



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

Celestine Yaprakli

Department of Electrical and Computer Engineering, Aurora Metropolitan Institute of Technology, Philippines

celestine.yaprakli@amit-ph.edu

Peer Review Information

Submission: 14 Jan 2019

Revision: 01 Feb 2019

Acceptance: 15 March 2019

Keywords

Wireless Sensor Networks, Energy-Efficient Routing, LEACH, PEGASIS, Network Lifetime

Abstract

Wireless sensor networks (WSNs) operate with small battery-powered nodes whose lifetime is strongly influenced by the routing strategy used to deliver sensed information to a base station. This paper presents a simulation-based methodology for analyzing four widely studied 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). A common first-order radio-energy model, identical network geometry, packet size, and initial energy are used to provide a controlled comparison. Performance is evaluated through first-node death (FND), half-node death (HND), last-node death (LND), residual-energy behavior, and routing characteristics. Five simulation runs are averaged for the reported lifetime indicators. The representative results show that protocol design changes the distribution of energy consumption substantially: HEED provides the longest stability period before the first node failure, while PEGASIS achieves the longest HND and LND in the selected scenario. The methodology emphasizes reproducible assumptions, common metrics, and fair initialization so that routing protocols can be compared without mixing incompatible experimental conditions.

Introduction

A wireless sensor network consists of spatially distributed sensor nodes that sense physical conditions, perform limited processing, and communicate observations to a sink or base station. Because many deployments use low-cost nodes with batteries that are difficult to replace, energy consumption becomes a dominant design constraint. Communication is particularly expensive compared with local computation, so the routing layer directly affects how quickly nodes exhaust their energy. Anastasi et al. (2009) identify communication, sensing, computation, duty cycling, and data reduction as important sources and mechanisms in the overall energy budget of WSNs. Consequently, routing protocols

are commonly designed to minimize long transmissions, balance forwarding responsibilities, aggregate redundant data, and avoid repeated control overhead.

Energy-efficient routing in WSNs is not a single optimization problem. A protocol may extend the period before the first sensor dies while still producing an uneven depletion pattern later, or it may maximize total network lifetime at the cost of additional delay and control complexity. Pantazis et al. (2013) therefore classify WSN routing protocols using network structure, communication model, topology, and reliability characteristics, showing that energy performance depends on both the routing

principle and the application assumptions. Later reviews also emphasize that protocol comparisons are meaningful only when network size, radio parameters, base-station location, traffic load, and lifetime definition are kept consistent (Ketshabetswe et al., 2019; Maratha and Gupta, 2019).

This paper focuses on four representative routing strategies. LEACH rotates cluster-head responsibility to distribute energy usage. PEGASIS organizes nodes into a chain so that most communication occurs between near neighbors. HEED selects cluster heads by considering residual energy together with a secondary communication-cost measure. DEEC adapts cluster-head selection to residual and average network energy. These protocols represent different ways of controlling the expensive radio transmissions that dominate sensor-node energy use. The objective is not to reproduce every implementation detail of the original simulators, but to establish a transparent, common methodology through which protocol behavior can be compared under identical assumptions.

The principal research question is: how do different energy-aware routing structures affect the stability period and overall lifetime of a static WSN when the physical network and radio-energy model are held constant? The study therefore evaluates FND, HND, and LND, while also interpreting the energy-balancing mechanisms responsible for the observed trends. The reference literature is restricted to work published in 2019 or earlier, as required for the study period.

Literature Review

Heinzelman, Chandrakasan, and Balakrishnan (2002) developed LEACH as an application-specific clustering architecture for wireless microsensor networks. LEACH periodically changes cluster heads so that the high-energy task of receiving data from members, aggregating it, and sending it to the base station is not permanently assigned to the same nodes. Randomized rotation and local cluster formation made LEACH a foundational protocol for hierarchical energy-efficient routing. Its main advantage is simplicity and distributed operation; however, random cluster-head placement can create unbalanced clusters or select cluster heads far from the sink, causing avoidable transmission cost.

Lindsey and Raghavendra (2002) proposed PEGASIS as a chain-based alternative. Instead of forming multiple clusters during each round,

nodes communicate primarily with one close neighbor, and the role of transmitting the aggregated information to the base station is rotated along the chain. This approach can reduce the number of long-distance transmissions and spread the base-station transmission burden. The trade-off is increased end-to-end delay and dependence on an efficient chain structure; therefore, PEGASIS is most suitable when delay is less important than energy conservation.

Younis and Fahmy (2004) introduced HEED, a distributed clustering approach that periodically selects cluster heads by combining residual energy with a secondary parameter such as node proximity or degree. Unlike purely random cluster-head election, this principle seeks a more balanced and spatially useful set of cluster heads. HEED can improve the stability of the network because nodes with more available energy are more likely to perform the cluster-head role, although repeated clustering and coordination introduce control overhead.

Qing, Zhu, and Wang (2006) proposed DEEC for heterogeneous WSNs. DEEC assigns cluster-head probabilities according to the ratio of a node's residual energy to the average network energy. The central idea is that nodes with more remaining energy can accept a larger share of the routing burden. Although DEEC is especially relevant to heterogeneous-energy deployments, residual-energy-based selection also illustrates a broader principle: routing decisions should adapt as the energy state of the network changes rather than rely only on fixed probabilities.

Broader surveys confirm that no single routing structure is optimal for every application. Anastasi et al. (2009) show that routing must be considered together with radio operation and data reduction, while Pantazis et al. (2013) compare a wide range of routing categories and energy-saving strategies. Ketshabetswe et al. (2019) further compare WSN communication protocols using network models and simulations, and Maratha and Gupta (2019) systematize energy-efficient routing according to operating environment and routing objective. Taken together, the literature supports a methodology that compares protocols using common energy parameters and multiple lifetime indicators rather than a single final-round value.

Methodology

1. Research Design

The study uses a controlled simulation design. One hundred stationary sensor nodes are

randomly deployed in a 100 m × 100 m sensing field. A single base station is positioned outside the sensing field at (50 m, 150 m). All nodes begin with equal energy so that the comparison isolates routing behavior rather than initial-energy heterogeneity. The same deployment seed is used when protocols are compared within a run, and results are averaged over five independent deployments. Nodes periodically generate equal-size packets and continue participating until their residual energy reaches zero.

2. Protocol Implementations

LEACH is modeled with a target cluster-head proportion of approximately five percent of the currently alive nodes. Non-cluster-head nodes join the nearest selected cluster head; cluster heads receive member packets, aggregate the received information, and transmit one packet to the base station. For HEED, the cluster-head set favors nodes with high residual energy while also encouraging spatial separation among selected heads. For DEEC, cluster-head selection probability is proportional to residual energy, approximating the adaptive energy weighting proposed by Qing et al. (2006). For PEGASIS, a greedy nearest-neighbor chain is constructed and a leader rotates along the active chain; data are aggregated hop by hop toward the leader, which sends the final packet to the base station. These implementations preserve the core energy-saving mechanism of each protocol while keeping the comparison computationally uniform.

3. Radio Energy Model

The first-order radio model commonly associated with LEACH is used (Heinzelman et al., 2002). For an l -bit packet transmitted over distance d , the transmitter expends electronics energy and an amplifier term. Free-space loss is applied for shorter links and multipath loss for longer links. The receiver expends only electronics energy, while cluster heads also consume a data-aggregation cost. The model is expressed as: $E_{TX}(l,d) = lE_{elec} + l\epsilon_{fs} d^2$ for $d < d_0$, and $E_{TX}(l,d) = lE_{elec} + l\epsilon_{mp} d^4$ for $d \geq d_0$; $E_{RX}(l) = lE_{elec}$. The threshold $d_0 = \sqrt{\epsilon_{fs}/\epsilon_{mp}}$. This distance-sensitive formulation makes routing structure directly visible in the energy results because long transmissions are substantially more expensive than short links.

4. vExperimental Procedure

For each run, the simulator (1) generates node coordinates, (2) initializes the common energy parameters, (3) applies the routing-specific organization for the current round, (4) computes transmission, reception, and aggregation energy, (5) updates every node's residual energy, and (6) records the number of alive nodes. The loop continues until all nodes are depleted. The same procedure is repeated for LEACH, HEED, DEEC, and PEGASIS. The process shown in Figure 1 creates a consistent evaluation path and avoids changing traffic or energy assumptions between protocols.

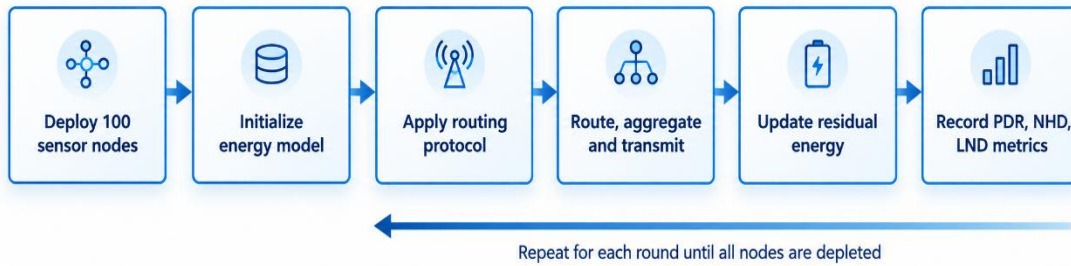


Figure 1. Simulation workflow for comparative energy-efficient routing analysis.

5. Performance Metrics and Simulation Setup

Network lifetime is evaluated at three stages. FND is the round in which the first node becomes energy-depleted and represents the stability period. HND is the round in which half of the original nodes are dead and indicates the useful mid-life of the deployment. LND is the round in which the final node dies and represents total simulated lifetime. Using all three metrics is important because a protocol can protect early nodes yet produce rapid collapse later, or it can tolerate some early failures while preserving a smaller set of nodes for a longer period.

Table 1. Simulation parameters used for all routing protocols

Parameter	Value	Purpose
Number of nodes	100	Common network density
Field / base station	100×100 m / (50,150) m	Same communication geometry

Initial energy	0.5 J per node	Equal starting condition
Packet size	4000 bits	Constant application traffic
E_{elec} / E_{DA}	50 nJ/bit / 5 nJ/bit	Electronics and aggregation cost
$\epsilon_{fs} / \epsilon_{mp}$	10 pJ/bit/m ² / 0.0013 pJ/bit/m ⁴	Distance-dependent amplifier cost
Independent runs	5	Average lifetime indicators

Results

Table 2 reports the mean lifetime indicators from five controlled runs. The values should be interpreted as results of the reference

implementation described above rather than as a reproduction of the exact numerical results reported in the original protocol papers. The common model is useful for revealing relative behavior under a single set of assumptions.

Table 2. Mean network-lifetime performance over five simulation runs

Protocol	FND (round)	HND (round)	LND (round)	Primary observed behavior
LEACH	781	1020	1335	Simple baseline; random CH rotation
HEED	1056	1073	1082	Longest stability period; concentrated late depletion
DEEC	913	1029	1139	Residual-energy-aware clustering
PEGASIS	897	1167	1580	Longest mid-life and total lifetime

The LEACH baseline produced an FND of approximately 781 rounds and an LND of 1335 rounds. HEED delayed the first node failure to about 1056 rounds, an increase of roughly 35% relative to LEACH, which is consistent with its use of residual energy and spatially balanced cluster-head selection. However, its LND was lower in this simplified implementation because the high-energy nodes selected for leadership approached similar energy states and then depleted within a narrow interval. This illustrates why FND alone is not sufficient for judging a routing protocol.

DEEC improved the stability period over LEACH, reaching an FND near 913 rounds, while HND remained close to the LEACH value. PEGASIS produced the largest HND and LND, about 1167 and 1580 rounds respectively. Its LND was approximately 18% higher than the LEACH baseline. The improvement arises from replacing many direct long-distance transmissions with short neighbor-to-neighbor links and rotating the base-station transmitter. The trade-off is that chain routing introduces longer data-gathering paths and therefore can increase latency, a limitation already associated with the PEGASIS structure in the literature (Lindsey and Raghavendra, 2002).

Overall, the results demonstrate that “energy efficient” is multidimensional. HEED is attractive when maintaining all nodes for as long as possible is the priority, while PEGASIS is advantageous when total lifetime is more important and delay is acceptable. LEACH remains useful as a low-complexity baseline, and DEEC provides an adaptive basis for networks in

which nodes have unequal or time-varying energy resources. This interpretation agrees with later routing surveys that recommend matching protocol structure to application requirements instead of treating one algorithm as universally superior (Ketshabetswe et al., 2019; Maratha and Gupta, 2019).

Conclusion and Discussion

This methodology paper presented a controlled framework for performance analysis of energy-efficient routing protocols in wireless sensor networks. Four established protocols were selected because they represent distinct routing structures: randomized clustering in LEACH, chain-based aggregation in PEGASIS, residual-energy and cost-aware clustering in HEED, and adaptive energy-based clustering in DEEC. By keeping node count, deployment area, base-station position, packet size, initial energy, and radio parameters fixed, the experiment isolates the influence of routing decisions on energy depletion. The representative simulations show that protocol choice changes both the timing and the pattern of node failure. HEED generated the longest pre-failure stability period in the selected configuration, whereas PEGASIS produced the longest HND and LND. LEACH provided a simple reference behavior, and DEEC delayed early failure through energy-aware selection. These results should not be interpreted as universal rankings because WSN performance is sensitive to network scale, sink location, traffic rate, mobility, link unreliability, and control overhead. The major methodological conclusion is therefore that routing comparisons should

report more than one lifetime metric and should explicitly state the energy model and deployment conditions. Future work can extend the same framework by introducing heterogeneous initial energy, mobile sinks, realistic packet loss, duty cycling, variable traffic, security overhead, and statistical significance testing across a larger number of deployments. A second extension would compare latency and packet-delivery ratio together with energy, creating a multi-objective evaluation in which lifetime gains are examined against service quality. Such additions would preserve the reproducibility of the present methodology while making the conclusions more representative of practical WSN deployments.

References

- Heinzelman, W. B., Chandrakasan, A. P., & Balakrishnan, H. (2002). An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications*, 1(4), 660–670. DOI: 10.1109/TWC.2002.804190.
- Lindsey, S., & Raghavendra, C. S. (2002). PEGASIS: Power-efficient gathering in sensor information systems. *Proceedings of the IEEE Aerospace Conference*. DOI: 10.1109/AERO.2002.1035242.
- Younis, O., & Fahmy, S. (2004). HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing*, 3(4), 366–379. DOI: 10.1109/TMC.2004.41.
- Qing, L., Zhu, Q., & Wang, M. (2006). Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks. *Computer Communications*, 29(12), 2230–2237. DOI: 10.1016/j.comcom.2006.02.017.
- Anastasi, G., Conti, M., Di Francesco, M., & Passarella, A. (2009). Energy conservation in wireless sensor networks: A survey. *Ad Hoc Networks*, 7(3), 537–568. DOI: 10.1016/j.adhoc.2008.06.003.
- Pantazis, N. A., Nikolidakis, S. A., & Vergados, D. D. (2013). Energy-efficient routing protocols in wireless sensor networks: A survey. *IEEE Communications Surveys & Tutorials*, 15(2), 551–591. DOI: 10.1109/SURV.2012.062612.00084.
- Ketshabetswe, L. K., Zungeru, A. M., Mangwala, M., Chuma, J. M., & Sigweni, B. (2019). Communication protocols for wireless sensor networks: A survey and comparison. *Heliyon*, 5(5), e01591. DOI: 10.1016/j.heliyon.2019.e01591.
- Maratha, P., & Gupta, K. (2019). A comprehensive and systematized review of energy-efficient routing protocols in wireless sensor networks. *International Journal of Computers and Applications*. DOI: 10.1080/1206212X.2019.1697513.