\epsilon_{mp} d^4$ is used. Receiving requires $E_{RX}(k) = kE_{elec}$, while aggregation consumes E_{DA} per processed bit. The threshold distance is $d_0 = \sqrt{(\epsilon_{fs}/\epsilon_{mp})}$. This model captures the essential reason that long direct transmissions are expensive and supports fair comparison of routing structures.

3. Routing Strategies Evaluated

Four strategies are evaluated. (1) Direct transmission sends each packet from every alive node directly to the base station. (2) LEACH-like clustering randomly elects approximately 5% of alive nodes as cluster heads per round; non-cluster-head nodes join their nearest cluster, and each cluster head aggregates and sends one packet to the base station. (3) A PEGASIS-inspired scheme creates a greedy nearest-neighbor chain and rotates the leader used for base-station transmission. (4) The proposed Residual-Energy and Distance-Aware Multi-Hop method (REDA-MH) uses energy-weighted cluster-head election and allows a cluster head to relay its aggregated packet through a better-

positioned cluster head when that hop substantially reduces transmission cost. The LEACH-like and PEGASIS-inspired labels are used because the implementation is intentionally simplified for controlled methodological comparison rather than a bit-for-bit reproduction of the original protocol software.

4. Proposed REDA-MH Design

At the beginning of each round, every alive node reports or locally estimates its residual energy E_i and its distance d_i to the base station. A cluster-head weight is computed from three terms: normalized residual energy, a distance preference that discourages very costly long-range cluster-head positions, and a fairness term that reduces repeated selection of the same node. Candidate cluster heads are sampled from these weights. Ordinary nodes join the nearest selected cluster head. After receiving and aggregating member packets, a cluster head either sends to the base station or selects a closer active cluster head as a relay when the relay hop has a markedly lower radio cost. This design combines the residual-energy principle associated with HEED and DEEC [4], [7] with the distance-sensitive energy behavior emphasized throughout WSN routing literature [5], [11].

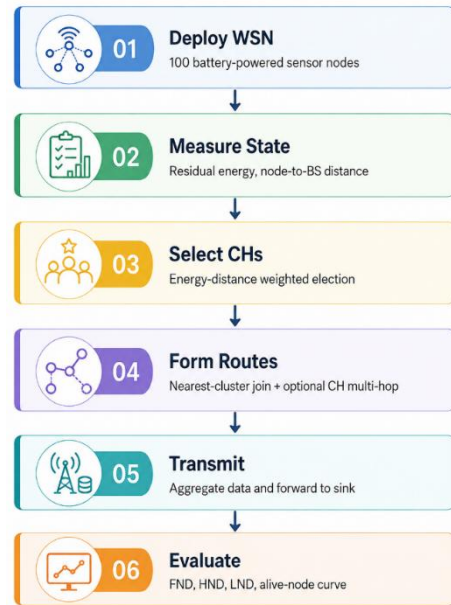


Figure 1. Step-by-step workflow used to design and evaluate the energy-efficient routing strategies.

5. Simulation Parameters and Performance Metrics

The principal outputs are First Node Death (FND), the round in which the first sensor exhausts its energy; Half Node Death (HND), the

round by which only 50% of nodes remain alive; and Last Node Death (LND), the round in which the final node fails. FND represents the stability period and is particularly relevant when an application requires uniform spatial coverage. HND reflects mid-life robustness, while LND captures the longest residual tail. The alive-node

curve is also inspected because two protocols with similar LND values can have very different coverage trajectories. These metrics are consistent with the network-lifetime emphasis in classical clustering research and energy-efficiency surveys [2], [7], [9].

Table 2. Common parameters used in the illustrative simulation.

Parameter	Value	Purpose
Number of nodes	100	Common dense WSN test case
Field / base station	100×100 m / (50,150) m	Creates mixed communication distances
Initial energy	0.5 J per node	Equal-energy baseline
Packet size	4000 bits	Periodic sensing payload
E _{elec}	50 nJ/bit	Tx/Rx electronics
$\epsilon_{fs} / \epsilon_{mp}$	10 pJ/bit/m ² / 0.0013 pJ/bit/m ⁴	Distance amplifier losses
E _{DA}	5 nJ/bit	Cluster data aggregation
Nominal CH fraction	5–8%	Hierarchical routing control

To reduce dependence on a single topology, the same procedure should ideally be repeated with multiple random deployment seeds and the mean and standard deviation reported. For this compact methodology paper, one fixed seed is retained so that the protocol behavior and lifetime tradeoffs remain transparent and reproducible. In a full experimental study, sensitivity analysis should additionally vary node count, sink position, packet size, cluster-head percentage, and initial energy.

Results

The simplified simulation was executed with a fixed random deployment seed so that all routing methods faced the same node geometry. The resulting values should be interpreted as methodological benchmark outcomes under the stated assumptions, not as direct reproductions of the original published protocol results. The comparison confirms a major theme in the literature: energy efficiency depends on which stage of network lifetime is valued.

Table 3. Illustrative lifetime results under the common simulation model.

Routing strategy	FND (round)	HND (round)	LND (round)	Interpretation
Direct transmission	167	671	1641	Very poor stability; long low-coverage tail
LEACH-like clustering	770	1022	1303	Balanced clustering baseline
PEGASIS-inspired chain	759	1160	1435	Strong HND/LND; increased chain dependence
Proposed REDA-MH	1062	1130	1179	Best FND; energy depletion is more synchronized

Direct transmission produces the earliest node failure because distant sensors repeatedly pay the full long-range radio cost. Its comparatively large LND is misleading if interpreted alone: after many nodes have already died, a small number of favorably located nodes continue operating, so the network retains little uniform sensing coverage. LEACH-like clustering delays FND from 167 to 770 rounds by replacing many long transmissions with local member-to-cluster-head links and aggregated cluster-head transmissions, consistent with the energy rationale of LEACH [2].

The PEGASIS-inspired chain gives the strongest HND and LND among the structured baselines, reaching 1160 and 1435 rounds. Neighbor-to-neighbor forwarding keeps per-hop distance small, but a chain can introduce delay and makes performance sensitive to leader selection and route ordering [3]. REDA-MH achieves the highest FND at 1062 rounds, approximately 38% later than the LEACH-like baseline. Its HND is also about 11% later than LEACH-like clustering. However, its LND is lower because residual-energy-aware decisions equalize depletion more aggressively, causing a shorter interval between the first and last failures. For monitoring

applications that require a large fraction of sensors to remain active simultaneously, this higher stability period can be more useful than a long tail of isolated surviving nodes.

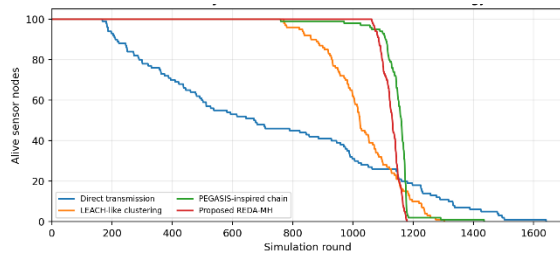


Figure 2. Alive-node trajectories from the simplified common-model simulation.

The results also show why routing evaluations should report multiple metrics. A protocol optimized only for LND may allow large portions of the sensing field to disappear early, while a protocol optimized for FND can sacrifice the late-stage tail. Thus, performance analysis should include at least stability, mid-life robustness, final lifetime, control overhead, delay, and packet-delivery behavior. This conclusion agrees with broad WSN surveys that treat routing as an application-dependent tradeoff rather than a single-objective problem [6], [8], [11].

Conclusion and Discussion

This paper presented a step-by-step methodology for designing and analyzing energy-efficient routing protocols in wireless sensor networks using references published up to 2015. The review showed that data-centric routing, clustering, chain-based collection, and residual-energy-aware methods reduce energy in different ways. LEACH demonstrates the benefit of clustering and rotating high-cost roles [2]; PEGASIS reduces long-range transmissions through chain-based forwarding [3]; HEED and DEEC demonstrate the importance of residual energy in cluster formation [4], [7]; and the broader surveys show that routing performance depends on network structure, traffic, reliability, and application constraints [5], [6], [11]. Under the common first-order radio model used here, direct transmission has the weakest stability, while hierarchical and chain-based methods markedly postpone energy exhaustion. The proposed REDA-MH methodology combines residual-energy weighting, distance awareness, fairness, aggregation, and optional multi-hop forwarding. In the illustrative simulation it produced the best first-node-death value, indicating improved stable coverage, but it also concentrated node deaths into a shorter later interval. This demonstrates an important design

lesson: balancing energy across nodes can be preferable when sensing quality requires most nodes to remain active, even if the absolute final death time is not maximized. The study has limitations. The simulation omits collisions, retransmissions, sleep scheduling, imperfect links, mobility, and variable traffic; therefore, its numerical values should not be treated as deployment measurements. Future methodological extensions should evaluate the same routing strategies in NS-3 or hardware testbeds, include link-quality and delay constraints, vary base-station location and node density, and measure packet delivery ratio and control overhead. Energy conservation should also be coordinated across MAC, routing, sensing, and data-processing layers because the total node lifetime is determined by more than routing alone, as emphasized by Anastasi et al. [9].

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