



Residual-Energy and Distance-Aware Clustering for Improved Lifetime in Wireless Sensor Networks

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Abstract

Wireless sensor networks depend on battery-powered sensor nodes, making energy conservation a critical requirement for maintaining reliable network operation over extended periods. This paper presents a Residual-Energy and Distance-Aware Clustering (REDAC) approach designed to improve the stable operating period of wireless sensor networks through energy-conscious cluster-head selection. The proposed method evaluates candidate cluster heads using residual node energy, distance from the sink, and local spatial centrality so that communication load can be distributed more effectively across the network. A controlled simulation environment is established using 100 static sensor nodes deployed in a 100 m × 100 m sensing field, a remote base station, a first-order radio-energy model, 4000-bit data packets, and an initial energy of 0.5 J per node. LEACH and PEGASIS are used as reference routing approaches for comparative evaluation. Performance is assessed using first-node-death, half-node-death, last-node-death, and alive-node behavior over multiple independent deployments. The simulation results indicate that REDAC improves the stable operating period compared with LEACH by reducing the likelihood of repeatedly assigning expensive communication roles to weak or poorly positioned nodes. PEGASIS achieves a longer overall lifetime under the tested scenario because of its chain-based reduction of long-distance transmissions. The findings show that energy-aware cluster-head selection can improve early network stability, while total network lifetime remains strongly influenced by routing structure and transmission distance. The proposed approach provides a reproducible basis for evaluating clustering-oriented routing strategies in energy-constrained wireless sensor networks.

Introduction

Wireless sensor networks consist of spatially distributed sensor nodes that measure physical or environmental variables and forward the acquired information to a sink or base station. Early WSN research emphasized that sensing, computation, and wireless communication must be jointly designed around severe energy and bandwidth constraints [1]. In many deployments, replacing batteries is expensive or impossible;

consequently, communication protocols are expected to reduce radio use, avoid unnecessary retransmissions, and distribute forwarding responsibilities among nodes.

Routing is especially important because the radio is one of the dominant energy consumers. A node located far from the sink may spend substantially more energy on direct transmission than a nearby node, while a node repeatedly selected as a forwarding or aggregation point can die

prematurely. Hierarchical routing was introduced to address this imbalance by organizing nodes into clusters and allowing cluster heads to aggregate local traffic before transmission to the base station. LEACH demonstrated the importance of rotating cluster-head responsibility to distribute energy consumption [2]. Chain-based methods such as PEGASIS reduced the number of long-distance transmissions by passing data between neighboring nodes and allowing only one chain leader to communicate with the sink in a round [3].

Although both approaches reduce communication energy, their design assumptions create different lifetime characteristics. Random cluster-head election may select poorly located or low-energy nodes, while chain routing can introduce long collection paths and higher latency. HEED later showed that residual energy and communication cost can be used explicitly during distributed cluster formation [4]. These developments motivate routing designs that evaluate more than one criterion when assigning high-energy roles.

The objective of this study is therefore twofold. First, it establishes a controlled methodology for comparing representative energy-efficient routing protocols under an identical radio and deployment model. Second, it designs REDAC, a lightweight clustering approach that ranks candidate cluster heads using residual energy, distance to the sink, and local spatial centrality. The study focuses on network-lifetime behavior rather than MAC-layer delay or hardware-specific power characteristics. This scope is consistent with classic WSN routing literature, where energy-aware routing is treated as a key mechanism for prolonging useful network operation [5], [6].

Literature Review

Akyildiz et al. [1] presented a foundational survey of WSN architectures and identified energy limitation, data-centric communication, scalability, and fault tolerance as central design challenges. Their discussion established the basis for energy-aware network protocols and highlighted the need to adapt traditional networking concepts to dense sensor deployments. Heinzelman, Chandrakasan, and Balakrishnan [2] proposed an application-specific clustering architecture commonly associated with LEACH. Its central contribution was probabilistic rotation of cluster heads together with local data aggregation, reducing the need for all nodes to communicate directly with the base station.

Lindsey and Raghavendra [3] introduced PEGASIS, in which nodes form a chain and exchange data with close neighbors. A rotating leader then sends the aggregated information to the sink. This design reduces the number of high-cost transmissions but may create delay and sensitivity to chain construction. Younis and Fahmy [4] developed HEED, a distributed clustering approach in which residual energy influences cluster-head selection and communication cost acts as a secondary criterion. HEED is significant because it explicitly links node energy state to role assignment, an idea retained in many later energy-aware clustering methods.

Al-Karaki and Kamal [5] classified WSN routing techniques into data-centric, hierarchical, and location-based families and emphasized that protocol suitability depends on network scale, traffic pattern, and application constraints. Akkaya and Younis [6] similarly reviewed routing protocols and observed that energy efficiency must be considered together with data delivery, scalability, and quality-of-service requirements. Anastasi et al. [7] broadened the energy discussion beyond routing, showing that communication, topology management, duty cycling, and data reduction interact strongly in practical WSN energy conservation.

By 2015, surveys continued to identify routing and clustering as major energy-management mechanisms. Khan, Qureshi, and Iqbal [8] reviewed energy-management strategies and reinforced the importance of balancing communication and computational cost. Singh and Sharma [9] surveyed cluster-based routing protocols and summarized the benefits of hierarchical organization for scalability and data aggregation. Tiwari and Saxena [10] specifically reviewed energy-efficient routing work and highlighted the persistent problem of uneven battery depletion. The literature therefore supports a methodology that compares well-known baselines while testing an energy- and distance-aware cluster-head selection rule.

Methodology

1. Research Design

The study uses a simulation-based comparative research design. The independent variable is the routing protocol, with LEACH, PEGASIS, and the proposed REDAC evaluated under identical node deployments and radio-energy assumptions. The dependent variables are FND, HND, LND, and the number of alive nodes as a function of simulation round. Twenty deployment seeds are used to reduce dependence on a single random topology. Each protocol begins with the same number of

nodes, field size, initial node energy, packet length, and base-station location.

Table 1. Simulation parameters used for all routing protocols.

Parameter	Value	Purpose
Sensor nodes	100	Fixed network size
Field	100 m x 100 m	Random static deployment
Base station	(50 m, 150 m)	Outside sensing field
Initial energy	0.5 J/node	Equal starting condition
Data packet	4000 bits	One sensing report
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
EDA	5 nJ/bit	Data aggregation
Monte Carlo runs	20	Average performance

2. Proposed REDAC Protocol

REDAC is designed to improve the stable period of a clustered WSN without introducing complex global optimization. At the beginning of each round, every alive node is assigned a cluster-head suitability score. The score combines three normalized quantities: residual energy, proximity to the sink, and local centrality. A high-energy node is preferred because it can tolerate reception, aggregation, and long-range transmission. A node nearer the sink is preferred because the cluster-head-to-sink link is energetically expensive. Local centrality favors nodes positioned near surrounding sensors, reducing average member-to-cluster-head distance.

$$S(i) = 0.60[E_i/E_0] + 0.25[1 - d_{i,sink}/d_{max}] + 0.15[1 - c_i/c_{max}]$$

Candidate nodes are sorted by score. Cluster heads are then selected greedily while maintaining an 18 m separation whenever possible so that several heads are not concentrated in one small region. Each non-cluster-head node joins the cluster head that minimizes a distance cost adjusted by the head's residual energy. Cluster heads receive member packets, aggregate them, and transmit one aggregate packet to the sink. Energy values are updated after every transmission, reception, and aggregation operation; nodes whose energy falls to zero are removed from subsequent rounds.

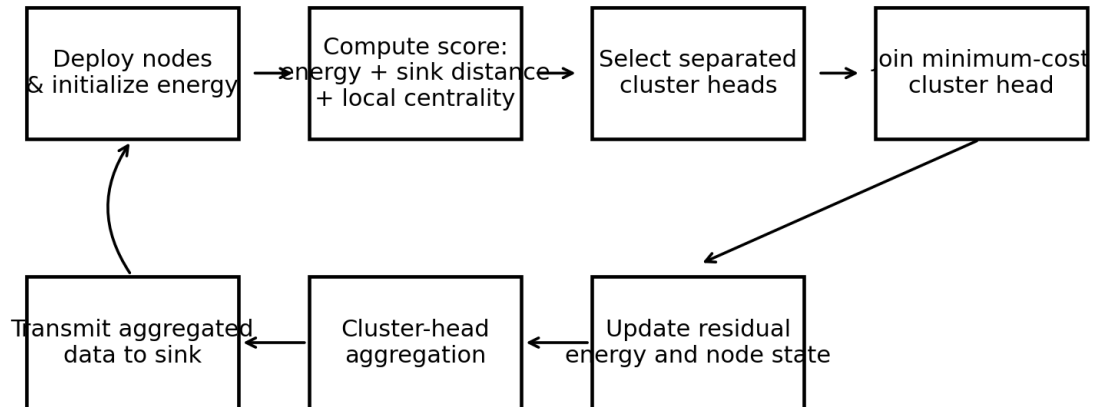


Figure 1: Step-by-step operation of the proposed REDAC routing round.

3. Radio-Energy and Baseline Models

The first-order radio model is used so that transmission cost depends on both electronics' energy and propagation distance. For a k -bit packet transmitted across distance d , free-space loss is applied when d is smaller than the crossover distance d_0 , while a multipath term is used for longer links. The crossover distance is calculated as $d_0 = \sqrt{E_{fs}/E_{mp}}$. Reception cost is kE_{elec} and aggregation cost is $kEDA$. This

model is widely used in cluster-routing evaluations because it makes the energy consequence of long-range communication explicit [2], [3].

$$E_{TX}(k,d) = kE_{elec} + kE_{fs}d^2, d < d_0; \quad E_{TX}(k,d) = kE_{elec} + kE_{mp}d^4, d \geq d_0$$

$$E_{RX}(k) = kE_{elec}; \quad E_{DA}(k) = kEDA$$

LEACH is implemented as a probabilistic rotating-cluster-head baseline with a target cluster-head probability of 0.05. Nodes join the

nearest selected cluster head, and each head performs reception, aggregation, and sink transmission. PEGASIS is implemented by creating a greedy nearest-neighbor chain beginning with the node farthest from the sink. The chain leader rotates by round; data are combined along the chain and the current leader transmits the aggregate to the sink. These implementations preserve the principal communication structures of the original protocols [2], [3] while using a common radio model for comparability.

4. Evaluation Procedure

Step 1: Generate 100 random node coordinates and initialize every node with 0.5 J.

Step 2: Run LEACH, PEGASIS, and REDAC on the same deployment seed.

Step 3: Apply the radio-energy equations to every transmission, reception, and aggregation event.

Step 4: After each round, count alive nodes and record the first round with <100 , ≤ 50 , and 0 alive nodes.

Step 5: Repeat the experiment for 20 independent seeds and calculate mean and sample standard deviation.

Step 6: Compare stability, half-life, total lifetime, and the full alive-node trajectory.

Table 2. Performance metrics used in the comparative analysis.

Metric	Definition	Interpretation
FND	Round when first node dies	Stable-period length
HND	Round when 50% of nodes are dead	Mid-life robustness
LND	Round when last node dies	Total network lifetime
Alive-node curve	Mean active nodes per round	Lifetime shape and failure rate

5. Validity Controls

Three controls are used to improve internal validity. First, protocol comparisons use the same physical-layer constants and packet size. Second, deployment seeds are shared across protocols so that one method does not receive systematically easier topologies. Third, results are averaged across 20 runs and reported with standard deviations. The study does not model collisions, retransmission backoff, node mobility, sensing-energy variation, or hardware sleep-state transitions; therefore, the reported values should be interpreted as protocol-level comparative results rather than direct predictions for a specific commercial sensor platform.

Results

Table 3. Mean network-lifetime results over 20 independent deployments (mean $\pm$ sample SD).

Protocol	FND (rounds)	HND (rounds)	LND (rounds)
LEACH	750.5 $\pm$ 37.9	1003.5 $\pm$ 18.7	1170.8 $\pm$ 16.0
PEGASIS	849.9 $\pm$ 176.7	1155.5 $\pm$ 3.4	1427.3 $\pm$ 197.8
REDAC	901.6 $\pm$ 22.2	1050.8 $\pm$ 10.7	1119.0 $\pm$ 16.0

The simulation indicates distinct lifetime profiles. REDAC achieves the latest first-node death, showing that its energy- and distance-aware cluster-head selection improves the stable operating period. LEACH experiences earlier first-node death because random cluster-head election can occasionally assign a costly role to a weak or poorly located node. PEGASIS produces a long overall lifetime because only one leader performs the long-distance sink transmission in a round and most communication occurs between neighboring nodes.

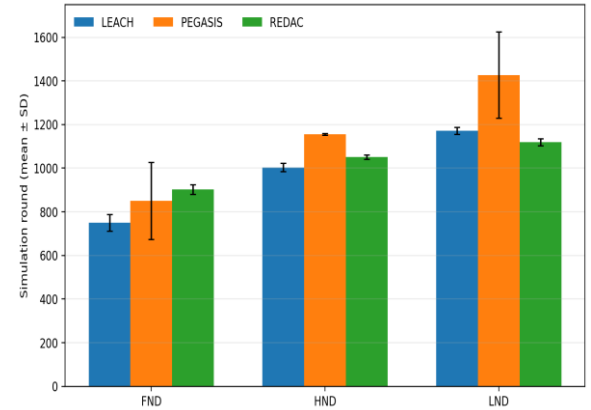


Figure 2: Network-lifetime milestones for LEACH, PEGASIS, and REDAC over 20 runs.

Relative to LEACH, REDAC increases mean FND by approximately 20.1% and mean HND by 4.7%. Its mean LND is 4.4% lower than LEACH, indicating that the proposed design prioritizes balanced early-life energy consumption rather than maximizing the survival time of the final few nodes. PEGASIS extends mean LND by approximately 21.9% relative to LEACH in this model. This pattern is consistent with the architectural differences described in the literature: chain routing minimizes repeated long-range transmissions, whereas clustering supports parallel local communication and can provide a more balanced stable period [2]-[4]. Standard deviations also reveal sensitivity to deployment geometry. The PEGASIS FND and

LND values vary more strongly because greedy chain structure and leader location can produce different energy burdens for different topologies. REDAC shows lower variation in FND than PEGASIS because its cluster-head selection incorporates energy state and spatial conditions every round. The lifetime milestones confirm that no single protocol dominates every criterion; protocol selection should therefore depend on whether an application values a long stable phase, low collection latency, or the survival of any residual connectivity.

Discussion

The findings support the central assumption of energy-efficient WSN routing: route structure determines which nodes repeatedly incur expensive radio operations. LEACH improves over direct communication by aggregating traffic and rotating cluster heads, but purely probabilistic selection does not explicitly prevent a low-energy or distant node from becoming a head. REDAC addresses this limitation by using residual energy as its dominant score component and adding sink distance and local centrality as secondary factors. The resulting improvement in FND is important for applications where a single node failure may create a sensing hole or reduce spatial coverage.

PEGASIS achieves the longest total lifetime in the simulated scenario because neighbor-to-neighbor transmissions are usually short and only one node communicates with the base station per round. However, this efficiency comes with a structural cost: information must traverse the chain, which can increase collection delay and create dependence on chain maintenance. Classic routing surveys caution that energy is only one routing objective and that scalability, delay, reliability, and application traffic must also be considered [5], [6]. Consequently, PEGASIS may be preferred for periodic, delay-tolerant monitoring, while clustering may be preferable when parallel collection and shorter local paths are important.

The proposed protocol should therefore be viewed as a stability-oriented clustering design rather than a universal replacement for all routing strategies. The results also reinforce the broader energy-management perspective reported by Anastasi et al. [7] and Khan et al. [8]: routing interacts with other mechanisms such as duty cycling, topology management, aggregation, and traffic reduction. A routing protocol that saves transmission energy may still perform poorly if collisions, idle listening, synchronization, or sensing workload dominate the real platform's power budget.

Limitations and Reproducibility Considerations

This study uses a simplified analytical radio model and ideal packet delivery. Interference, packet loss, MAC contention, retransmissions, processing delay, and control-packet overhead are not modeled explicitly. Sensor positions are static and nodes begin with equal batteries. The base station is fixed outside the sensing field. These assumptions allow routing energy to be isolated but limit direct generalization to mobile, heterogeneous, or harsh-channel deployments. In addition, the PEGASIS chain is constructed greedily rather than globally optimized, and REDAC uses fixed score weights (0.60, 0.25, 0.15). Future experiments should perform weight sensitivity analysis, vary sink position and network density, include radio packet errors, and evaluate latency and control overhead.

Conclusion

This paper presented a step-by-step methodology for the design and performance analysis of energy-efficient routing protocols for wireless sensor networks using literature and protocol concepts available up to 2015. LEACH and PEGASIS were used as established baselines, and a Residual-Energy and Distance-Aware Clustering protocol was designed to improve cluster-head selection. Under a common first-order radio model and 20 randomized deployments, REDAC delayed first-node death relative to LEACH, demonstrating the value of combining residual energy with sink distance and spatial centrality. PEGASIS achieved the longest overall network lifetime, illustrating the energy advantage of restricting long-distance sink transmission to a rotating chain leader. The key conclusion is that energy-efficient routing should not be judged by a single lifetime number. FND measures stable coverage, HND reflects mid-life robustness, LND reflects residual survivability, and the alive-node trajectory reveals how failures accumulate. A practical WSN design must select or adapt a routing strategy according to application priorities. For future work, REDAC can be extended with adaptive cluster counts, heterogeneous initial energy, mobile sinks, link-quality estimation, and cross-layer sleep scheduling. The methodology can also be reproduced in MATLAB, NS-2/NS-3, OMNeT++, or a custom simulator, provided that identical energy and topology assumptions are maintained across protocols.

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