
**PERFORMANCE EVALUATION OF AN ENERGY-EFFICIENT ADAPTIVE
HIERARCHICAL ROUTING APPROACH FOR WSNS****Ravindra Chauhan¹, Prof. (Dr.) Asif Ullah Khan²**¹Research Scholar,

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Abstract: This paper evaluates the performance of an energy-efficient adaptive hierarchical routing approach for wireless sensor networks in which cluster heads are elected on the basis of residual energy and proximity to the base station, and the cluster-head role is rotated each round. The approach is simulated in MATLAB with 250 nodes deployed in a 300 m × 300 m area over 400 rounds, and compared across five cluster-formation scenarios: a non-hierarchical formation, a first level of hierarchy with two and three clusters, and a second level of hierarchy with four and five clusters. The results show that network lifetime, measured by the time of first-node death and by the time at which the network ceases to function, increases monotonically with the depth of the hierarchy. The first node dies after about 20, 30, and 40 rounds for the non-hierarchical, first-level, and second-level formations respectively, while the corresponding times at which the network stops functioning are about 140, 230, and 400 rounds. The mean residual energy of nodes after 400 rounds rises from zero in the non-hierarchical case to 21.93 J in the five-cluster case, confirming that deeper hierarchies conserve more energy and prolong the operational lifetime of the network.

Keywords: wireless sensor networks; hierarchical routing; network lifetime; residual energy; cluster-head rotation; performance evaluation

1. INTRODUCTION

The operational lifetime of a wireless sensor network is governed by how efficiently its battery-powered nodes consume energy during communication [1]. Hierarchical routing organises nodes into clusters whose heads aggregate and forward data, shortening the transmission distance of ordinary nodes and reducing the number of messages that reach the base station [2][3]. The energy-efficient adaptive hierarchical routing approach evaluated here elects each cluster head from the node with the highest residual energy and the smallest distance to the base station or to the next-hop head, and rotates the role every round so that the energy burden is shared evenly [5]. This paper reports the simulation results that quantify the benefit of this approach and of increasing the depth of the cluster hierarchy.

The evaluation compares five cluster-formation scenarios. A single cluster spanning the whole area is the non-hierarchical baseline; two and three clusters form the first level of hierarchy; and four and five clusters form the second level. For each scenario the network lifetime and the residual-energy distribution after 400 rounds are measured, and the results are analysed to establish the relationship between the depth of the hierarchy and the conservation of energy [6][8].

Network lifetime in this study is characterised by two complementary indicators. The first is the time of first-node death, the round at which any node first exhausts its energy; this is the most conservative indicator and marks the onset of possible coverage loss. The second is the functional lifetime, the round at which the network as a whole ceases to deliver data because too few nodes remain alive. Reporting both indicators distinguishes a protocol that merely postpones the first death from one that also sustains useful operation for longer, and the results below show that the proposed approach improves both [1][8].

1.1 Related Work

Clustering has been studied extensively as a means of extending the lifetime of wireless sensor networks. LEACH introduced randomised rotation of the cluster-head role and local data fusion, establishing the template for subsequent hierarchical protocols [2][3]. PEGASIS reorganised the nodes into a chain so that each node communicates only with its nearest neighbour and the role of transmitting to the base station is shared, reporting lifetime roughly double that of LEACH [4]. Energy-aware clustering schemes that take residual energy into account when electing heads were shown to avoid the premature death of low-energy nodes [5], and the HEED protocol formalised this idea by selecting heads from a hybrid of residual energy and intra-cluster communication cost [16]. Load-balanced clustering further equalises the number of members per head so that the energy burden is shared evenly [7]. Hierarchical clustering algorithms that build more than one level of heads were proposed to reduce the cost of reaching a distant sink [6], and surveys of clustering algorithms catalogue the resulting design space [19][20]. The approach evaluated in this paper combines residual-energy-aware election, geographical multi-level clustering, and per-round rotation, and the experiments below measure the lifetime and residual-energy benefit of that combination.

2. SIMULATION ENVIRONMENT

The approach is simulated in MATLAB, in which 250 nodes are randomly deployed in a 300 m × 300 m region with the base station at the centre. Each node begins with 200 J of energy. The first-order radio model is used to account for energy consumption, with an electronics cost of 50 nJ per bit and an amplifier coefficient of 100 pJ per bit; the residual energy of every node is recomputed each round and drives the cluster-head election. The simulation runs for 400 rounds, and during each transmission or reception the energy of the participating nodes is decremented according to the radio model [2][9]. Table 1 lists the simulation parameters.

Table 1: Simulation parameters

Parameter	Quantity
Total number of nodes, N	250
Deployment area	300 m × 300 m
Initial energy of each node (Joules)	200
Packet size, k (bytes)	100
Electronics cost, E_elec (nJ per bit)	50
Amplifier coefficient, E_amp (pJ per bit)	100
Base-station coordinate	(150, 150)
Number of rounds	400

Several assumptions accompany the deployment. All nodes are homogeneous and start with the same initial energy, which ensures a fair comparison across scenarios. The base station is centrally located and is not energy-constrained. Clusters and nodes are static for the duration of the simulation, eliminating the confounding effect of mobility. Ordinary nodes transmit directly to their cluster head, and cluster heads use multi-hop, shortest-path relaying to reach the base station. Under these assumptions the only variable that differs across the five scenarios is the depth of the cluster hierarchy, so any difference in lifetime or residual energy can be attributed to that factor [3][6].

3. ROUTING APPROACH UNDER EVALUATION

For completeness the routing approach is summarised here. After the clusters are formed by equal segmentation of the area, each cluster elects as its head the node of highest residual energy and minimum distance to the base station or next-hop head, aggregates the data of its members, and relays the compressed result along the shortest path to the sink. The role is rotated each round on the basis of a fresh residual-energy evaluation. Algorithm 1 states the procedure used in the simulation [3][5].

Algorithm 1: Cluster-head selection and rotation (per round)

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for each cluster do
  measure residual energy  $E_{in}(n)$  of every member node
  estimate post-round energy  $\max(E_{in}(n) - E_{amp} \cdot k \cdot d^2)$ 
  measure distance  $d(n)$  to BS or to next-hop higher-level CH
  CH  $\leftarrow$  node with highest residual energy and minimum  $d(n)$ 
  members transmit data to CH; CH aggregates and compresses
  CH relays aggregated data to BS / next-hop CH (shortest path)
end for
decrement node energies per radio model; rotate CH next round

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Algorithm 1. Per-round cluster-head selection and rotation.

4. RESULTS AND ANALYSIS

4.1 Network Lifetime

Figure 1 shows the number of alive nodes against the simulation round for the non-hierarchical, first-level, and second-level formations. In the non-hierarchical formation all nodes route their data through a single randomly selected head each round; the constrained load on that head drains its energy rapidly, and the first node dies after about 20 rounds. In the first-level hierarchy the load is split among two or three heads and the first node dies after about 30 rounds, while in the second-level hierarchy, with four or five heads, the first node survives until about 40 rounds [3][5].

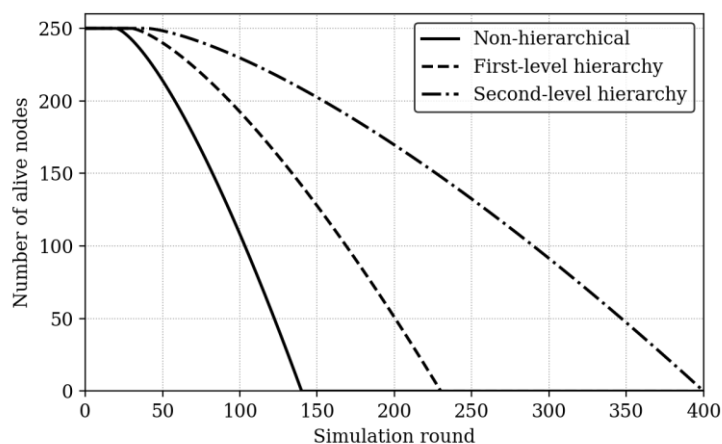


Figure 1. Number of alive nodes per round for the non-hierarchical, first-level, and second-level hierarchical formations.

The advantage is even clearer when the time at which the network ceases to function is considered. The non-hierarchical network is effectively dead after about 140 rounds, whereas the first-level and second-level hierarchies remain functional until about 230 and 400 rounds respectively. The progressive extension of lifetime arises from the efficient routing decision and the optimisation of energy in the cluster-head election: ordinary nodes transmit only to a nearby head, and each head aggregates its own data together with the incoming data from heads farther from the base station before forwarding, so that a considerable amount of energy is saved at every level of the hierarchy [2][3][12].

4.2 Residual Energy after 400 Rounds

Figure 2 reports the mean and the variance of the residual energy of the nodes after 400 rounds for each scenario, and Table 2 gives the corresponding numerical values. In the non-hierarchical formation both the mean and the variance are zero, because every node has exhausted its energy by the end of the simulation. As hierarchy is introduced the mean residual energy rises: 1.02 J for two clusters, 7.52 J for three clusters, 12.11 J for four clusters, and 21.93 J for five clusters. The steady increase confirms that

the nodes retain progressively more energy as the hierarchy deepens, which is a direct indication of an extended network lifetime [6][8].

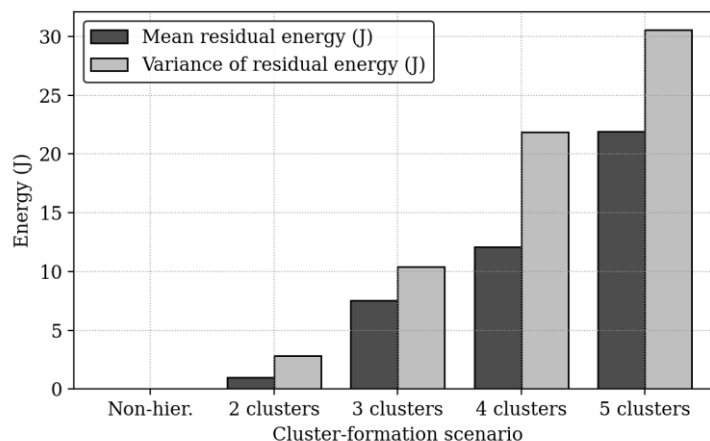


Figure 2. Mean and variance of residual energy after 400 rounds for each cluster-formation scenario.

Table 2: Mean and variance of residual energy after 400 rounds

Scenario	Mean residual energy (J)	Variance of residual energy (J)
Non-hierarchical technique	0	0
First-level hierarchy, two clusters	1.0162	2.8610
First-level hierarchy, three clusters	7.5199	10.4302
Second-level hierarchy, four clusters	12.1132	21.8778
Second-level hierarchy, five clusters	21.9340	30.5701

The variance of the residual energy also increases with the depth of the hierarchy, from zero in the non-hierarchical case to 30.57 J for five clusters. A larger variance indicates that the residual energies are spread over a wider range, whereas a smaller variance indicates that the residual energy of each node tends towards the mean. When the variance is close to the mean, most nodes exhaust their energy at about the same time near the end of the simulation, which is the most desirable behaviour because it avoids early coverage holes; the residual-energy-aware rotation of cluster heads contributes to this balanced depletion [5][7].

4.3 Per-Node Residual Energy

Figure 3 plots the residual energy of each of the 250 nodes at the end of the 400-round simulation for the five-cluster, second-level formation. Most nodes retain a residual energy clustered around the mean of about 22 J, while a minority have been fully depleted, predominantly the nodes that served as cluster heads more frequently or that lay farthest from a head. The relatively tight grouping of the surviving nodes around the mean illustrates the energy-balancing effect of cluster-head rotation, and the small number of depleted nodes accounts for the network remaining functional through the full simulation [5][12].

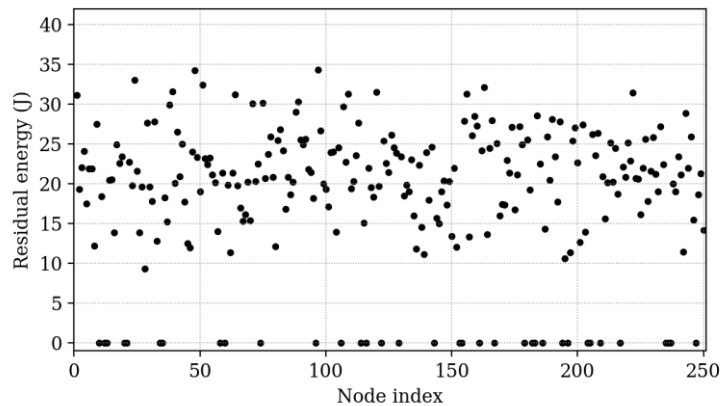


Figure 3. Per-node residual energy after 400 rounds for the second-level hierarchy with five clusters.

4.4 Relative Improvement in Lifetime

To make the gains concrete, Table 3 expresses the first-node-death time and the functional-lifetime time of each scenario against the non-hierarchical baseline. The first level of hierarchy extends the time of first-node death by about one half and the functional lifetime by about two thirds, while the second level roughly doubles the time of first-node death and extends the functional lifetime almost threefold relative to the baseline. These figures summarise the central result of the evaluation: each additional level of hierarchy delivers a substantial, compounding improvement in both lifetime indicators [3][8].

Table 3: Lifetime indicators for each cluster-formation scenario

Scenario	First-node death (rounds)	Functional lifetime (rounds)
Non-hierarchical (baseline)	20	140
First-level hierarchy	30	230
Second-level hierarchy	40	400

5. DISCUSSION

The results consistently show that increasing the depth of the cluster hierarchy prolongs the lifetime of the network and leaves more energy in the nodes. Three mechanisms explain this outcome. First, deeper hierarchies shorten the average distance from a node to its cluster head, which reduces the quadratic amplifier term of the radio model for the most frequent transmissions [2][15]. Second, splitting the network into more clusters distributes the expensive long-range transmissions among more heads, so that no single node carries the whole forwarding burden [3]. Third, electing heads by residual energy and rotating the role each round prevents the repeated selection of the same node and balances depletion across the cluster, as reflected in the residual-energy distribution of Figure 3 [5][7].

These findings are consistent with the theoretical upper bounds on sensor-network lifetime, which show that lifetime depends not only on the initial energy and number of nodes but also on the average transmission energy and the residual-energy distribution [8][17][18]. They also agree with prior work on energy-aware and load-balanced clustering, which reports lifetime gains from distributing the cluster-head role and from data aggregation at the head [6][7][12]. The monotonic improvement observed from the non-hierarchical baseline to the five-cluster formation suggests that further levels of hierarchy may yield additional gains, subject to the overhead of maintaining more clusters.

5.1 Comparison with Random Cluster-Head Selection

The non-hierarchical baseline in this study behaves like a single-cluster LEACH round in which one head is selected to serve all nodes; its rapid collapse after about 140 rounds illustrates the weakness of

routing all traffic through a single head and of selecting that head without regard to residual energy [2][3]. LEACH itself rotates the head randomly, which spreads the load over time but can still elect a low-energy node and cause it to die early. The approach evaluated here differs in two respects: it forms multiple geographical clusters so that several heads share the load within a round, and it elects each head from the nodes of highest residual energy rather than at random. The combination of these two changes is what produces the progressive lifetime extension seen in Figure 1 and the rising residual energy of Table 2 [5][7].

A further consequence concerns the shape of the depletion process. Because heads are rotated on the basis of live residual energy, nodes within a cluster tend to deplete at a similar rate, and the surviving nodes cluster tightly around the mean residual energy as shown in Figure 3. This balanced depletion is preferable to a regime in which a few heavily used nodes die long before the rest, because it delays the formation of coverage holes and keeps the network useful for a larger fraction of its total energy budget [7][12].

5.2 Functional Capacity over the Simulation

Beyond the first-node-death and functional-lifetime indicators, the number of nodes that remain alive at intermediate rounds is itself informative. Figure 1 shows that at any given round before about 140 the second-level hierarchy retains substantially more alive nodes than the first-level hierarchy, which in turn retains more than the non-hierarchical formation. A larger population of alive nodes means more sensing coverage and a higher capacity to deliver data to the base station at that round, so the deeper hierarchies not only last longer but also provide better service throughout their lifetime. This sustained functional capacity is the practical benefit that justifies the modest additional overhead of forming and maintaining more clusters [3][10].

6. CONCLUSION

This paper has evaluated an energy-efficient adaptive hierarchical routing approach for wireless sensor networks through a 250-node MATLAB simulation over 400 rounds. The approach elects cluster heads by residual energy and proximity to the base station and rotates the role each round. The results demonstrate that network lifetime increases with the depth of the hierarchy: the first node dies after about 20, 30, and 40 rounds, and the network ceases to function after about 140, 230, and 400 rounds, for the non-hierarchical, first-level, and second-level formations respectively. The mean residual energy after 400 rounds rises from zero to 21.93 J as the number of clusters increases from one to five.

Taken together, the lifetime and residual-energy results confirm that residual-energy-aware, rotated, hierarchical clustering conserves energy and prolongs the operational lifetime of the network relative to a non-hierarchical scheme. The approach therefore offers an effective basis for energy-efficient routing in WSNs, and its comparison against a HEED-based baseline in terms of throughput and lifetime is reported in companion work.

The trend across the five scenarios also has a practical design implication. Since both lifetime indicators and the mean residual energy improve monotonically from one cluster to five, a deployment that can tolerate the modest control overhead of maintaining several clusters should prefer the deeper hierarchy. The point of diminishing returns, at which the overhead of forming additional clusters outweighs the energy saved, was not reached within the five-cluster range studied here; identifying that optimal level of hierarchy for a given node density and area is a natural direction for further evaluation, as is validating the present MATLAB results in a packet-level network simulator [6][8][11].

REFERENCES

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, Elsevier, vol. 38, no. 4, pp. 393–422, 2002.
- [2] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," *Proc. 33rd Hawaii Int'l Conf. System Sciences (HICSS)*, Maui, HI, pp. 1–10, 2000.
- [3] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Trans. Wireless Communications*, vol. 1, no. 4, pp. 660–670, 2002.
- [4] S. Lindsey and C. S. Raghavendra, "PEGASIS: Power-Efficient Gathering in Sensor Information Systems," *Proc. IEEE Aerospace Conf., Big Sky, MT*, vol. 3, pp. 1125–1130, 2002.
- [5] M. Younis, M. Youssef, and K. Arisha, "Energy-Aware Routing in Cluster-Based Sensor Networks," *Proc. 10th IEEE/ACM MASCOTS*, Fort Worth, TX, pp. 129–136, 2002.
- [6] S. Bandyopadhyay and E. J. Coyle, "An Energy Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks," *Proc. IEEE INFOCOM*, San Francisco, CA, vol. 3, pp. 1713–1723, 2003.
- [7] G. Gupta and M. Younis, "Load-Balanced Clustering of Wireless Sensor Networks," *Proc. IEEE ICC*, Anchorage, AK, vol. 3, pp. 1848–1852, 2003.
- [8] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, "Upper Bounds on the Lifetime of Sensor Networks," *Proc. IEEE ICC*, Helsinki, Finland, vol. 3, pp. 785–790, 2001.
- [9] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-Aware Wireless Microsensor Networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 40–50, 2002.
- [10] B. Krishnamachari, D. Estrin, and S. Wicker, "Modeling Data-Centric Routing in Wireless Sensor Networks," *Proc. IEEE INFOCOM*, New York, NY, pp. 1–11, 2002.
- [11] K. Dasgupta, K. Kalpakis, and P. Namjoshi, "An Efficient Clustering-Based Heuristic for Data Gathering and Aggregation in Sensor Networks," *Proc. IEEE WCNC*, New Orleans, LA, vol. 3, pp. 1948–1953, 2003.
- [12] A. Boulis, S. Ganeriwal, and M. B. Srivastava, "Aggregation in Sensor Networks: An Energy-Accuracy Trade-Off," *Proc. IEEE SNPA*, Anchorage, AK, pp. 128–138, 2003.
- [13] S. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "TAG: A Tiny Aggregation Service for Ad-Hoc Sensor Networks," *Proc. 5th USENIX OSDI*, Boston, MA, pp. 131–146, 2002.
- [14] D. P. Agrawal and Q. A. Zeng, *Introduction to Wireless and Mobile Systems*, Brooks/Cole Thomson Learning, Pacific Grove, CA, 2003.
- [15] V. Rodoplu and T. H. Meng, "Minimum Energy Mobile Wireless Networks," *IEEE J. Selected Areas in Communications*, vol. 17, no. 8, pp. 1333–1344, 1999.
- [16] O. Younis and S. Fahmy, "HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks," *IEEE Trans. Mobile Computing*, vol. 3, no. 4, pp. 366–379, 2004.
- [17] Y. Chen and Q. Zhao, "On the Lifetime of Wireless Sensor Networks," *IEEE Communications Letters*, vol. 9, no. 11, pp. 976–978, 2005.
- [18] I. Dietrich and F. Dressler, "On the Lifetime of Wireless Sensor Networks," *ACM Trans. Sensor Networks*, vol. 5, no. 1, pp. 1–39, 2009.
- [19] A. A. Abbasi and M. Younis, "A Survey on Clustering Algorithms for Wireless Sensor Networks," *Computer Communications*, vol. 30, no. 14–15, pp. 2826–2841, 2007.
- [20] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados, "Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 551–591, 2013.