



Energy-Efficient Routing Protocols for Wireless Sensor Networks: A Comparative Study

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Peer Review Information	Abstract
<i>Submission: 17 Aug 2018</i> <i>Revision: 03 Sep 2018</i> <i>Acceptance: 18 Sep 2018</i> Keywords <i>Wireless Sensor Networks, Energy-Efficient Routing, LEACH, PEGASIS, Clustering</i>	Wireless sensor networks (WSNs) are constrained primarily by the finite battery capacity of sensor nodes, making routing strategy a decisive factor in network lifetime. This methodology paper presents a comparative framework for four influential energy-efficient routing protocols: Low-Energy Adaptive Clustering Hierarchy (LEACH), Power-Efficient Gathering in Sensor Information Systems (PEGASIS), Hybrid Energy-Efficient Distributed clustering (HEED), and Distributed Energy-Efficient Clustering (DEEC). The study combines literature-based protocol analysis with a controlled first-order radio-energy simulation. A common 100-node, 100 m x 100 m deployment, 0.5 J initial node energy, 4000-bit packets, and identical radio-energy coefficients are applied to all protocols. Performance is evaluated using first-node death, half-node death, last-node death, routing overhead, scalability, and load-balancing behavior. The simulation indicates that PEGASIS provides the longest tail lifetime, while HEED and DEEC delay the first node failure through energy-aware cluster-head selection. LEACH remains simple and scalable but is more sensitive to random cluster-head placement. The comparative results show that no single protocol dominates every criterion; protocol choice depends on whether an application prioritizes stability, total lifetime, delay, or implementation simplicity.

Introduction

Wireless sensor networks consist of many small sensing devices that measure physical or environmental conditions and cooperatively deliver observations to a sink or base station. Their usefulness in environmental monitoring, industrial control, surveillance, health monitoring, and infrastructure observation depends on long unattended operation. However, radio communication, sensing, processing, and idle listening consume energy from batteries that may be difficult or impossible to replace after deployment. Consequently, the network layer must minimize communication cost while retaining acceptable connectivity and data delivery [1].

Routing is particularly important because the energy cost of radio transmission increases with distance. Direct transmission from every sensor to a distant base station can exhaust remote nodes rapidly, whereas multi-hop forwarding can overuse nodes located on heavily travelled routes. Hierarchical and chain-based approaches attempt to distribute this cost. LEACH introduced randomized rotation of cluster heads and local data aggregation to spread the expensive long-range transmission task among nodes [2]. PEGASIS replaced clusters with a chain so that most communication occurs only between nearby neighbors and one rotating leader transmits aggregated data to the base station [3]. HEED uses residual energy together with a

communication-cost parameter when selecting cluster heads [4], while DEEC explicitly relates cluster-head election probability to residual and average network energy [6].

The routing literature shows that energy efficiency cannot be judged by a single quantity. A protocol may delay the first node death but still lose the remaining nodes quickly; another may maximize the last-node death while increasing delay or control complexity. Surveys therefore compare protocols using network lifetime, stability, scalability, message overhead, communication model, topology assumptions, and load balancing [5], [7]. Later reviews continued to identify clustering and energy-aware election as central mechanisms for reducing WSN energy consumption [8]-[12].

This paper develops a compact methodology for comparing representative protocols under one controlled radio-energy model. The objective is not to reproduce every implementation detail of the original protocols, but to isolate their dominant routing principles under identical assumptions. The study asks three questions: (1) how does protocol structure affect the time to first, half, and last node death; (2) which design is most suitable when stability versus total lifetime is prioritized; and (3) what trade-offs appear in control overhead, delay, scalability, and implementation complexity?

Literature Review

Akyildiz et al. [1] established energy limitation, large-scale deployment, self-organization, and application-specific operation as defining WSN design constraints. Their survey explains why conventional routing cannot be transferred directly to sensor networks: nodes possess limited energy and computation, traffic is usually many-to-one, and data from nearby sensors are often correlated. These conditions motivated data aggregation and energy-aware topology management.

Heinzelman, Chandrakasan, and Balakrishnan [2] developed LEACH as an application-specific protocol architecture using randomized cluster formation, cluster-head rotation, time-division scheduling, and data aggregation. The key contribution is the rotation of the high-energy cluster-head role, which avoids permanently burdening the same nodes. LEACH is distributed and simple, but random cluster-head placement can create uneven cluster sizes or long cluster-head-to-base-station distances. This sensitivity becomes important when the base station is far from the sensing field.

Lindsey and Raghavendra [3] proposed PEGASIS as a chain-based alternative. Each node communicates with a close neighbor, sensed information is fused as it travels along the chain, and nodes take turns acting as leader for the final base-station transmission. The design reduces the number of long transmissions and can extend total network lifetime. Its principal disadvantage is increased data-delivery delay because information may traverse several chain links before reaching the leader, and chain maintenance becomes difficult when topology changes.

Younis and Fahmy [4] introduced HEED, which periodically selects cluster heads by combining residual energy with a secondary communication-cost parameter such as node proximity or degree. This improves cluster distribution and avoids relying only on random election. Al-Karaki and Kamal [5] classified routing approaches into data-centric, hierarchical, and location-based groups and emphasized that application requirements determine the appropriate routing structure. Their survey is useful for interpreting because a protocol that is energy efficient in a static monitoring network may be inappropriate for delay-sensitive or mobile scenarios.

Qing, Zhu, and Wang [6] proposed DEEC for heterogeneous networks. DEEC assigns cluster-head election probability according to the ratio between the residual energy of a node and the estimated average network energy. This mechanism is especially useful when nodes have unequal initial energy, although the residual-energy principle is also informative in homogeneous comparisons because it explicitly balances the cluster-head burden over time.

Pantazis, Nikolidakis, and Vergados [7] provided a broad taxonomy of energy-efficient WSN routing protocols and showed that hierarchical routing is one of several possible mechanisms for saving energy. Dehghani et al. [8] compared cluster-based algorithms using metrics including scalability, message overhead, and complexity, reinforcing the need to evaluate more than network lifetime alone. Jan et al. [9] reviewed hierarchical clustering and highlighted cluster formation, cluster-head selection, re-clustering cost, and topology construction as major determinants of energy consumption.

Ogundile and Alfa [10] distinguished energy-efficient from energy-balanced routing and argued that efficient average energy use does not necessarily prevent particular nodes from being exhausted early. This distinction motivates using both first-node death and last-node death in the

present methodology. Asha and Gowrishankar [11] demonstrated continuing interest in hybrid clustering and routing for sustained WSN operation, while Akhtar et al. [12] summarized cluster-based protocols using energy efficiency, scalability, delay, complexity, and clustering approach. Collectively, the literature supports a multi-metric comparison rather than ranking protocols by a single lifetime value.

Methodology

1. Comparative Research Design

The study uses a controlled comparative simulation supported by protocol characteristics documented in the literature. LEACH, HEED, DEEC, and PEGASIS are selected because they represent four different energy-management ideas: randomized cluster-head rotation, residual-energy-and-cost-aware clustering, residual-energy-weighted clustering, and chain-based neighbor communication. All protocols are evaluated over the same node positions and

radio parameters for each random seed. Five independent random deployments are used, and reported lifetime values are the arithmetic mean of those runs. This design reduces the influence of one favorable or unfavorable node placement.

2. Network and Radio-Energy Model

A static homogeneous network of 100 nodes is randomly distributed over a 100 m x 100 m square field. The base station is located at (50 m, 100 m). Each node begins with 0.5 J of energy and generates one 4000-bit report per communication round. The first-order radio model used in LEACH-related studies is adopted conceptually [2]. Electronic energy is 50 nJ/bit, free-space amplifier energy is 10 pJ/bit/m^2 , multipath amplifier energy is $0.0013 \text{ pJ/bit/m}^4$, and data aggregation requires 5 nJ/bit. The transmitter uses the free-space term for distances below the model crossover distance and the multipath term for longer distances.

Table 1. Common simulation parameters

Parameter	Value	Purpose
Number of nodes	100	Common network density
Field / base station	100 m x 100 m; (50,100)	Identical geometry
Initial energy	0.5 J per node	Homogeneous baseline
Packet size	4000 bits	One report per round
Cluster-head target	5% of alive nodes	Comparable cluster density
$E_{\text{elec}} / E_{\text{DA}}$	50 / 5 nJ per bit	Radio + aggregation cost
$E_{\text{fs}} / E_{\text{mp}}$	10 pJ/bit/m^2 ; $0.0013 \text{ pJ/bit/m}^4$	Distance-dependent amplifier
Independent deployments	5	Average placement variability

3. Protocol Abstraction and Execution

LEACH: approximately 5% of currently alive nodes are selected as cluster heads using distributed random rotation. Non-cluster-head nodes join the nearest cluster head. Each member transmits one packet to its cluster head, the cluster head receives and aggregates the member data, and then sends one aggregated packet to the base station. This captures LEACH's core randomized clustering and data-aggregation behavior [2].

HEED: the target number of cluster heads is retained, but cluster-head sampling is weighted by residual energy divided by a local communication-cost estimate derived from nearby-node distance. Nodes with higher remaining energy and lower local cost are therefore more likely to become cluster heads. This is a simplified abstraction of HEED's hybrid residual-energy and secondary-cost selection [4].

DEEC: cluster heads are sampled with probability proportional to current residual energy. A node

with energy above the alive-node average is more likely to accept the costly cluster-head role, approximating the residual-to-average energy principle used by DEEC [6]. Member association and radio-energy accounting are then performed in the same manner as the other clustered protocols.

PEGASIS: a nearest-neighbor chain is constructed from the static node positions. During each round, packets are passed along the chain toward a rotating leader, with aggregation at receiving nodes; only the leader makes the final base-station transmission. When a node dies it is removed from the active chain. This preserves PEGASIS's core design goal of replacing repeated long-range transmissions with local neighbor communication [3].

4. Energy Accounting and Performance Measures

For a k -bit packet transmitted over distance d , energy is computed as $E_{\text{TX}}(k,d) = kE_{\text{elec}} + kE_{\text{fs}} d^2$ for short links and

$E_{TX}(k,d)=kE_{elec}+kE_{mp} d^4$ for long links. Reception energy is $E_{RX}(k)=kE_{elec}$, and aggregation adds kE_{DA} per processed packet. After every round, node energies are updated and any node with non-positive residual energy is considered dead. The principal lifetime metrics are First Node Death (FND), Half Nodes Death (HND), and Last Node Death (LND). FND represents the stability period, HND provides a mid-life robustness indicator, and LND represents the tail or total lifetime. Qualitative metrics—scalability, delay, control overhead, and load balancing—are interpreted from the routing structure and prior studies [7]-[12].

5. Reproducibility and Scope

The experiment is intentionally protocol-level rather than physical-layer complete. It assumes static nodes, error-free packet delivery, no retransmissions, no interference, and ideal scheduling. Those assumptions isolate routing energy from MAC-layer and channel effects, but they also limit direct prediction of deployment lifetime. Therefore, the numerical results should be read as a controlled comparison under a shared model, not as universal performance values. The methodological advantage is transparency: all protocols use the same topology generation, radio constants, traffic load, and stopping criteria.

Step-by-Step Evaluation Procedure

Step 1 - Deploy the network. For each independent run, 100 sensor coordinates are generated from a uniform distribution inside the 100 m x 100 m field. Every protocol receives exactly the same coordinate set for that run. This paired-topology design is important because distance strongly affects amplifier energy and could otherwise confound the protocol comparison. The base-station position and all radio constants remain fixed.

Step 2 - Initialize protocol state. Each sensor is assigned 0.5 J and marked alive. For clustered protocols, the target cluster-head proportion is set to 0.05. LEACH initializes equal election weights; HEED calculates a local communication-cost quantity from nearby-node distances; DEEC uses current residual energy as the election weight. PEGASIS constructs a nearest-neighbor chain from the static topology. These protocol-specific states are initialized before the first communication round.

Step 3 - Select the forwarding structure for the current round. LEACH samples cluster heads without energy bias, HEED biases selection toward nodes having both greater remaining energy and favorable local communication cost,

and DEEC biases selection toward higher residual energy. For each clustered method, ordinary nodes associate with the nearest elected cluster head. For PEGASIS, the active chain is obtained by removing failed sensors from the original chain and a round-robin leader is selected.

Step 4 - Account for communication energy. Every member-to-cluster-head or chain-neighbor transmission is charged using the distance-dependent first-order radio expression. Each receiving node is charged electronic reception energy, and nodes that fuse reports are charged data-aggregation energy. A clustered protocol then charges each active cluster head for one aggregated transmission to the base station. PEGASIS charges only the current leader for the long base-station transmission. This common accounting prevents one protocol from receiving a more favorable physical-layer assumption than another.

Step 5 - Update node status and lifetime milestones. Residual energy is reduced after all communication events in a round. A node is classified as dead when its energy becomes zero or negative and is excluded from later routing decisions. The round of the first failure is stored as FND. When no more than 50 nodes remain alive, the round is stored as HND. The round at which the final sensor dies is stored as LND. Alive-node count is also recorded after each round to obtain the lifetime curve.

Step 6 - Repeat and aggregate. Steps 1-5 are repeated for five independent random deployments. FND, HND, and LND are averaged across the five runs. The alive-node curve is formed by averaging the number of active sensors at each round. Finally, the numerical results are interpreted together with non-numerical protocol properties from the literature, especially clustering overhead, latency, scalability, and sensitivity to topology [7]-[12]. This final step prevents a purely numerical ranking from hiding application-relevant trade-offs.

6. Validity Considerations

Three forms of validity are considered. Internal validity is strengthened by using identical topology, traffic, packet size, and radio constants across protocols; however, simplified abstractions do not reproduce every message exchanged by the original algorithms. Construct validity is addressed by using three lifetime milestones rather than a single definition of network lifetime, because FND reflects stability while LND reflects persistence [10]. External

validity is limited because real deployments experience fading, collisions, retransmissions, clock drift, sensing-energy variation, and possibly mobile sinks. The comparison is therefore most appropriate for explaining routing-design trade-offs and for screening candidate protocols before higher-fidelity simulation or test-bed validation.

Results

Table 2 summarizes the average lifetime milestones obtained over five random deployments. PEGASIS achieved the highest HND

and LND, indicating a strong advantage in total lifetime under the assumed static topology. HEED produced the latest FND, with DEEC close behind, suggesting that energy-aware cluster-head selection can protect the weakest nodes during the stable operating period. LEACH showed the earliest FND because random cluster-head placement occasionally assigns expensive roles or long links to unfavorable nodes. These patterns are consistent with the design principles reported for LEACH [2], PEGASIS [3], HEED [4], and DEEC [6], although exact values depend on the simplified model used here.

Table 2. Comparative lifetime and routing characteristics

Protocol	FND	HND	LND	Main strength	Main trade-off
LEACH	815	1109	1329	Simple, distributed clustering	Random CH placement / variable stability
HEED	977	1108	1207	Strong stable-period load balance	Iterative/cost-aware cluster formation overhead
DEEC	963	1113	1180	Residual-energy-aware CH rotation	Requires energy-state estimation
PEGASIS	943	1172	1812	Longest tail lifetime; few long links	Higher delay and chain-maintenance sensitivity

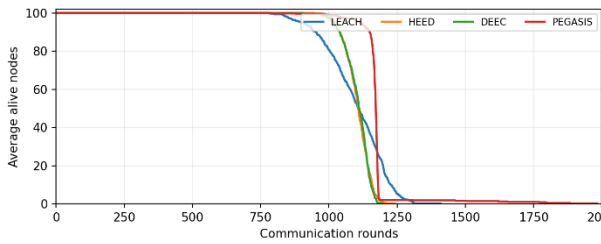


Figure 1. Average alive nodes versus communication rounds (five controlled deployments).

Figure 1 clarifies the distinction between stability and tail lifetime. HEED and DEEC postpone initial failures relative to LEACH because residual energy influences cluster-head selection. Their curves then decline over a relatively compact interval because the same balancing mechanism tends to consume the network more uniformly. PEGASIS begins losing some nodes earlier than HEED in certain deployments, but its chain structure preserves a long tail and keeps a smaller set of nodes alive for many additional rounds. Thus, PEGASIS is attractive when total sensing persistence matters more than minimum end-to-end delay.

From an implementation perspective, LEACH remains the simplest of the four and is attractive for homogeneous, moderately sized, delay-tolerant WSNs. HEED improves cluster placement by adding residual energy and communication cost, but this requires more state and cluster-formation logic [4]. DEEC is

especially suitable when node energies differ because its election probability adapts to residual and average energy [6]. PEGASIS minimizes long-distance transmissions effectively, but a long chain introduces latency and can be less convenient when nodes are mobile or links vary rapidly [3]. Reviews through 2018 similarly emphasize that scalability, overhead, delay, and clustering assumptions must be considered together with lifetime [8]-[12].

The comparative evidence therefore does not support a universal winner. If an application defines success as preserving full or near-full coverage for as long as possible, HEED or DEEC can be preferred because their energy-aware selection improves the stability period. If the objective is to keep at least part of a static network operational for the maximum duration, PEGASIS is favored in this experiment. LEACH remains a useful baseline and practical choice when low protocol complexity is more important than optimal energy balancing.

Conclusion and Discussion

This study presented a step-by-step methodology for comparing energy-efficient WSN routing protocols under one common radio-energy model. The literature review showed an evolution from randomized clustering in LEACH [2] to chain-based aggregation in PEGASIS [3], hybrid energy-and-cost clustering in HEED [4],

and residual-energy-weighted clustering in DEEC [6]. Surveys and comparative studies published up to 2018 confirm that energy efficiency must be evaluated together with scalability, overhead, delay, cluster formation, and load balance [7]-[12]. Under the controlled simulation, HEED produced the strongest FND value, DEEC also improved stability relative to LEACH, and PEGASIS produced the greatest HND and LND. The result illustrates an important methodological point: FND and LND describe different application goals. A protocol that distributes energy evenly may provide a long stable region but a shorter tail after failures begin, whereas a protocol that minimizes per-round communication can preserve a subset of nodes for much longer. Selection should therefore be tied to application requirements rather than to one headline lifetime number. The principal limitations are the static topology, ideal links, homogeneous starting energy, fixed data rate, and simplified protocol abstractions. Future work can extend the same framework to heterogeneous batteries, mobile sinks, packet loss, retransmission cost, duty cycling, QoS delay, security overhead, and real test-bed measurements. Metaheuristic or machine-learning cluster-head selection can also be compared, but such extensions should retain the same controlled-energy accounting so that improvements are attributable to routing decisions rather than changed assumptions.

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