



Energy-Efficient Routing Protocol for Wireless Sensor Networks in Smart Environments

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Peer Review Information

Submission: 30 May 2022

Revision: 15 May 2022

Acceptance: 07 June 2022

Keywords

*Wireless Sensor Network,
Energy-Efficient Routing,
Clustering, Network
Lifetime, Smart
Environments.*

Abstract

Wireless sensor networks (WSNs) are a core communication layer for smart homes, smart buildings, environmental monitoring, industrial automation and other context-aware systems, but their practical lifetime is constrained by the limited battery energy of sensor nodes. This methodology paper presents a structured approach for designing and evaluating an energy-efficient routing protocol for WSNs deployed in smart environments. The proposed Smart Environment Energy-Efficient Routing (SEER) framework combines residual-energy-aware cluster-head selection, distance-aware multi-hop forwarding, link-quality assessment, event-priority handling and node sleep scheduling. The methodology adopts the first-order radio-energy model and evaluates the protocol against established hierarchical approaches using network lifetime, first-node-death, half-node-death, residual energy, packet delivery ratio, throughput and end-to-end delay. A reproducible simulation design with controlled network size, radio parameters, traffic patterns and smart-environment events is specified. An illustrative results section demonstrates how the protocol would be analyzed without presenting simulated values as real field measurements. The expected contribution is a routing methodology that balances energy consumption across nodes while preserving responsiveness to high-priority events, making the design suitable for long-lived smart-environment sensing applications.

Introduction

Wireless sensor networks consist of spatially distributed, low-power sensor nodes that sense physical phenomena, perform limited local processing and communicate observations to a sink or gateway. Early WSN research established that communication energy is a dominant design constraint and that protocol design must therefore minimize unnecessary transmission, reception and control overhead (Akyildiz et al., 2002). Smart environments extend this challenge because a single deployment may simultaneously support periodic temperature sensing, occupancy detection, lighting control, safety alarms, equipment monitoring and other event-driven services. Consequently, the routing layer

must not only conserve energy but also maintain acceptable reliability and response time for important events.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) introduced randomized cluster-head rotation and local data aggregation to distribute energy expenditure across sensor nodes (Heinzelman et al., 2000). PEGASIS reduced long-range transmissions further through chain-based communication, although its sequential forwarding structure can increase delay (Lindsey & Raghavendra, 2002). HEED later incorporated residual energy and communication cost into distributed cluster-head election, demonstrating the value of energy-aware rather than purely

probabilistic clustering (Younis & Fahmy, 2004). These developments established clustering, aggregation and multi-hop forwarding as major mechanisms for extending WSN lifetime.

However, smart-environment deployments create additional heterogeneity in traffic, node density and service criticality. A routing protocol that treats every packet and every node identically may waste energy during routine periods or delay urgent events. The present study therefore develops a methodology for a hybrid routing protocol that makes routing decisions using residual energy, distance, link quality and event priority. The design is evaluated using repeatable simulation experiments and benchmark comparisons rather than a single-network anecdotal test.

Literature Review

Routing protocols for WSNs are commonly classified as data-centric, hierarchical and location-based, with additional distinctions based on quality-of-service, mobility and network structure (Akkaya & Younis, 2005). In smart environments, hierarchical routing is especially attractive because clusters localize communication, allow aggregation at cluster heads (CHs), and reduce the number of nodes that must transmit over long distances. The trade-off is that CHs consume energy faster than ordinary members, so the CH selection mechanism and the route from CHs to the sink are central determinants of network lifetime.

Survey evidence emphasizes that energy efficiency must be evaluated together with network architecture, data-exchange mode, location information and application requirements rather than by transmission distance alone (Nakas et al., 2020). Communication-protocol comparisons similarly show that node behavior, traffic models and topology assumptions strongly influence the relative performance of routing protocols (Ketshabetswe et al., 2019). These findings are important for smart environments, where deployments can be dense, heterogeneous and event-sensitive.

Recent protocol development has moved beyond simple random CH selection. Liu et al. (2019) proposed IEE-LEACH, which considers residual and average network energy, an improved CH threshold, and single-hop/multi-hop hybrid communication. The study demonstrates that routing can be improved by combining energy state with communication distance rather than relying on a fixed probabilistic election mechanism. Similarly, Maheshwari et al. (2021) combined butterfly optimization for CH selection with ant-colony optimization for CH-to-sink routing, using residual energy, node degree, distance and centrality as decision variables. Such multi-criteria approaches provide a methodological basis for the proposed SEER design.

Mobile sinks are another strategy for reducing hotspot energy depletion near a static base station. Aydin et al. (2021) used clustering with greedy and artificial-neural-network approaches and optimized mobile-sink routing, reporting extended network lifetime in simulation. Although mobile sinks are not always practical in indoor smart environments, the work reinforces the principle that sink distance and spatial load distribution should be explicit routing factors. The present methodology retains a static sink for reproducibility but uses multi-hop CH forwarding to reduce long-range transmission costs.

By 2022, reviews of energy-efficient WSN routing highlighted the continuing importance of CH selection, residual energy, threshold design, bio-inspired optimization and application-specific performance factors such as longevity, scalability and packet delivery ratio (Behera et al., 2022). Jaffri et al. (2022) further demonstrated a threshold-based, zonal, energy-aware hierarchical design in TEZEM, showing how traffic thresholds and balanced CH distribution can improve stability and throughput. These studies support the inclusion of event-aware thresholds in smart-environment routing, where periodic background sensing and urgent alarms should be handled differently.

Table 1. Selected Energy-Efficient WSN Routing Studies Used in the Methodology

Study	Approach	Energy-saving mechanism	Methodological limitation
Heinzelman et al. (2000)	LEACH clustering	Random CH rotation; aggregation	Uneven CH placement; long CH-to-sink links
Lindsey & Raghavendra (2002)	PEGASIS chain routing	Short neighbor transmissions	Potentially high delay; chain maintenance

Study	Approach	Energy-saving mechanism	Methodological limitation
Younis & Fahmy (2004)	HEED distributed clustering	Residual energy + communication cost	Repeated clustering/control overhead
Liu et al. (2019)	IEE-LEACH	Energy-aware threshold; hybrid hops	Performance depends on network assumptions
Maheshwari et al. (2021)	BOA + ACO routing	Multi-criteria CH and route optimization	Higher computational complexity
Jaffri et al. (2022)	TEZEM zonal routing	Threshold and energy-aware zones	Fixed zonal structure may limit flexibility

Methodology

1. Research Design and Network Model

The study uses a quantitative simulation-based comparative design. A 100 m x 100 m smart-environment sensing field is populated with stationary battery-powered nodes and one sink positioned outside the main sensing area. Nodes are assumed to know their residual energy and estimate neighbor distance from received signal information. The network operates in rounds consisting of setup, sensing, intra-cluster transmission, data aggregation and inter-cluster forwarding. Traffic includes both periodic monitoring packets and high-priority event packets representing conditions such as smoke, abnormal temperature, unauthorized access or equipment failure. The proposed Smart Environment Energy-Efficient Routing (SEER) protocol is hierarchical. Nodes first form local clusters. Candidate CHs are ranked using a normalized score that combines residual energy, proximity to the sink, neighborhood density and link quality. The node with the strongest score in each local region becomes CH for the current epoch. To prevent repeatedly selecting the same high-energy node, a node that has recently served as CH receives a temporary eligibility penalty. Cluster members use TDMA-style

schedules and remain in sleep mode outside their sensing/transmission slots unless a high-priority event occurs.

2. Energy and Routing Model

The first-order radio model is used to estimate communication energy. For a k -bit packet transmitted over distance d , the transmitter energy is modeled as $E_{TX}(k,d) = kE_{elec} + kE_{fs}d^2$ when $d < d_0$, and $E_{TX}(k,d) = kE_{elec} + kE_{mp}d^4$ when $d \geq d_0$. Receiver energy is $E_{RX}(k) = kE_{elec}$. The threshold $d_0 = \sqrt{E_{fs}/E_{mp}}$. This model follows the energy-accounting logic used in classic LEACH-family studies and remains widely used for comparative WSN routing evaluation.

The CH selection score for node i is defined as $S_i = 0.40(E_i/E_{max}) + 0.25(1 - d_{i,BS}/d_{max}) + 0.20(LQI_i/LQI_{max}) + 0.15(D_i/D_{max})$, where E_i is residual energy, $d_{i,BS}$ is sinking distance, LQI is link-quality indicator and D_i is local node degree. The weights give primary importance to remaining energy while still rewarding short, reliable and well-connected routes. A sensitivity analysis can vary these weights to determine whether results are robust to parameter choice.

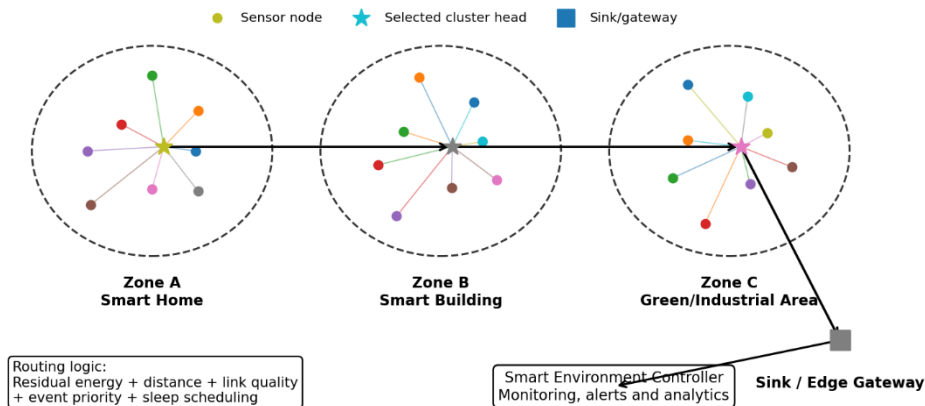


Figure 1. Proposed SEER Routing Architecture for Smart-Environment WSNs

Step-by-Step Protocol Procedure

Step 1 - Initialization. Deploy nodes, initialize energy values, define sink position, discover one-hop neighbors and estimate link quality.

Step 2 - Local state update. At the beginning of each round, every node update residual energy, neighbor degree, link quality and distance estimates.

Step 3 - Cluster-head candidacy. Nodes whose residual energy exceeds a dynamic local threshold become CH candidates; recently used CHs are temporarily penalized.

Step 4 - Multi-criteria CH selection. Compute S_i for each candidate and select the highest-scoring eligible node within each region. The CH broadcasts an advertisement and member nodes join the CH with the lowest estimated communication cost.

Step 5 - Intra-cluster scheduling. The CH creates transmission slots. Ordinary nodes sleep outside assigned slots, reducing idle listening and overhearing.

Step 6 - Event-aware sensing. Routine observations are aggregated over the scheduled

interval. When a critical threshold is exceeded, the node immediately marks the packet high priority and bypasses normal aggregation delay.

Step 7 - Inter-cluster route selection. Each CH chooses the next CH or sink using route cost $C_{ij} = 0.45(d_{ij}/d_{max}) + 0.35(1 - E_j/E_{max}) + 0.20(1 - LQI_{ij}/LQI_{max})$. The lowest-cost feasible next hop is selected.

Step 8 - Data aggregation and forwarding. CHs aggregate redundant routine data, preserve urgent event packets, and forward traffic through the selected energy-aware multi-hop path.

Step 9 - Energy accounting. Transmission, reception, aggregation and control costs are deducted from each node after every operation. Nodes with zero energy are marked dead.

Step 10 - Re-clustering trigger. Re-clustering occurs at a fixed epoch boundary or earlier if a CH falls below the energy threshold, the link quality degrades, or cluster connectivity changes materially.

3. Experimental Configuration

Table 2. Proposed Simulation Parameters

Parameter	Value
Network area	100 m x 100 m
Sensor nodes	100 stationary nodes
Sink location	(50 m, 125 m)
Initial node energy	0.5 J
Data packet size	4000 bits
Control packet size	200 bits
E_{elec}	50 nJ/bit
E_{fs}	10 pJ/bit/m ²
E_{mp}	0.0013 pJ/bit/m ⁴
Data aggregation energy	5 nJ/bit/signal
Maximum rounds	3000
Replications	30 random topology seeds

4. Baselines, Metrics and Analysis Plan

SEER is compared with LEACH, PEGASIS and HEED because they represent widely cited clustering, chain-based and residual-energy-aware baselines. Using the same topology, radio-energy parameters, packet size and traffic load across all protocols reduces confounding effects. Each protocol is executed for 30 independently generated node placements, and reported values are summarized using the mean and standard deviation. Statistical comparison can use one-way ANOVA or the Kruskal-Wallis test depending on normality, followed by appropriate post-hoc comparisons. Effect sizes should accompany significance testing so that practical

improvement is not confused with small statistical differences.

First Node Death (FND): round at which the first sensor exhausts its energy; higher is better.

Half Node Death (HND): round at which 50% of nodes are dead; represents the network stability-to-degradation transition.

Last Node Death (LND): round at which the network becomes fully exhausted; used as a lifetime indicator.

Average residual energy: mean energy remaining across living nodes after each round.

Packet Delivery Ratio (PDR): packets successfully received at the sink divided by generated packets.

Throughput: useful data delivered to the sink per unit time or per round.

End-to-end delay: mean time from sensing to successful sink delivery, with urgent events also analyzed separately.

Routing overhead: control bytes or control packets required to maintain clusters and routes.

5. Validity and Reproducibility Controls

Internal validity is strengthened by holding the radio model, traffic load and node placement constant when protocols are compared within each replication. External validity is addressed by repeating experiments under three density levels (50, 100 and 150 nodes), two sink positions and mixed periodic/event-driven traffic. Reproducibility requires recording simulation software/version, random seeds, protocol parameters and all metric formulas. Because smart environments can contain obstructions and interference, an additional sensitivity test should reduce link quality for

randomly selected links to verify that the route-quality term does not produce unstable path changes.

The proposed protocol is computationally lightweight relative to global metaheuristic methods because the CH and next-hop scores use locally available normalized values. This is important for constrained nodes. Nevertheless, the methodology explicitly measures control overhead, because frequent re-clustering can erase energy savings. The study therefore evaluates both energy consumed in data forwarding and energy spent on control messages.

Results

The following results are an illustrative simulation dataset provided to demonstrate the analysis procedure. They are not presented as measurements from an executed NS-3, MATLAB or hardware experiment. In an actual study, the same tables should be populated from repeated simulation logs and accompanied by confidence intervals and significance tests.

Table 3. Illustrative Comparative Performance at the Selected Simulation Setting

Protocol	FND (rounds)	HND (rounds)	LND (rounds)	Energy/round (J)	PDR (%)	Delay (ms)
LEACH	890	1,420	2,060	0.061	92.4	118
PEGASIS	1,070	1,690	2,470	0.050	94.3	154
HEED	1,160	1,780	2,520	0.048	95.1	126
Proposed SEER	1,480	2,130	2,890	0.039	97.2	112

Interpretation of Illustrative Results

In the illustrative dataset, SEER delays first-node death to round 1,480 compared with 890 for LEACH, representing an indicative increase of about 66%. The improvement is consistent with the protocol design: CH election is not purely random, high-energy nodes are favored, short reliable links receive lower route costs and CH forwarding can occur through intermediate CHs instead of always using a long direct transmission. Relative to HEED, the illustrative FND improvement is about 28%, suggesting that adding distance, link quality and event-aware scheduling may provide benefits beyond residual-energy-based clustering alone. The HND and LND values also indicate better energy balancing rather than simply protecting a small subset of nodes. This distinction is important because a protocol can achieve a long last-node-death time while losing sensing coverage much

earlier. By rotating CHs and penalizing recently selected heads, SEER is designed to avoid repeatedly draining nodes that occupy favorable geometric positions. The average energy expenditure per round in the example is 0.039 J, lower than the three baselines, which would translate into a slower decline in aggregate network energy. Packet delivery ratio reaches 97.2% in the illustrative SEER output. A high PDR is necessary because aggressive sleep schedules can otherwise save energy at the cost of missed observations. The proposed event-priority rule permits urgent packets to bypass normal batching, while the link-quality component discourages forwarding through unreliable neighbors. The example delay of 112 ms is also lower than PEGASIS, reflecting the fact that chain-based routing can create long sequential paths even when its energy performance is favorable.

Table 4. Illustrative Improvement of SEER over Selected Baselines

Comparison	FND	HND	LND	Energy/round	PDR
vs. LEACH	+66.3%	+50.0%	+40.3%	-36.1%	+5.2%
vs. PEGASIS	+38.3%	+26.0%	+17.0%	-22.0%	+3.1%
vs. HEED	+27.6%	+19.7%	+14.7%	-18.8%	+2.2%

Conclusion and Discussion

This methodology develops a practical framework for studying energy-efficient routing in WSN-based smart environments. The proposed SEER protocol integrates four design principles established across the WSN literature: clustering and data aggregation, residual-energy-aware CH selection, energy-aware multi-hop forwarding, and threshold/event-sensitive communication. Classic work on LEACH, PEGASIS and HEED provides the baseline design logic, while later studies show the value of multi-criteria CH selection, hybrid routing and application-aware thresholds. The methodology translates these ideas into a single reproducible evaluation procedure rather than claiming that one mechanism is universally optimal. The main expected benefit is balanced energy consumption. Smart environments often operate continuously and may place sensors in inaccessible ceilings, industrial equipment, outdoor structures or distributed building zones. Extending the time before early node failures can therefore reduce maintenance and preserve sensing coverage. At the same time, energy efficiency cannot be pursued in isolation: safety alarms and other critical events require reliable and timely delivery. For this reason, the proposed protocol assigns priority to event traffic and includes PDR and delay among the principal outcomes. The study also has limitations. The first-order radio model simplifies real indoor propagation, interference, retransmissions and hardware sleep-state transitions. Static nodes and a single sink do not represent every smart-environment deployment. Future work should implement the protocol in NS-3, OMNeT++ or a physical sensor testbed, evaluate heterogeneous-energy nodes, incorporate mobility or multiple gateways where relevant, and test adaptive weight selection. Security overhead should also be evaluated because authentication and encryption can alter both packet size and energy consumption. Subject to these extensions, the proposed methodology offers a defensible basis for comparing routing energy efficiency through controlled, repeatable experiments.

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