

Spatially deterministic dual-grid clustering for energy-efficient wireless sensor networks in IoT monitoring

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ABSTRACT

The LEACH protocol remains a foundational clustering algorithm for wireless sensor networks, yet random cluster head selection can produce uneven energy consumption and premature spatial degradation. This paper proposed G²LEACH, a dual-grid extension that separates fine-grained measurement coverage into micro-areas from coarse-grained cluster head coverage in a Grid of Head Areas (GHA). Six configurations were evaluated with 1200 static nodes over 100 independent cluster head election runs in two deployment scenarios. In the 1000 × 1000 m scenario, mean First Node Dead remained 1.00-1.03 rounds, while mean Half Nodes Alive increased from 11.0 to 59.5–116.4 rounds (+440% to +958%) and mean Last Node Dead increased from 444.6 to 830.4-932.6 rounds (+87% to +110%). In the 100 × 100 m scenario, G²LEACH-o2-v2 increased mean First Node Dead from 637.9 to 948.8 rounds (+48.7%) but reduced Half Nodes Alive and Last Node Dead by 2.1% and 2.3%, respectively. The results show that fixed spatial organization provides its strongest benefit under long-range multipath propagation, while individual variants exhibit objective-dependent trade-offs.

Keywords: wireless sensor networks, LEACH, grid-based clustering, energy efficiency, spatial coverage, network lifetime.

INTRODUCTION

Internet of Things (IoT) systems demand scalable, energy-efficient sensor architectures for long-term, area-wide monitoring. Application domains with these requirements include precision agriculture [1, 2], environmental and forestry monitoring [3], surveillance of military zones and critical infrastructure [4,5], and Industry 4.0 deployments [6, 7]. These environments share regular or semi-regular terrain that can be partitioned deterministically and a need to maintain uniform measurement coverage despite limited per-node energy budgets.

Among the families of WSN organization algorithms, clustering protocols are particularly attractive for such applications because they reduce radio traffic and balance energy consumption. The canonical benchmark in this family is LEACH [8], which periodically rotates cluster

head (CH) roles. Nodes transmit to their CH, and each CH aggregates and forwards a packet to the base station (BS), reducing long-range transmissions. The novelty claimed here is not grid partitioning alone. To the best of authors' knowledge, prior LEACH variants did not combine a fixed fine grid for measurement-coverage status, an independently configurable coarse grid that enforces CH representation, CH-count and counter-reset policies operating at the coarse-grid level, and lifetime metrics defined for both spatial resolutions. This work proposed and analyzed G²LEACH as an integrated dual-grid model.

The Related Work section reviewed existing LEACH modifications with emphasis on spatial structuring. The Proposed Solution section described the proposed G²LEACH algorithm, energy model, and simulation results. The mechanisms responsible for the observed improvements

are then analyzed. The Conclusions section summarizes the findings and outlines future work.

RELATED WORK

LEACH variants can be grouped by their primary objective. Energy-uniformity variants modify the threshold function or election logic LEACH-E [9], LEACH-C [10], LEACH-TLC [11], while LEACH-DCHS [12] weights the election by node-to-BS distance. Mobility-aware variants such as LEACH-M [13] and LEACH-Mobile [14] support node or sink mobility, and security-oriented variants SLEACH [15] and RLEACH [16] add cryptographic or attack-detection layers. Multi-hop extensions M-LEACH [17], Multi-Hop LEACH [18], and TL-LEACH [19] relay traffic through intermediate CHs. Energy-aware clustering protocols beyond the LEACH family include SEP [20] for heterogeneous networks, HEED [21] for hybrid election criteria, threshold-driven TEEN [22] and APTEEN [23], and chain-based PEGASIS [24]. The closest prior work concerns spatial structuring. LEACH-G-K [25] combines grid-size selection with K-means clustering, AG-LEACH [26] dynamically adapts and merges grid cells, and S-LEACH [27] uses fixed sectors centered on the BS with residual-energy-based CH selection. Zone-based IFZ-LEACH [28] and FZ-LEACH [29] organize far and near regions, while Cell-LEACH [30] uses hexagonal cells and multi-hop forwarding. These methods use a single partition for cluster formation, adapt the partition to the topology, or define hierarchy through forwarding paths. G²LEACH instead retains two co-registered but functionally independent spatial resolutions. Micro-areas represent measurement continuity, whereas GHAs constrain CH availability and count. The geometry remains fixed during operation and is independent of the instantaneous CH topology. This distinction also enables the proposed FMAD, HMAD, FGHAD, and HGHAD metrics, which quantify coverage degradation at both resolutions.

PROPOSED SOLUTION

System model

Let N denote the set of nodes n deployed over an area A , and let (x_n, y_n) represent the coordinates of node n . We further introduce a micro-area grid

that partitions the area A into an $M_r \times M_c$ grid of sub-areas, where a_{ij} denotes a micro-area with $i = 1, \dots, M_r$ and $j = 1, \dots, M_c$. Each micro-area represents the smallest spatial unit within which at least one node should remain operational to maintain measurement coverage. Consequently, the set of nodes within a micro-area is defined as $N_{ij} = \{n : (x_n, y_n) \in a_{ij}\}$. This model allows for the formal assignment of each node to a uniquely determined micro-area of the grid, which provides the foundation for subsequent node grouping, for instance, in the clustering process.

The grid of head areas (GHA) constitutes a higher-level grid the resolution of which defines the density of cluster heads serving the nodes located within specific micro-areas. This grid serves as a superordinate structure relative to the micro-areas a_{ij} and partitions the entire area A into larger units with a resolution of $G_r \times G_c$. The entire area A is defined as a union of pairwise disjoint higher-level areas A_{pq} , where $p = 1, \dots, G_r$ and $q = 1, \dots, G_c$, with S_{pq} being the set of index pairs (i, j) of micro-areas a_{ij} contained within the GHA area A_{pq} . Consequently, the set of nodes belonging to the higher-level area A_{pq} is defined by Equation 1.

$$N_{pq} = \{n : n \in N_{ij}, (i, j) \in S_{pq}\} \quad (1)$$

The GHA grid resolution defines the density of cluster head deployment across the entire network and thereby determines the number of nodes assigned to each cluster head. Furthermore, each Head Area constitutes a local management region in which one or more nodes serve as cluster heads, managing all nodes belonging to the micro-areas assigned to that unit. The concept of the multi-layered grid is illustrated in Figure 1. The spatial structuring based on micro-areas a_{ij} as elementary units, enables local evaluation of node availability, energy reserve, and measurement continuity. These cells remain fixed throughout a run and do not define clusters directly. Instead, the coarser GHA grid constrains CH representation while the identities of individual CHs and their member nodes continue to change. Separating the fixed measurement scale from the fixed CH-management scale is the central structural distinction of the proposed model.

Algorithm

Classical LEACH (Figure 2a) operates in two alternating phases (setup and steady-state) and rotates the CH role to distribute energy consumption uniformly across the network. Two limitations

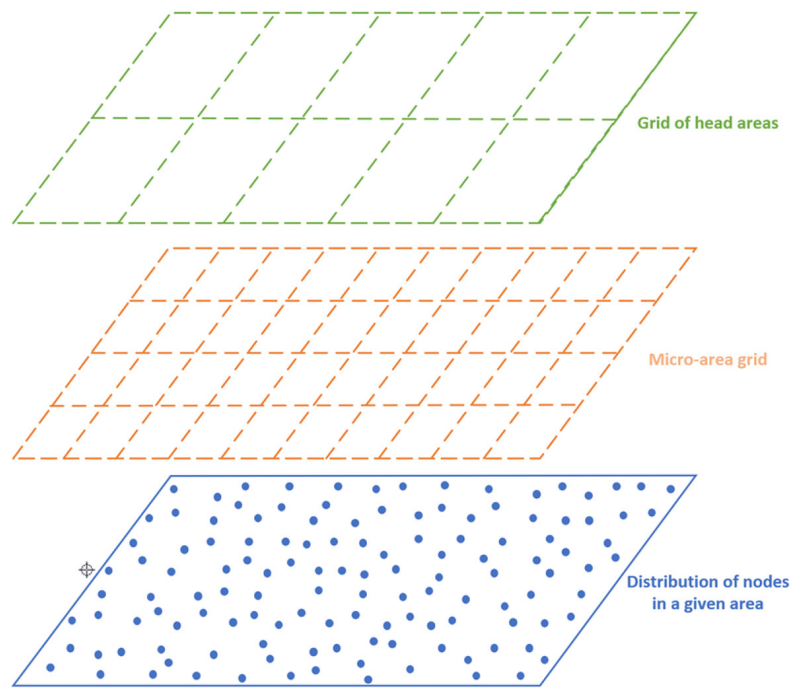


Figure 1. Multi-layered grid: GHA grid (coarse-grained, 5×5) and micro-area grid (fine-grained, 20×20)

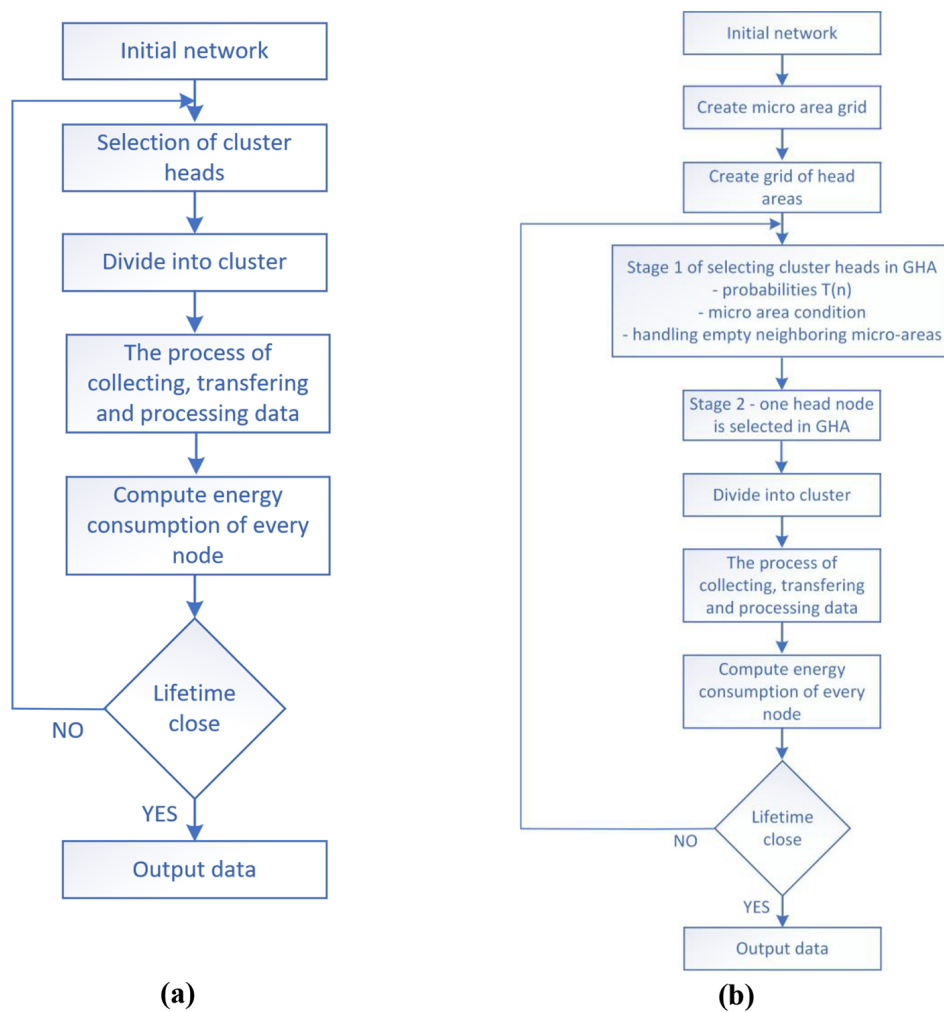


Figure 2. (a) Classical LEACH algorithm; (b) Proposed G²LEACH baseline configuration

motivate the implemented modifications: (i) random CH selection can leave entire regions without a local CH, forcing peripheral nodes to transmit over long distances and depleting them rapidly, and (ii) the protocol has no notion of geometrically defined management regions, which are essential for the applications discussed in the Introduction section. The adopted G²LEACH (Figure 2b) addresses both limitations through a two-level spatial grid and a per-sector coverage guarantee.

Like classical LEACH, the proposed solution alternates a setup phase and a steady-state phase. In the setup phase, for each qualifying node in A_{pq} a random value is drawn and compared with the threshold $T(n)$ defined in Equation 2 [8].

$$T(n) = \begin{cases} \frac{p}{1-p*(r \bmod \frac{1}{p})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where: p is the desired CH percentage (e.g., 0.1), r is the current round, and G is the set of nodes that have not served as CH in the last $1/p$ rounds.

A node becomes a CH if its drawn value is below $T(n)$, otherwise it joins the nearest existing cluster. The steady-state phase uses TDMA/CDMA scheduling, and after a fixed number of packets, the system returns to setup.

A pure stochastic election admits a non-zero probability that no node satisfies the threshold in a given round, resulting in an empty round with no data delivery. To eliminate this confounding effect across all evaluated configurations (including the

CLASSIC baseline), an Emergency Cluster Head (E-CH) mechanism is added. When the standard election produces no leader, the node with the longest interval since its last CH service is deterministically nominated. This guarantees transmission continuity and favors a node that has rested longest since its previous CH service. G²LEACH adds spatial structuring on two levels. Micro-areas control local measurement density, whereas GHAs ensure uniform CH coverage at the network scale. After the baseline election, Option 1 applies a second probabilistic pass, whereas Option 2 applies deterministic GHA-level reduction.

Stage 1 – Cluster head candidates within GHA (L1)

The standard election runs node-by-node using the threshold $T(n)$, restricted to nodes not active in the previous $1/p$ rounds. Two additional conditions apply. A node may not become a CH if it is the only active node in its micro-area, which would waste energy on a degenerate single-node cluster. In addition, the node closest to an empty neighboring micro-area is reserved as a sensor to preserve measurement coverage near the depleted area (Figure 3).

Unlike the global E-CH mechanism (which fires only when no CH is elected anywhere), G²LEACH enforces coverage at the GHA level. If a probabilistic election yields no candidate within a particular GHA sector, the node in that sector with the longest interval since its last CH role is deterministically assigned. This guarantees that

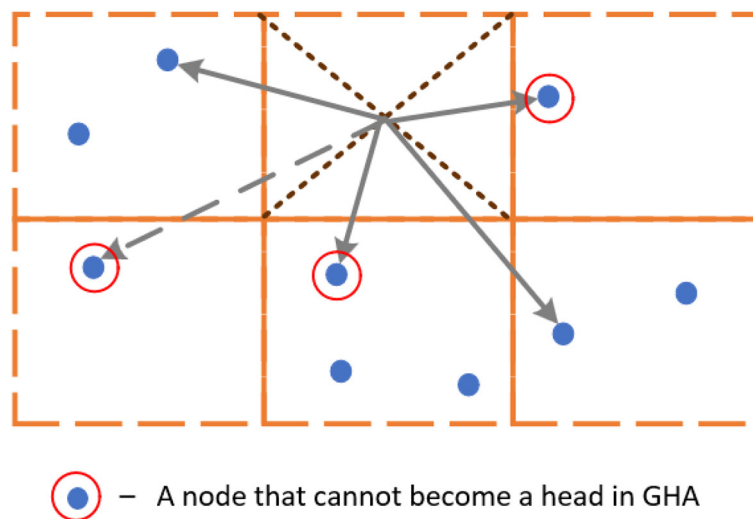


Figure 3. Handling of empty neighboring micro-areas. Nodes closest to empty cells (marked with a red border) cannot become cluster heads, ensuring continued measurements in the proximity of depleted areas

every active GHA sector has at least one CH. In the baseline G²LEACH configuration, the L1 candidates serve directly as the final CHs. Option 1 adds a second probabilistic election stage, whereas Option 2 adds a deterministic GHA-reduction stage (Figure 4).

Extended CH selection within GHA

Option 1 subjects each L1 candidate to a second probabilistic pass with threshold $T(n)$. GHA enforcement guarantees at least one L2 leader per sector containing L1 candidates. Option 2 instead performs no second draw; it deterministically reduces the initially elected CHs to at most one per active GHA sector.

Option 1 – multiple CHs per GHA permitted (the second draw may leave more than one leader per sector).

Option 2 – single CH per GHA. If more than one CH is initially elected in a sector, only the most “rested” node (with the longest interval since its last CH role) is kept. The others revert to ordinary nodes.

Option 1 distributes the leader load across multiple nodes (improves intra-sector load balance in dense sectors) at the cost of more long-range CH-BS transmissions. Option 2 minimizes long-range transmissions but concentrates the energy burden on a single leader. The rest-based selection criterion partially mitigates this.

After the election, every non-CH joins the nearest CH (Euclidean distance), and each CH aggregates and forwards a single packet to the BS. The two counter-reset variants are defined below.

Variant 1 – reset the CH election counter for every node in the L1 candidate set, whether or not it was promoted to L2.

Variant 2 – reset only for nodes that actually served as L2. L1 candidates not promoted have their counter restored to the pre-election value and do not receive the ordinary non-CH increment in that round.

Summary of algorithm configurations

The combination of two options (Option 1 and Option 2) with two counter reset variants (Variant 1 and Variant 2) yields four G²LEACH configurations, which together with the baseline G²LEACH and the classical LEACH protocol constitute the following six evaluated algorithms. 1. CLASSIC – the standard LEACH protocol

without any spatial constraints. Cluster heads are elected purely through the probabilistic threshold $T(n)$ with no regard for spatial distribution. The implementation includes the Emergency Cluster Head (E-CH) mechanism described in the Algorithm section, which guarantees at least one CH per round. This

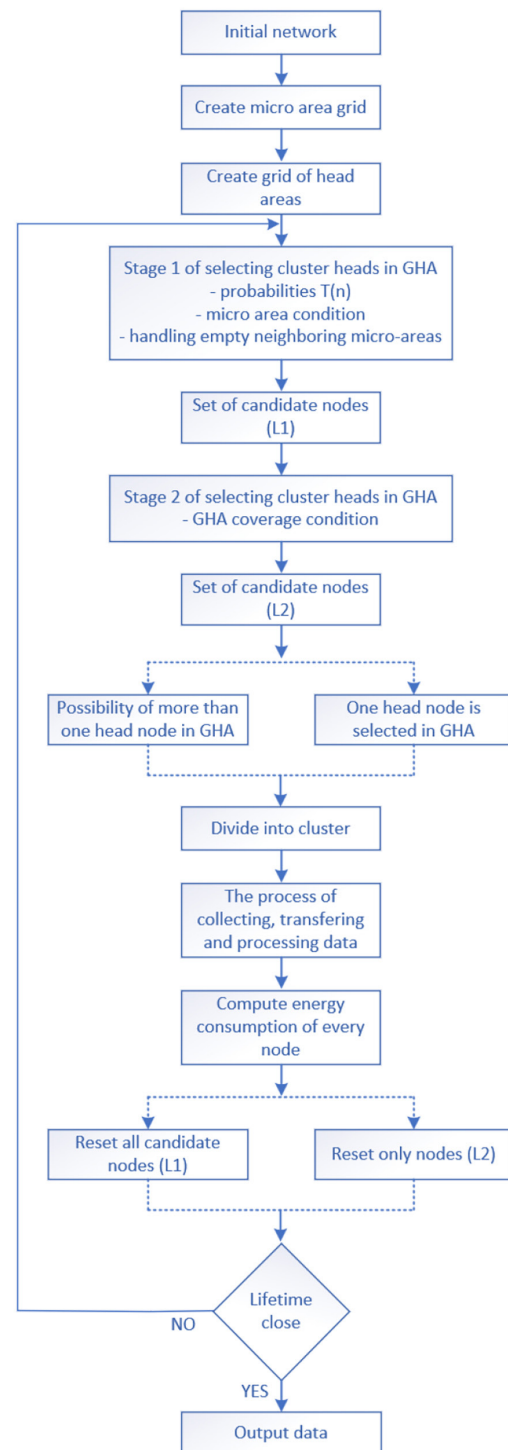


Figure 4. G²LEACH extended with Option 1/2 and Variant 1/2

serves as the baseline for all comparisons.

2. G²LEACH – the baseline variant of the proposed algorithm. It introduces the dual-layer spatial grid (micro-area grid and GHA grid), the node reservation mechanism for empty micro-areas, and the GHA coverage enforcement guaranteeing at least one CH per sector. Multiple CHs per GHA sector are permitted. All elected CHs receive the counter reset.
3. G²LEACH-o1-v1 – Option 1 with Variant 1. A two-stage election process is employed: Stage 1 produces L1 candidates using the base G²LEACH mechanism, and Stage 2 selects final L2 leaders from L1 through a second probabilistic pass with GHA enforcement. Multiple L2 leaders per sector are permitted. In Variant 1, all L1 candidates receive the counter reset, regardless of whether they were promoted to L2. This acknowledges their participation in the election process.
4. G²LEACH-o1-v2 – Option 1 with Variant 2. The same two-stage election as o1-v1, but only the final L2 leaders receive the counter reset. L1 candidates not promoted to L2 have their counter restored to the pre-election value without the ordinary non-CH increment in that round. This implementation reserves the reset privilege for nodes that actually served as CH.
5. G²LEACH-o2-v1 – Option 2 with Variant 1. The base G²LEACH election is followed by a GHA reduction phase that limits each sector to at most one CH – the node with the highest pre-election counter value. This minimizes long-range CH-BS transmissions while retaining one CH in each active GHA sector. In Variant 1, all initially elected CHs (including those subsequently demoted) retain their counter reset.
6. G²LEACH-o2-v2 – Option 2 with Variant 2. The same GHA reduction as o2-v1 is applied, but demoted CHs have their counter restored to the pre-election value without the ordinary non-CH increment in that round. Only the surviving CH in each sector receives the full reset. This configuration tests whether reserving the reset for nodes that actually performed the CH role can extend the stable period without concentrating the later energy burden excessively.

The configurations differ in two principal dimensions. Option 1 permits multiple CHs to remain in a GHA sector, whereas Option 2 retains at most one. Variant 1 preserves the counter reset for all initially selected candidates, whereas

Variant 2 restores the pre-election counter for the candidates that do not become final CHs. These choices affect CH rotation, energy use, network lifetime, and spatial redundancy.

Energy model

The simulation employs the standard energy model for sensor networks (“First Order Radio Model”), which accounts for the nonlinear dependence of energy consumption on transmission distance [8, 31]. The algorithm automatically switches between two models depending on the distance to the receiver (relative to the threshold $d_0 \approx 87.7$ m). The Free Space model assumes direct line of sight and is applied for short-range communication. In this case, energy increases proportionally to the square of the distance. The second model (Multipath) is employed for long-range communication and accounts for signal fading due to ground reflections and obstacles. In this case, energy increases proportionally to the fourth power of the distance. Energy consumption in the network is calculated based on the processes of transmission, reception, and data fusion, and may differ depending on the node’s distance. Each transmitting node incurs a transmission energy cost denoted as E_T . Equation 3 defines this cost.

$$E_T = \begin{cases} E_{TX} \times L + \varepsilon_{mp} \times L \times d^4, & \text{if } d \geq d_0 \\ E_{TX} \times L + \varepsilon_{fs} \times L \times d^2, & \text{if } d < d_0 \end{cases} \quad (3)$$

where: E_{TX} – energy consumed per bit of transmitted data, L – the amount of data transmitted, $\varepsilon_{mp}/\varepsilon_{fs}$ – depend on the transmitter amplifier model, ε_{fs} is used for the free-space model (d^2), while ε_{mp} is used for the multipath model (d^4), d – the Euclidean distance between the transmitter and the receiver, d_0 – the distance threshold.

The Threshold Distance d_0 is not an arbitrary constant but rather derives from the physical equalization of the energy costs of both propagation models. It is the point at which the energy consumed under the Free Space model (d^2) equals that under the Multipath model (d^4). Equating these terms gives Equation 4.

$$d_0 = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} \quad (4)$$

Additionally, a receiving node incurs a reception energy cost denoted as E_R . Equation 5 defines this cost.

$$E_R = (E_{RX} + E_{DA}) \cdot L \quad (5)$$

where: E_{RX} – energy consumed per bit during data reception, E_{DA} – energy consumed in the data fusion process.

Simulations

The experiments use controlled synthetic inputs, rather than field measurements. Each scenario contains 1200 homogeneous, stationary sensors. Three coordinates were sampled uniformly once within each of the 400 cells of a 20×20 micro-area grid, then stored and reused for every algorithm and repetition. This stratified deployment guarantees identical initial measurement coverage and prevents deployment variation from confounding the CH-election comparison. A 5×5 GHA grid groups 4×4 micro-areas per sector, and the BS is fixed at the center of the monitored area.

The radio parameters in Table 1 follow the First Order Radio Model and values commonly used with LEACH [8, 31]. The 1000×1000 m scale was selected as a long-range stress case in which most CH-BS transmissions enter the multipath regime, whereas the 100×100 m scale keeps all CH-BS distances below d_0 and isolates the effect of spatial CH organization under free-space propagation. Node count, logical grid dimensions, energy

budget, packet size, and election probability are held constant across the two scales.

The algorithms were implemented in a custom Python 3.11.10 simulator using NumPy 2.1.1, Matplotlib 3.9.2, and Pillow 10.4.0 on an arm64 macOS platform. 12 worker processes were used only to parallelize independent runs. Each configuration was executed 100 times with the same stored deployment and varying stochastic CH-election draws. Lifetime metrics were calculated separately for every run and then summarized as the arithmetic mean $\pm$ sample standard deviation. Computing event metrics separately for each run avoids conflating the earliest FND and latest LND observations, which can occur when thresholds are extracted from an ensemble-averaged curve.

The scope is a controlled comparison of clustering geometry. The model assumes static homogeneous nodes, symmetric error-free links, ideal data aggregation, and no interference, collision, mobility, synchronization, or control-packet cost. These assumptions are retained across all configurations to isolate the proposed spatial mechanism. Evaluation under realistic radio and traffic traces is left for future work.

Scenario 1 (1000×1000 m) is a long-range stress case in which most CH-BS transmissions exceed the threshold $d_0 \approx 87.7$ m, activating the multipath model (d^4). Scenario 2 (100×100 m) represents a compact deployment in which every direct CH-BS transmission falls within the d_0 range and therefore uses the free-space model for

Table 1. Simulation parameters

Parameter	Scenario 1 (1000 m)	Scenario 2 (100 m)
Network area	1000×1000 m	100×100 m
BS position	(500, 500)	(50, 50)
Number of nodes	1200	1200
Micro-area grid	20×20 (50×50 m)	20×20 (5×5 m)
GHA grid	5×5 (200×200 m)	5×5 (20×20 m)
Nodes per micro-area	3	3
E_0 (initial energy)	1 J	1 J
$E_{elec} = E_{TX} = E_{RX}$	50 nJ/bit	50 nJ/bit
E_{DA} (data fusion)	5 nJ/bit	5 nJ/bit
ϵ_{fs}	10 pJ/bit/m ²	10 pJ/bit/m ²
ϵ_{mp}	0.0013 pJ/bit/m ⁴	0.0013 pJ/bit/m ⁴
Packet size (L)	8000 bits	8000 bits
p (CH percentage)	0.1 (10%)	0.1 (10%)
Max. rounds	1800	1800
Number of repetitions	100	100

Note: E_0 denotes the initial node energy, E_{elec} represents the energy dissipated in the transceiver electronics.

this long-range link (d^2). The paired scales expose how the spatial grid behaves with and without multipath amplification on the CH-BS link.

The comparison covers the six configurations described in the Summary of Algorithm Configurations section: CLASSIC, G²LEACH, G²LEACH-o1-v1, G²LEACH-o1-v2, G²LEACH-o2-v1, and G²LEACH-o2-v2. Each configuration is evaluated in 100 independent CH-election runs for both spatial scales.

Network lifetime

Network lifetime is evaluated with the following standard metrics:

- FND (First Node Dead) – the round in which the first node exhausts its energy. This marks the end of the stable period.
- HNA (Half Nodes Alive) – the round in which 50% of nodes have depleted their energy. This marks the midpoint of degradation.
- LND (Last Node Dead) – the round in which the last node dies, marking the total operational time of the network.
- FMAD (First Micro-Area Dead) – the round in which the first micro-area loses all its nodes, marking the onset of coverage gaps.
- HMA (Half Micro-Areas Dead) – the round in which 50% of initially active micro-areas have lost all their nodes, marking the midpoint of spatial coverage degradation.
- FGHAD (First GHA Dead) – the round in which the first GHA sector loses all its nodes, marking the onset of sector-level coverage failure.
- HGHAD (Half GHA Dead) – the round in which 50% of initially active GHA sectors have lost all their nodes, marking the midpoint of sector-level coverage loss.

Note that the last micro-area and last GHA sector invariably die in the same round as the last node (LND), since a single surviving node constitutes both an active micro-area and an active

GHA sector. Therefore, separate LMAD and LGHAD metrics are not reported.

The network lifetime results for the 1000 × 1000 m scenario are presented in Table 2.

Run-level analysis yielded FND = 1 in all 100 runs for CLASSIC, baseline G²LEACH, o1-v2, and o2-v2. For o1-v1 and o2-v1, FND = 1 occurred in 99 and 97 runs, respectively, and FND = 2 in the remaining runs. The corresponding mean FND values were 1.01 and 1.03 rounds.

The mean node-to-BS distance in the fixed deployment is 382.8 m. The CH-BS transmission cost evaluated at this distance is approximately 0.224 J. Because the multipath cost scales with the fourth power of distance, this value is not the mean across all node positions, which is approximately 0.406 J. For an 8000-bit packet, CH-BS transmission in the multipath regime costs $E_{\text{CH-BS}}(d) = 0.0004 + 1.04 \times 10^{-11}d^4$ J before reception and aggregation. This cost exceeds the complete 1 J initial budget at $d \geq 556.8$ m. In the fixed deployment, 132 of 1200 nodes (11.0%) lie beyond this distance. When one of these peripheral nodes becomes CH, it can die in the first round from the BS transmission alone. Reception and aggregation only increase the cost. Mean first-round death counts were 12.8 ± 3.3 for CLASSIC, 13.6 ± 3.3 for baseline G²LEACH, and 2.9-3.1 for the four extended variants.

Therefore, FND cannot discriminate the methods at this extreme scale. HNA and LND provide a more informative comparison. The Option 2 variants reach a mean HNA of 116.2-116.4 rounds versus 11.0 for CLASSIC (+956% to +958%), while all proposed variants increase mean LND from 444.6 to 830.4-932.6 rounds (+87% to +110%). Mean FGHAD also rises from 11.0 to 62.3-62.7 rounds for Option 2, showing delayed sector-level coverage failure. In Figure 6, classical LEACH shows an abrupt drop of active nodes at the start of the simulation, driven by random CH placement that forces peripheral nodes to

Table 2. Network lifetime comparison (1000 × 1000 m), mean ± sample SD over 100 runs

Algorithm	FND	HNA	LND	FMAD	HMA	FGHAD	HGHAD
CLASSIC	1.00 ± 0.00	11.0 ± 0.0	444.6 ± 82.5	3.2 ± 1.0	11.0 ± 0.0	11.0 ± 0.0	15.0 ± 5.2
G ² LEACH	1.00 ± 0.00	59.5 ± 0.6	932.6 ± 48.3	18.4 ± 2.9	72.0 ± 1.1	35.0 ± 0.8	97.1 ± 1.6
G ² LEACH-o1-v1	1.01 ± 0.10	78.3 ± 1.7	898.0 ± 57.8	20.0 ± 4.0	98.4 ± 2.2	54.8 ± 4.3	124.4 ± 4.6
G ² LEACH-o1-v2	1.00 ± 0.00	64.9 ± 0.8	878.7 ± 46.8	15.0 ± 3.7	78.1 ± 1.3	39.9 ± 1.5	103.8 ± 2.4
G ² LEACH-o2-v1	1.03 ± 0.17	116.2 ± 0.9	853.4 ± 75.3	35.0 ± 11.3	134.5 ± 5.1	62.7 ± 0.7	171.3 ± 1.5
G ² LEACH-o2-v2	1.00 ± 0.00	116.4 ± 0.6	830.4 ± 49.6	34.9 ± 10.6	127.6 ± 2.3	62.3 ± 0.5	168.1 ± 1.5

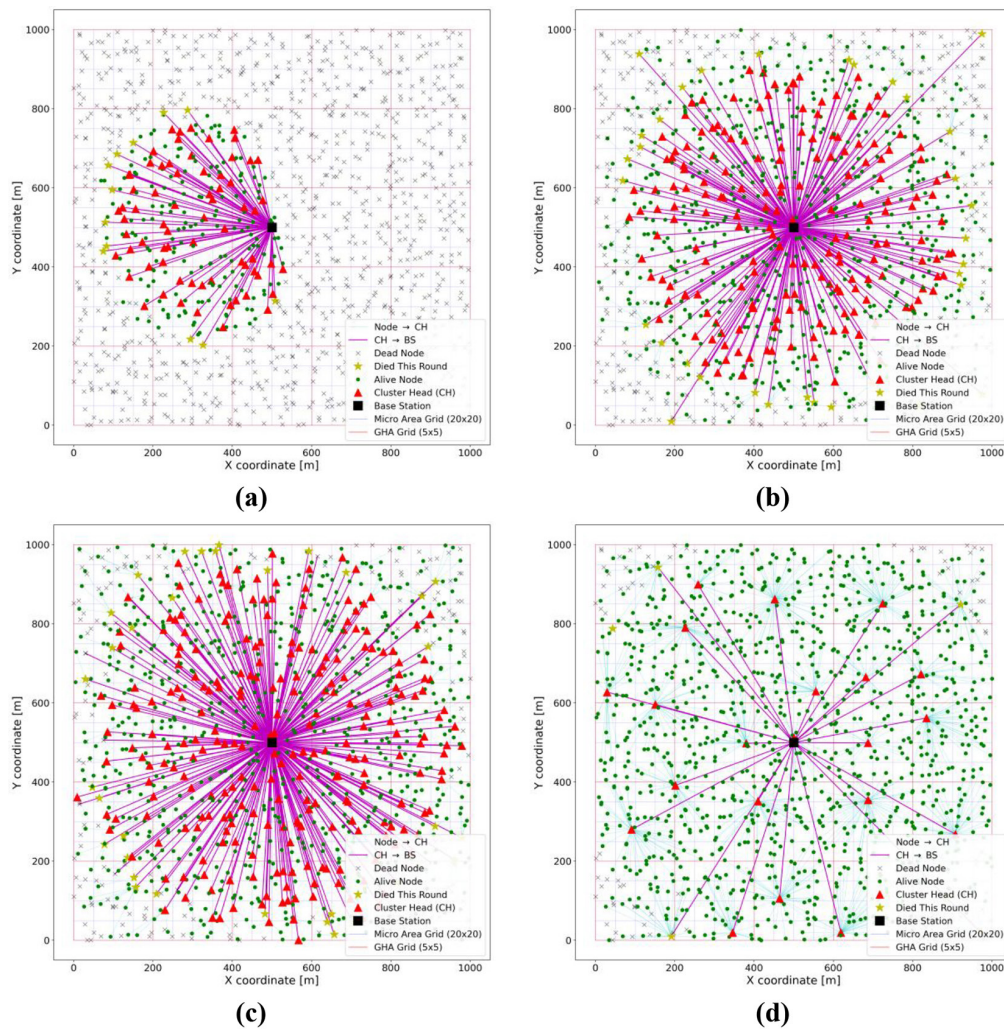


Figure 5. Network state at round 30 (1000 × 1000 m): (a) CLASSIC; (b) G²LEACH; (c) G²LEACH-o1-v1; (d) G²LEACH-o2-v2

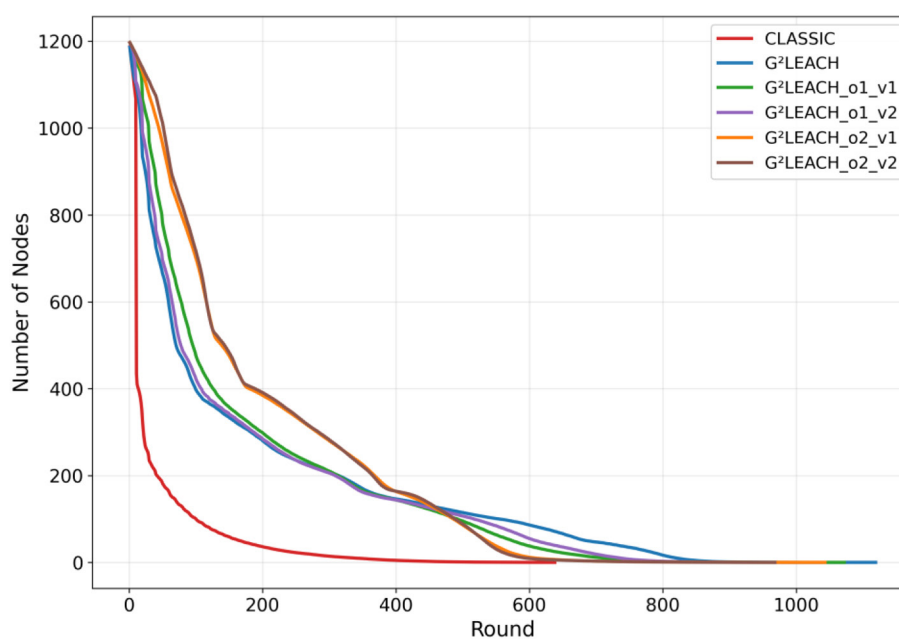


Figure 6. Number of active nodes vs. rounds (1000 × 1000 m, averaged over 100 simulations)

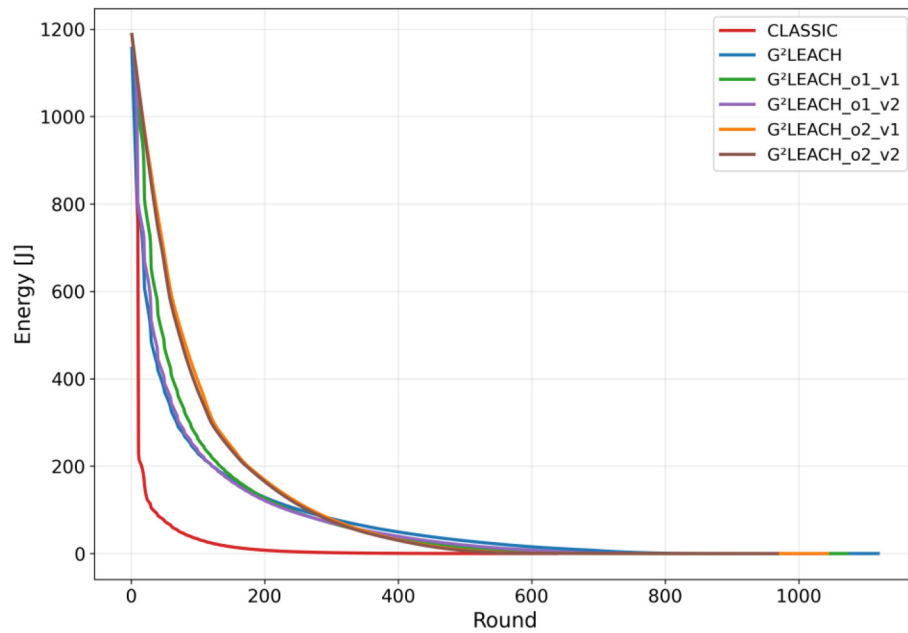


Figure 7. Total network energy vs. rounds (1000×1000 m)

transmit over long distances. G²LEACH variants maintain a substantially larger active population throughout, with G²LEACH-o2-v2 exhibiting the smallest decline gradient. The rapid peripheral depletion visible for classical LEACH around round 30 is illustrated in Figure 5. Dead nodes concentrate at the periphery, and active nodes survive mainly near the BS. Panels (b)-(d) show the corresponding state for G²LEACH, G²LEACH-o1-v1, and G²LEACH-o2-v2, where active nodes remain distributed throughout the monitored area.

The classical LEACH curve also declines most rapidly in the total network energy analysis (Figure 7), reflecting uneven energy consumption across nodes. The proposed G²LEACH variants exhibit a more linear and slower energy decline, with G²LEACH-o2-v2 retaining the largest energy reserve until the end of the simulation.

The “measurement holes” effect of classical LEACH is reflected in the monotonic decline of average energy across active micro-areas (Figure 8 – for comparison purposes, the micro-area

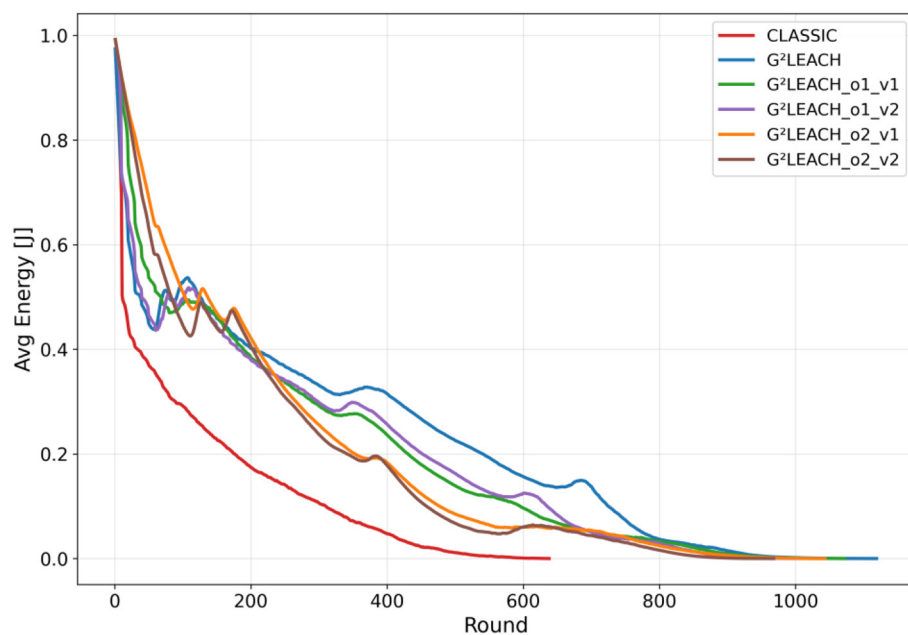


Figure 8. Average energy in active micro-areas (1000×1000 m)

structure was superimposed on classical LEACH, which does not natively use it). G²LEACH variants maintain higher and smoother trajectories, reflecting improved local energy balancing.

A temporary increase in average energy is visible in Figures 8 and 9. Two aggregation effects cause this pattern. The death of low-energy nodes raises the average among the survivors, and the deactivation of entire micro-areas or GHAs (no active nodes left) increases the average across the remaining active areas. Figure 9 shows that the

GHA structure extends the lifetime of critical network elements. G²LEACH-o2-v2 preserves GHA resources by limiting the number of leaders and locally optimizing their selection.

Figures 10 and 11 confirm that the spatial architecture maintains coverage continuity. Classical LEACH loses most micro-areas and GHA sectors within ~30 rounds, while G²LEACH variants remain operationally stable for an order of magnitude longer at both the micro- and macro-area level. Figure 12 shows the number of cluster

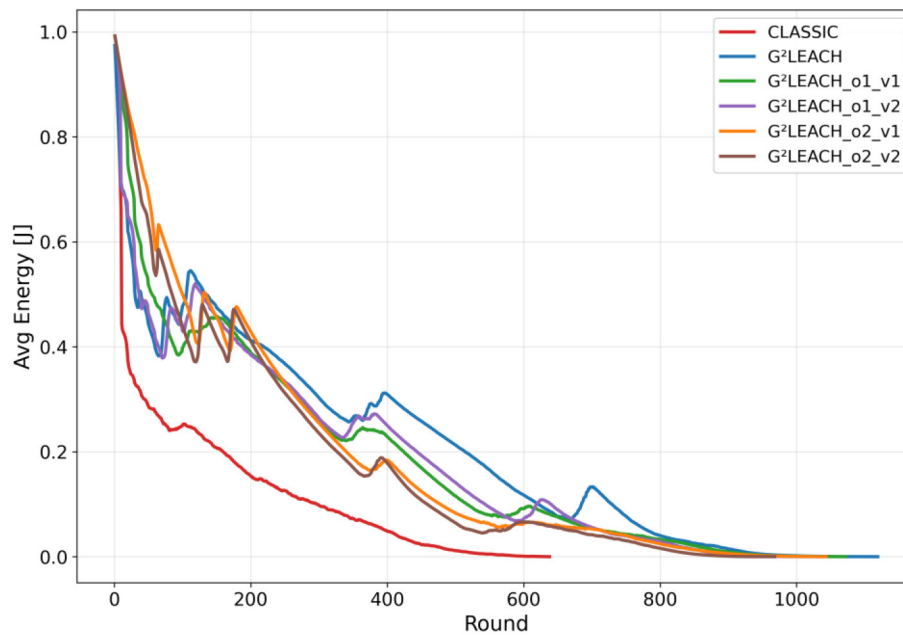


Figure 9. Average energy in active GHA sectors (1000×1000 m)

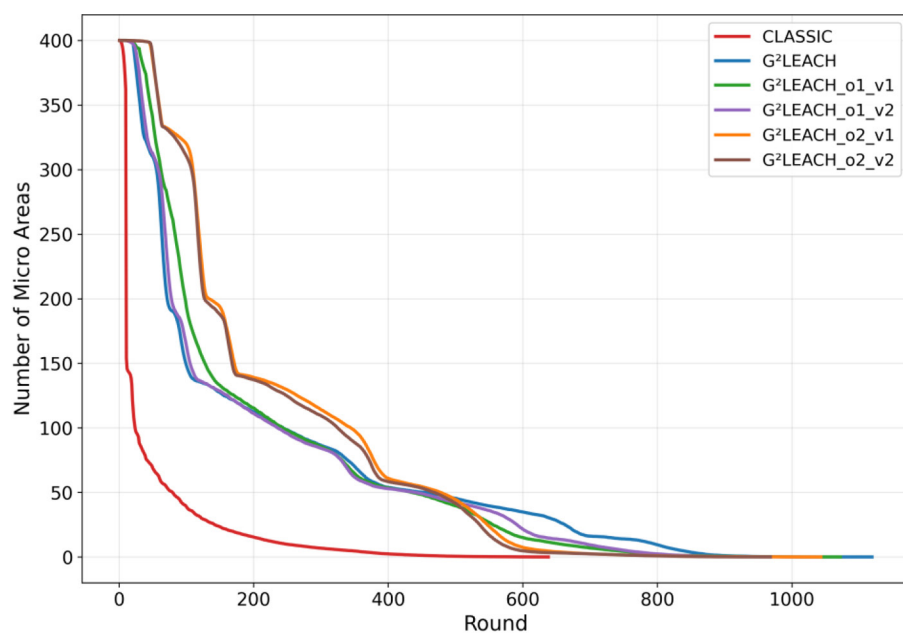


Figure 10. Number of active micro-areas vs. rounds (1000×1000 m)

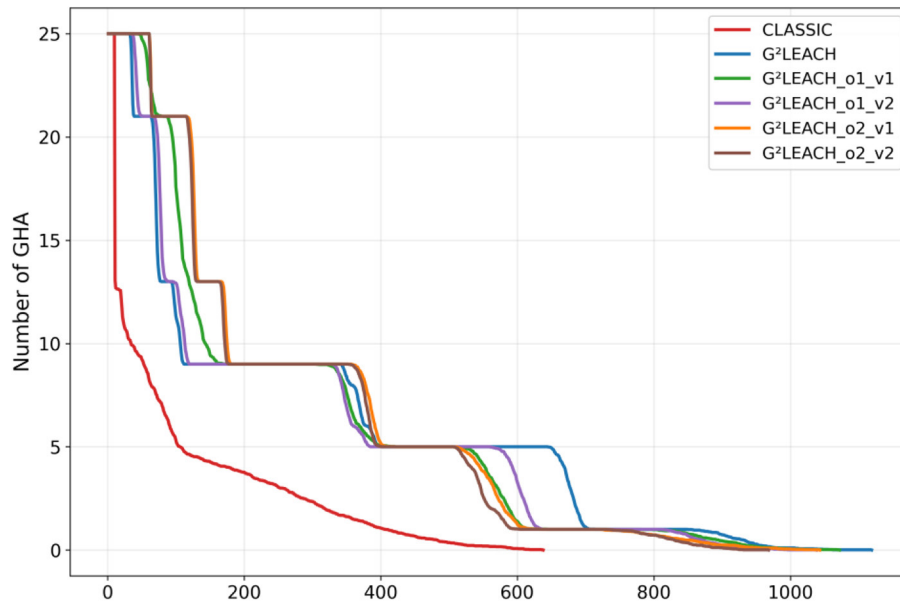


Figure 11. Number of active GHA sectors vs. rounds (1000 × 1000 m)

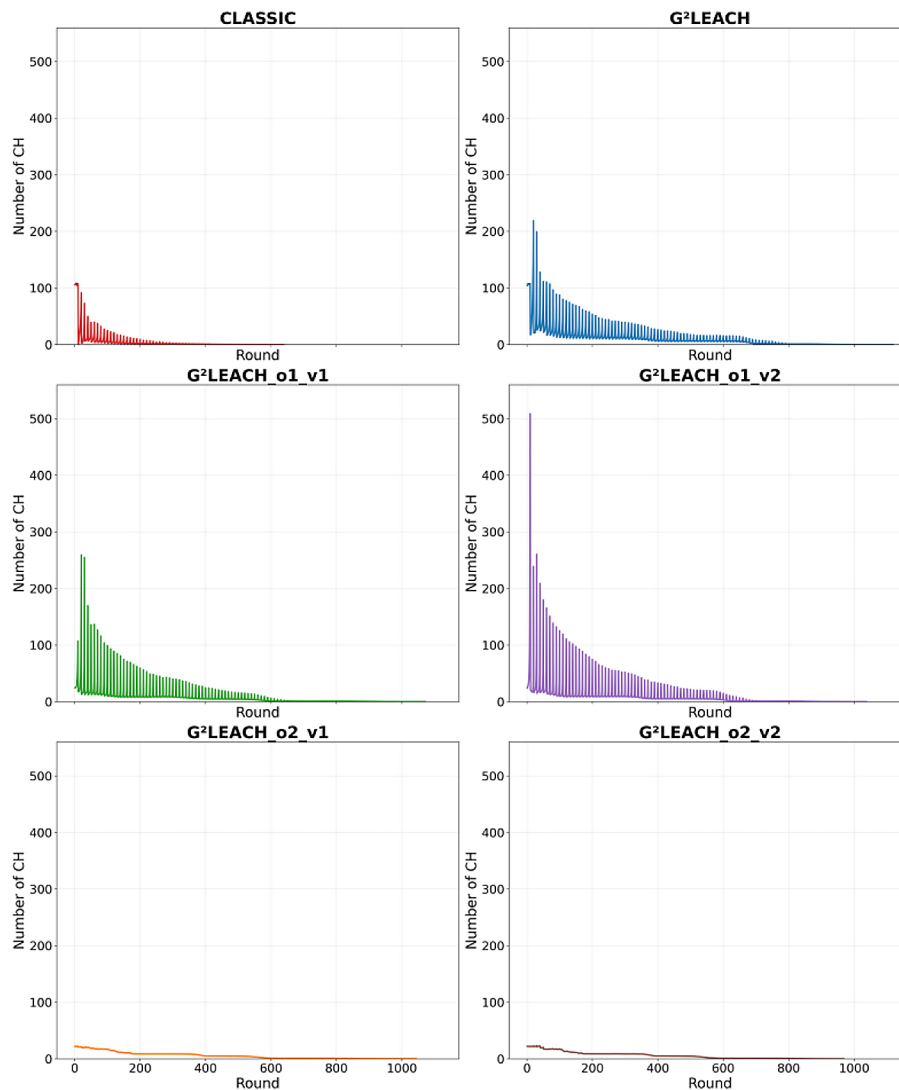


Figure 12. Number of cluster heads (CH) per round (scenario 1000 × 1000 m).
Each algorithm is presented on a separate panel

heads per round. Across run-level averages, CLASSIC uses 6.89 ± 0.49 CHs per round. The baseline G²LEACH, o1-v1, and o1-v2 configurations use 13.41 ± 0.63 , 9.62 ± 0.56 , and 12.12 ± 0.56 , respectively. The visible periodic oscillation is inherent to the $T(n)$ threshold because recent CHs are excluded for the remainder of the $1/p$ -round epoch. Option 2 suppresses the oscillation and yields 6.78 ± 0.50 and 6.83 ± 0.35 CHs per round by enforcing at most one CH per active GHA sector.

Energy consumption analysis

Table 3 presents the energy efficiency metrics for the 1000×1000 m scenario. CLASSIC depletes 2.796 ± 0.543 J per executed round on average, compared with 1.290 ± 0.064 J for baseline G²LEACH and 1.342 – 1.450 J for the four extended variants. Option 2 reaches 50% of initial network energy after 56.7 – 59.7 rounds, compared with 11.0 rounds for CLASSIC. The improvement follows from limiting long-range CH-BS transmissions, which dominate energy consumption at this scale.

Compact deployment scenario (100×100 m)

To isolate the contribution of the spatial grid mechanism from the energy model, the experiment was replicated in a compact 100×100 m deployment retaining the same 1200 nodes, 1800-round budget, and parameter set as Scenario 1. The maximum CH-BS distance (~ 70 m) lies below $d_0 \approx 87.7$ m, so all direct CH-BS transmissions operate in the free-space regime (d^2), eliminating the multipath term (d^4) that dominated the CH-BS energy budget in the larger scenario. This scale, therefore, reduces propagation amplification and makes the effect of structured cluster-head placement easier to distinguish.

Detailed metrics for this scenario are consolidated in Table 4. The key observation is that G²LEACH-o2-v2 achieves the longest mean

stable period, with $FND = 948.8 \pm 19.9$ rounds compared with 637.9 ± 69.4 for CLASSIC (+48.7%). Baseline G²LEACH also extends FND to 902.8 ± 30.8 rounds (+41.5%). These gains do not imply uniform superiority. The o2-v2 variant reduces HNA, LND, FGHAD, and HGHAD relative to CLASSIC, as discussed below. Option 2 reduces the average CH count from 72.64 ± 1.17 for CLASSIC to 21.91 ± 0.58 and 22.76 ± 0.35 , demonstrating a strong energy-stability trade-off in the compact regime.

Lifetime extension mechanisms

The observed improvements stem from three complementary mechanisms: (i) GHA coverage enforcement guarantees at least one CH per sector, reducing extreme intra-cluster distances and the energy holes that random CH selection can leave above d_0 , where the multipath model (d^4) dominates; (ii) micro-area constraints prevent degenerate single-node clusters where the sole survivor would otherwise transmit directly to the BS without aggregation gain, (iii) node reservation near empty micro-areas keeps the closest neighbor acting as a sensor instead of being promoted to CH, preserving measurement coverage as nodes die.

Impact of two-stage election (Option 1) and GHA reduction (Option 2)

Option 1 applies a second probabilistic filter to the L1 candidate set, reducing long-range CH-BS transmissions while GHA enforcement retains sector representation. Variant 2 restores the counter of L1 candidates not promoted to L2 to its pre-election value; these candidates do not receive the ordinary non-CH increment in that round. In the 1000×1000 m scenario, o1-v1 and o1-v2 reach mean HNA of 78.4 ± 1.7 (+612.3%) and 64.9 ± 0.8 (+489.9%), respectively, compared with 11.0 for CLASSIC. Their mean CH counts are 9.62 ± 0.56

Table 3. Energy efficiency (1000×1000 m), mean $\pm$ sample SD over 100 runs

Algorithm	Mean energy depletion/round [J]	Rounds to 50% energy
CLASSIC	2.796 ± 0.543	11.0 ± 0.0
G ² LEACH	1.290 ± 0.064	21.2 ± 0.4
G ² LEACH-o1-v1	1.342 ± 0.084	36.8 ± 1.3
G ² LEACH-o1-v2	1.369 ± 0.069	28.4 ± 0.5
G ² LEACH-o2-v1	1.417 ± 0.122	59.7 ± 0.6
G ² LEACH-o2-v2	1.450 ± 0.086	56.7 ± 0.4

Table 4. Network lifetime comparison (100 × 100 m), mean ± sample SD over 100 runs

Parameter	CLASSIC	G ² L	o1-v1	o1-v2	o2-v1	o2-v2
FND	637.9 ± 69.4	902.8 ± 30.8	717.7 ± 40.8	818.7 ± 38.8	760.5 ± 31.6	948.8 ± 19.9
HNA	1214.3 ± 1.7	1222.3 ± 1.9	1218.6 ± 3.5	1218.1 ± 2.6	1197.3 ± 3.3	1189.1 ± 1.3
LND	1497.4 ± 25.0	1553.7 ± 35.5	1674.0 ± 52.0*	1614.6 ± 37.1	1735.5 ± 47.7*	1462.2 ± 25.3
FMAD	1079.1 ± 23.0	1062.3 ± 31.0	911.4 ± 48.6	997.5 ± 40.0	954.9 ± 43.7	1041.2 ± 20.6
HMAD	1275.1 ± 3.2	1301.3 ± 3.1	1344.9 ± 4.8	1322.0 ± 4.0	1344.8 ± 5.4	1242.6 ± 2.6
FGHAD	1336.8 ± 14.1	1318.9 ± 15.9	1401.2 ± 21.0	1360.7 ± 16.3	1402.8 ± 26.2	1248.8 ± 9.1
HGHAD	1416.8 ± 7.7	1425.6 ± 12.9	1510.3 ± 15.0	1465.0 ± 14.0	1539.7 ± 19.0	1359.4 ± 9.7

Note: * Restricted LND at the 1800-round observation horizon. Three o1-v1 runs and 16 o2-v1 runs still contained active nodes and were treated as right-censored. The reported means are conservative.

and 12.12 ± 0.56 , versus 13.41 ± 0.63 for baseline G²LEACH. Option 2 enforces at most one CH per active GHA sector. In the large scenario, o2-v1 and o2-v2 achieve mean HNA of 116.2-116.4 rounds (+956% to +958%) and mean FGHAD of 62.3-62.7 rounds (+466% to +470%), while using approximately 6.8 CHs per round (Figure 12), close to CLASSIC but with controlled spatial distribution. The same restriction is not uniformly beneficial in the compact scenario, where long CH-BS links no longer dominate the energy budget.

Quantitative summary

Table 4 reports the run-level mean and sample standard deviation for the compact scenario. The corresponding large-scenario statistics are reported in Table 2. The two scenarios offer complementary perspectives. In the 1000 × 1000 m scenario, multipath cost (d^4) amplifies the benefit of controlled CH placement, and every proposed variant improves HNA, LND, and both spatial degradation scales. In the compact scenario, no configuration dominates all objectives. Baseline G²LEACH improves mean FND by 41.5% and LND by 3.8%. The o2-v1 variant provides the longest restricted LND (+15.9%) and improves FGHAD and HGHAD by 4.9% and 8.7%, but its FND gain is 19.2%. Conversely, o2-v2 provides the best FND gain (+48.7%) while HNA, LND, FGHAD, and HGHAD deteriorate by 2.1%, 2.3%, 6.6%, and 4.0%, respectively. This pattern is consistent with the stricter single-CH and counter-restoration policy, spreading CH duty effectively before the first failure but concentrating responsibility and reducing redundancy after failures begin. Therefore, o2-v2 is preferable when the stable period is the primary objective, not as a universally superior configuration.

CONCLUSIONS

The original contribution of G²LEACH is the integration of two fixed, independently configurable spatial resolutions with distinct functions. Micro-areas represent measurement continuity, GHAs enforce CH representation and count, and the associated FMAD, HMAD, FGHAD, and HGHAD metrics measure degradation at both levels. This geometry remains independent of the instantaneous CH topology, while CH identities continue to rotate through LEACH-style probabilistic election and counter policies.

Across 100 run-level observations per configuration, the large scenario shows no practical FND improvement but substantial gains in mean HNA (+440% to +958%), mean LND (+87% to +110%), and spatial coverage persistence. In the compact scenario, o2-v2 extends mean FND by 48.7% but slightly worsens HNA, LND, FGHAD, and HGHAD, demonstrating that variant selection must follow the operational objective. The evidence supports a fixed dual-grid organization most strongly when long-range multipath transmission dominates. Future work should test mobile or heterogeneous nodes, lossy links, interference, control overhead, and empirical deployment traces.

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