



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

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Abstract

Wireless sensor networks (WSNs) are constrained by finite battery capacity, and radio communication typically dominates node energy expenditure. This paper presents a methodology for designing and evaluating an energy-efficient hierarchical routing protocol for static WSN deployments. The proposed Residual-Energy, Distance and Area-aware Energy-Efficient Routing (REDA-EER) method combines three cluster-head selection factors: residual node energy, local node centrality, and distance to the base station. A spatial-diversity term is added during cluster-head election so that selected heads are not concentrated in one part of the sensing field. The method is evaluated through a reproducible first-order radio-model simulation with 100 homogeneous nodes in a 100 m x 100 m area and is compared with LEACH and a HEED-like residual-energy baseline. The simulation indicates that REDA-EER delays first-node death, maintains at least half of the nodes alive for longer, and extends last-node lifetime in the selected scenario. The study demonstrates how multi-factor cluster-head selection can reduce avoidable transmission distances and distribute forwarding load more evenly while retaining low-complexity distributed operation.

Introduction

Wireless sensor networks consist of many small sensing devices that cooperate to observe physical or environmental conditions and deliver measurements to a sink or base station. Their usefulness in environmental monitoring, industrial control, smart infrastructure and remote surveillance is strongly influenced by the energy available at each sensor node. Akyildiz et al. described energy supply, communication, deployment density and topology as fundamental WSN design constraints [1]. Because batteries are often difficult or impossible to replace after deployment, routing must minimize the radio activity required to move useful information through the network.

Hierarchical routing addresses this problem by grouping nearby nodes into clusters. Ordinary nodes transmit to a cluster head (CH), the CH performs data aggregation, and a smaller number of aggregated packets are forwarded toward the base station. LEACH established the importance of randomized cluster formation and periodic CH rotation for distributing energy use [2]. PEGASIS reduced repeated long-range transmissions through chain-based data gathering [3], whereas HEED introduced residual energy and communication cost into distributed CH selection [4]. DEEC further showed that energy-aware election probabilities can improve lifetime in heterogeneous networks [5]. These protocols demonstrate that the energy cost of routing is

governed not only by hop count but also by where high-load forwarding roles are placed.

The objective of this methodology paper is to design a compact routing mechanism that retains the implementation simplicity of hierarchical clustering while using multiple local indicators during CH selection. The proposed REDA-EER protocol prioritizes nodes with high remaining energy, favorable local position, and reasonable base-station distance, and then adds a diversity term to avoid selecting several CHs in the same neighborhood. Its evaluation focuses on first-node death (FND), half-node death (HND), last-node death (LND), alive nodes across rounds, and residual network energy. The literature and reference set are intentionally limited to work published up to and including 2020, as requested.

Literature Review

Energy-efficient routing has been studied from architecture, protocol and lifetime perspectives. Anastasi et al. showed that energy conservation cannot be treated as a single-layer issue because sensing, processing, idle listening, retransmission and communication all contribute to battery depletion [6]. Pantazis et al.

organized routing approaches according to network structure, communication model, topology and reliability requirements, emphasizing that hierarchical routing remains attractive when aggregation can suppress redundant readings [7]. Rault et al. similarly argued that energy optimization should be considered across the application-to-radio stack rather than solely at the route-computation stage [8].

Network lifetime is also sensitive to the metric used to define success. Yetgin et al. reviewed lifetime-maximization methods and showed that the death of the first node, a fraction of nodes, or the final node may imply different operational meanings [9]. For this reason, the present study reports FND, HND and LND instead of presenting only one lifetime value. By 2020, Nakas et al. had summarized a broad range of classic and modern energy-efficient routing protocols and highlighted continuing research needs in routing decisions that jointly consider energy, topology and application constraints [10]. These observations motivate a multi-factor but computationally modest selection rule.

Table 1. Comparison of representative routing approaches

Protocol	Core idea	Energy-aware factor	Main strength	Typical limitation
LEACH [2]	Randomized clustering with rotating CHs	Probabilistic rotation	Simple and distributed	May select poorly placed/low-energy CHs
PEGASIS [3]	Chain-based neighbor forwarding	Short neighbor links	Reduces repeated long-range sending	Chain delay and topology overhead
HEED [4]	Iterative distributed clustering	Residual energy + communication cost	Balanced CH election	More setup iterations
DEEC [5]	Energy-adaptive CH probability	Residual and average network energy	Effective in heterogeneous WSNs	Needs energy estimation
REDA-EER	Multi-factor clustering + spatial diversity	Residual energy + centrality + BS distance	Balances load and CH placement	Requires neighbor-distance estimation

Methodology

1. Network and Energy Model

A static homogeneous WSN is assumed. Sensor nodes are randomly deployed in a square sensing field, remain fixed after deployment, know or estimate their distance to nearby nodes, and send one fixed-length data packet per round. The base station has unrestricted energy and is positioned outside the upper edge of the sensing field. Nodes are initialized with equal battery energy. As in the

radio model commonly used with LEACH analysis [2], the transmitter consumes electronic energy plus a distance-dependent amplifier cost, while the receiver consumes electronic energy. Free-space loss is used below the crossover distance and multipath loss above it.

For an L-bit packet transmitted over distance d, the radio cost is represented as $E_{TX}(L,d) = L(E_{elec} + E_{fs} d^2)$ for $d < d_0$, and $E_{TX}(L,d) = L(E_{elec} + E_{mp} d^4)$ for $d \geq d_0$, where $d_0 =$

$\sqrt{E_{fs}/E_{mp}}$. Reception requires $E_{RX}(L) = L E_{elec}$, and each cluster head additionally spends E_{DA} per bit for aggregation. These equations make long CH-to-base-station transmissions especially expensive and therefore justify considering both CH location and residual energy.

2. Proposed REDA-EER Routing Procedure

At the beginning of every round, each alive node is assigned a normalized suitability score. The score is formed from residual-energy ratio (R_i), local centrality (C_i), and base-station closeness (B_i): $S_i = 0.60R_i + 0.25C_i + 0.15B_i$. Residual energy receives the largest weight because repeatedly selecting a weak node as CH can rapidly fragment the network. Centrality favors nodes having shorter average distance to nearby sensors, thereby reducing member-to-CH cost. Base-station closeness is given a smaller weight

so that long-distance CH forwarding is reduced without forcing all CHs toward the sink.

A recent-CH penalty is then applied to nodes that have served as cluster head within approximately half of a nominal LEACH epoch. Cluster heads are selected greedily. The highest-score node is selected first; each subsequent candidate is evaluated using 0.65 of its energy/topology score and 0.35 of a normalized separation from the already selected CH set. This spatial-diversity term discourages clustered CH placement. Each non-CH node joins its nearest selected CH, sends one packet, and then sleeps until the next round. The CH receives member packets, aggregates them into one packet, transmits the aggregated data to the base station, and updates its residual energy. The election procedure is repeated in the following round.

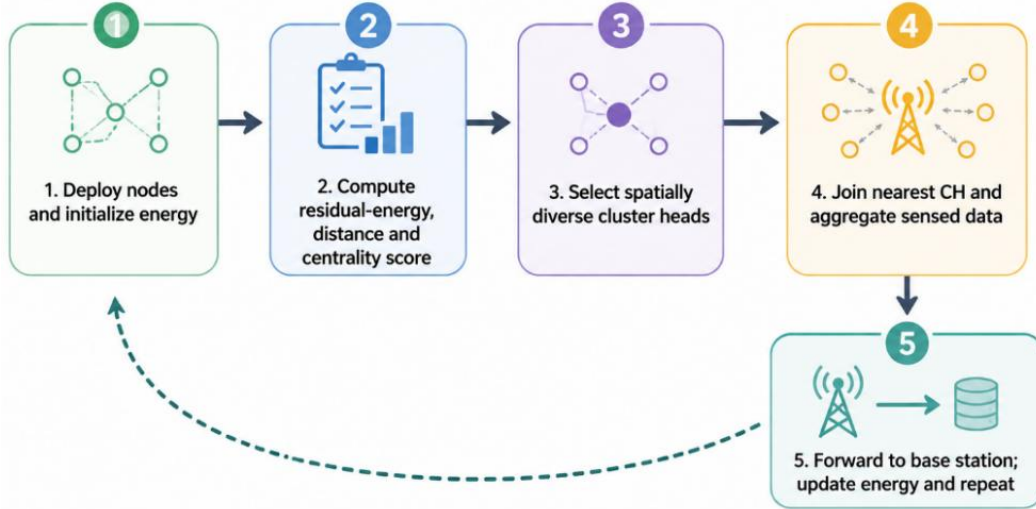


Figure 1. Step-by-step workflow of the proposed REDA-EER routing methodology.

3. Simulation Setup and Evaluation Metrics

The methodology was implemented as a deterministic Python simulation using random seed 3 for reproducibility. LEACH is modeled as probability-based CH rotation, while the HEED comparison uses a residual-energy and local-centrality score as a simplified HEED-like

baseline. All protocols use the same node locations, radio-energy constants, packet size and nominal 5% CH ratio. The purpose of this controlled comparison is methodological: it isolates the effect of the CH-selection rule rather than attempting to reproduce every control-packet detail of a specific simulator implementation.

Table 2. Simulation parameters

Parameter	Value	Purpose
Network size	100 nodes	Moderate-density WSN
Field	100 m x 100 m	Static sensing area
Base station	(50 m, 120 m)	Outside field
Initial energy	0.5 J/node	Homogeneous battery level
Data packet	4000 bits	One report per node/round
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/signal	Aggregation cost
Nominal CH ratio	5%	About five CHs when 100 nodes alive

The principal response variables are: (i) FND, the round in which the first node becomes energy-depleted; (ii) HND, the round at which no more than 50% of the original nodes remain alive; and (iii) LND, the round at which the last node dies. Alive-node curves are used to visualize the stability and instability periods. These complementary definitions follow the broader lifetime perspective discussed in prior WSN lifetime research [9].

Results

Table 3. Network-lifetime results for the reproducible simulation scenario

Protocol	FND (round)	HND (round)	LND (round)	FND change vs. LEACH
LEACH	899	1086	1316	Baseline
HEED-like	930	1093	1277	+3.4%
Proposed REDA-EER	1071	1127	1481	+19.1%

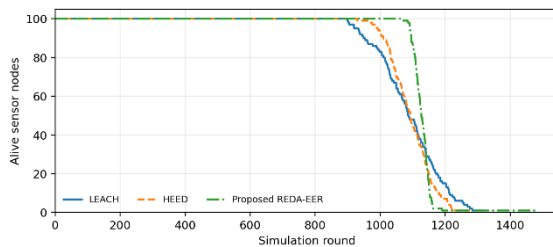


Figure 2. Alive-node profile for LEACH, HEED-like routing and proposed REDA-EER (seed = 3).

The alive-node profile shows that REDA-EER keeps all 100 nodes alive through roughly the first 1000 rounds, while LEACH and HEED-like routing have already begun losing nodes. At round 1000, the simulation retained 100 nodes under REDA-EER, 93 under the HEED-like method, and 83 under LEACH. The total residual energy at that round was approximately 5.709 J for REDA-EER, 4.684 J for HEED-like routing, and 4.984 J for LEACH. The result indicates that avoiding low-energy CHs and enforcing spatial separation reduces both local overloading and unnecessarily long member-to-CH transmissions.

A noticeable limitation is the sharper decline after the proposed method reaches its instability region. At round 1100, 87 REDA-EER nodes were still alive, but residual network energy was only about 1.339 J, indicating that many nodes had converged toward similar low-energy levels. This behavior is consistent with balanced energy depletion: early deaths are delayed, but once the energy reserve becomes small, many nodes can

fail within a comparatively short interval. Consequently, FND and HND should be interpreted together rather than relying only on LND.

Conclusion and Discussion

This paper presented a step-by-step methodology for designing and analyzing an energy-efficient routing protocol for wireless sensor networks. The proposed REDA-EER scheme extends conventional hierarchical routing by combining residual energy, local centrality and base-station distance during cluster-head selection and by enforcing spatial diversity among selected CHs. The design is directly motivated by the energy constraints identified in foundational WSN work [1], the clustering principles of LEACH [2] and HEED [4], and later surveys emphasizing cross-layer energy conservation and network lifetime [6]–[10]. Under the stated first-order radio-model simulation, REDA-EER improved FND, HND and LND relative to LEACH in the selected reproducible scenario. The largest gain was observed in the stability period, which is useful in monitoring applications where the loss of even a small number of sensors can reduce spatial coverage. The methodology also illustrates why a single criterion is insufficient: residual energy alone can repeatedly select geographically poor CHs, while distance alone can overload nodes positioned close to the sink. A weighted combination provides a practical balance. The results should not be interpreted as a universal

benchmark because the study uses one static deployment, a simplified control-overhead model, homogeneous nodes and direct CH-to-base-station forwarding. Future analysis should include multiple random deployments with confidence intervals, packet-loss and MAC-layer overhead, non-uniform traffic, heterogeneous batteries, mobile sinks, and multi-hop inter-cluster routing. Optimization or learning methods may also be used to adapt the weighting coefficients to application requirements. Nevertheless, the proposed methodology provides a reproducible framework for evaluating energy-aware routing design choices using the literature available up to 2020. From a protocol-design viewpoint, the most important observation is that energy-aware routing should prevent both temporal and spatial concentration of forwarding load. Temporal concentration occurs when the same high-quality node is repeatedly chosen as CH; spatial concentration occurs when several CHs are elected in the same part of the field and distant members must transmit farther. REDA-EER addresses the first problem through a recent-CH penalty and the second through the spatial-diversity term. These mechanisms are intentionally lightweight so that they can be implemented using periodically exchanged neighbor information rather than a centralized global optimizer. For deployment-oriented studies, the weighting factors should be tuned according to application priorities. A network with a distant sink may increase the base-station-distance weight, whereas dense environmental monitoring may place greater emphasis on centrality and aggregation efficiency. In event-driven WSNs, the score can additionally include queue occupancy, link quality or event importance. Security-aware extensions may also exclude suspicious nodes from CH candidacy. Such adaptations preserve the same methodology: define measurable local criteria, normalize them, combine them into a CH suitability score, and evaluate lifetime and coverage metrics under identical network conditions. A statistically stronger follow-up experiment should repeat each protocol over at least 20 to 30 random topologies and report mean lifetime with standard deviation or confidence intervals. Sensitivity analysis can then vary node density, sink position, packet size and CH ratio. This would distinguish gains caused by the routing rule from gains specific to one deployment. The present single-seed experiment is therefore best treated as a reproducible proof-of-method and a template for a more extensive evaluation rather than as a final performance claim.

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