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Accepted for publication in Ad Hoc Networks

https://doi.org/10.1016/j.adhoc.2026.104260

Gateway-Assisted Hybrid Region-Based Multi-Hop Routing for Sustainable IoT Sensor Deployments

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ARTICLE INFO

Keywords:
Cluster-based protocol
Energy-aware routing
Gateway-assisted communication
Network lifetime optimisation
IoT-enabled monitoring
Wireless sensor networks

ABSTRACT

Wireless sensor networks (WSNs) are a cornerstone of internet-of-things (IoT) applications but remain constrained by the limited energy resources of sensor nodes, particularly during data transmission. This paper proposes a hybrid, multi-hop routing protocol, gateway-assisted multi-hop enhanced stable election protocol (M-GESEP), designed to extend network lifetime in WSN-based IoT systems. The sensing field is partitioned into three logical regions: (i) Base station region (BR), (ii) Gateway region (GR), and (iii) Cluster region (CR). A hybrid communication strategy is employed, whereby nodes in BR and GR transmit data directly, while nodes in CR utilise cluster-based communication. This region-aware design reduces long-distance transmissions and balances the forwarding load, thereby minimizing energy consumption. Simulation results demonstrate that M-GESEP significantly enhances network lifetime compared to established baselines, achieving improvements of 74%, 58.2%, 11.1%, 34.5% and 13.3% relative to SEP, EDEEC, ESEP, EAGBRP, and HMGEAR, respectively, under identical settings. The results indicate that integrating gateway-assisted multi-hop routing with selective clustering provides a practical and efficient solution for energy-aware WSN deployment. The proposed protocol offers a clear, implementable framework for partitioned topologies and informs future developments in large-scale, heterogeneous IoT networks.

1. Introduction

With the rapid advancement of wireless sensing technologies, sensor nodes have become increasingly capable, fueling the pervasive adoption of the internet-of-things (IoT) across a wide range of applications. Modern IoT systems support ambient intelligence, real-time monitoring, automation, and intelligent decision-making, leveraging foundational technologies such as wireless sensor networks (WSNs), cloud computing, advanced sensing techniques, and RFID systems [1]. Among these enabling technologies, WSNs serve a foundational role in bridging the physical and digital domains by facilitating seamless data collection and transmission. Sensor nodes deployed within WSNs gather environmental or contextual information and forward it, either directly or via multi-hop communication paths, to a central sink node or base station (BS) [2]. Their widespread adoption is driven by attributes such as low cost, scalability, and resilience in harsh or remote environments [3]. Despite these advantages, the limited energy resources of battery-powered sensor nodes, particularly during communication with the BS, continue to pose a significant challenge to network longevity.

To address these energy constraints, researchers have extensively investigated energy-efficient routing strategies in WSNs. Evolutionary approaches have been proposed to enhance load balancing and quality of service (QoS) by optimising cluster-head (CH) selection and the utilisation of relay nodes [4]. Protocols aimed at maximising network lifespan through energy-aware clustering have demonstrated that well-structured CH election and optimised relay communication can substantially extend network operation [5]. Similarly, dynamic clustering optimisation methods have been developed for IoT-based WSNs, where cluster structures are adaptively updated to maintain efficiency in dynamic and heterogeneous environments [6]. Specialised approaches have further enhanced energy efficiency in WSNs. For instance, unequal multi-level clustering has been explored for underwater WSNs, where depth-based CH distribution and adaptive data aggregation are critical for coping with the challenging communication environment. Region-based clustering has also been identified as an effective strategy for balancing energy consumption by partitioning the sensing field into zones, thereby reducing communication overhead and improving network scalability [7]. Building on these concepts, refined hierarchical models such as the improved zonal SEP (IZ-SEP) incorporate both energy-awareness and regional constraints into CH election, resulting in more stable and longer-lasting network operation [8].

In addition to clustering strategies, gateway- and relay-assisted communication approaches have been widely recognised for mitigating the so-called "energy hole" problem. By offloading high-energy transmission tasks to more capable

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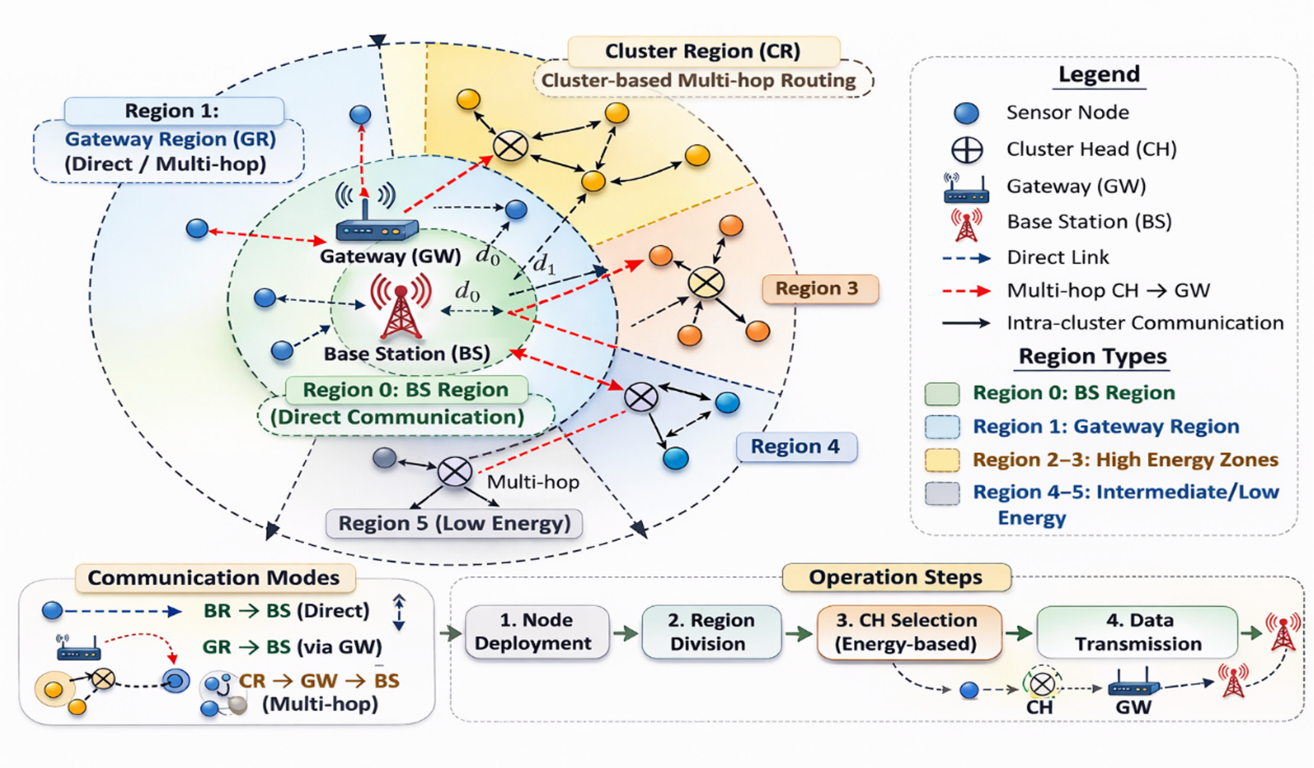

Figure 1: Conceptual illustration of the region-based communication architecture used in the proposed routing protocol.

nodes with extended communication range, gateway-based designs significantly reduce the burden on ordinary sensor nodes and prolong overall network lifetime [9]. Complementary contributions have also highlighted the importance of data aggregation [10] and optimised node placement [11] in conserving energy and enhancing network performance. Building upon these diverse contributions, this paper proposes M-GESEP, a gateway-assisted multi-hop routing protocol with regional clustering specifically designed for IoT-enabled WSNs.

The proposed protocol partitions the sensing field into three logical regions: the base station region (BR), the gateway region (GR), and the cluster region (CR), as illustrated in Fig. 1. A rechargeable gateway node is deployed to relay aggregated data from sensor nodes to the base station, thereby reducing long-distance transmissions and alleviating the energy burden on ordinary sensor nodes. Within the cluster region, cluster heads are elected using a weighted probabilistic approach that considers node location and residual energy, ensuring balanced energy consumption across the network. By integrating gateway-assisted routing with region-based clustering, the proposed M-GESEP protocol effectively reduces communication overhead, mitigates premature energy depletion, and significantly prolongs the overall network lifetime. In sensor networks, efficiently balancing energy consumption while reducing long-distance transmissions remains a critical challenge in heterogeneous IoT-enabled environments. To address these limitations, this work proposes a gateway-assisted hybrid region-based multi-hop routing protocol (M-GESEP) that combines regional network partitioning with energy-aware cluster-head selection and gateway-supported data forwarding.

The main contributions of this paper are summarised as follows:

1. *Hybrid region-based multi-hop routing architecture*: A novel communication framework is proposed that partitions the sensing field into three logical regions: the base station region, the gateway region, and the cluster region, thereby enabling adaptive communication strategies based on node location.
2. *Gateway-assisted energy-aware data forwarding mechanism*: The proposed protocol integrates a rechargeable gateway node to support energy-aware multi-hop data forwarding from distant cluster heads to the base station. Unlike direct CH-to-BS transmission or mobility-dependent approaches, this mechanism minimises long-range transmissions, reduces forwarding overhead, and effectively balances the communication load, leading to an extended stability period and overall network lifetime.

Table 1
List of Abbreviations

Abbreviation	Description
TSEP	Threshold sensitive Stable Election Protocol
TEZEM	Threshold-based Energy-aware Zonal Efficiency Measuring hierarchical routing protocol
CH	Cluster Head
EDEEC	Enhanced Distributed Energy Efficient Cluster ing scheme
ESEP	Enhanced Stable Election Protocol
IoT	Internet of Things
M-GESEP	Gateway-based Multi-hop Enhanced Stable Election Protocol
WSNs	Wireless Sensor Networks
SEP	Stable Election Protocol
ISEPSCMS	Improved Stable Election Protocol with Self Controlled Mobile Sink
EAGBRP	Energy-Aware Gateway Based Routing Protocol
HMGEAR	Heterogeneous Gateway-based EnergyAware multi-hop routing protocol

3. *Energy-aware cluster-head selection strategy*: A weighted probabilistic approach is employed for cluster-head election, considering node location and residual energy to distribute communication overhead and prevent excessive energy depletion in specific nodes.
4. *Comprehensive evaluation under heterogeneous IoT-WSN scenarios*: Extensive simulations under heterogeneous IoT-enabled WSN scenarios demonstrate that M-GESEP consistently outperforms both classical and recent gateway-based routing protocols in terms of network lifetime, stability period, throughput, and residual energy. The results confirm that the proposed region-aware and gateway-assisted design provides scalable and energy-efficient routing for IoT-oriented WSN deployments.

The remainder of this paper is organised as follows. Section 2 provides a comprehensive review of related work and the necessary preliminaries. Section 3 details the design and operation of the proposed M-GESEP protocol. Section 5 presents the simulation setup, performance evaluation, and discussion of results. Finally, Section 6 concludes the paper and outlines potential directions for future work. For clarity, the list of abbreviations in this paper are listed in Table 1.

2. Background and Preliminaries

This section presents a review of the current state-of-the-art and outlines the preliminaries necessary for understanding the proposed methodology.

2.1. Overview of the current state-of-the-art

Clustering techniques have been widely adopted in WSNs to balance energy consumption and prolong network lifetime. However, relying on ordinary nodes as cluster heads can quickly deplete their energy. To address this issue, researchers have introduced gateway nodes, more capable nodes that offload communication tasks, reduce energy consumption, and enhance network efficiency [12]. Given the central role of WSNs in IoT systems, recent studies have focused on developing smarter, energy-aware protocols. This section highlights key contributions that target energy optimisation, multi-hop routing, and cluster-based enhancements in WSNs. For example, Yanfei et al. [13] proposed a zone-based energy-efficient routing protocol that extends the classic TSEP by incorporating hybrid data transmission and integrating residual energy into CH selection. Simulation results demonstrated improvements in both network stability and throughput.

Jaffri et al. [14] introduced TEZEM, a novel energy-efficient routing protocol that leverages multilevel node heterogeneity and trust-based CH selection. TEZEM demonstrated improved energy conservation and higher packet delivery ratios compared to traditional protocols such as DEEC and SEP. Hossan et al. [15] developed an extended SEP protocol incorporating secondary cluster heads (SCH) to further balance energy consumption across the network. The SCH mechanism offloads data aggregation from the main CH, enhancing network stability periods by up to 89% compared to M-SEP. Narayan et al. [16] proposed a multivariate lifetime prediction model that employs regression and topology-based features to anticipate node failures, enabling proactive, energy-aware routing decisions. This approach represents a transition from fixed, rule-based clustering to prediction-driven network management. Tewelgne et al. [17] focused on inter-cluster multi-hop routing to mitigate energy holes and extend network lifetime. Their protocols optimise CH communication using energy-aware next-hop selection, outperforming classical schemes such as LEACH and DEEC in both energy efficiency and packet delivery.

Dass, et al. [18] proposed a cluster-based secure optimal path-routing protocol for wireless body area networks (WBANs). This approach combines security mechanisms with energy-efficient CH selection, making it particularly suitable for medical data transmission and other critical sensor applications. Abdul-Qawy, et al. [19] introduced an enhanced clustering protocol tailored for large-scale IoT deployments. By optimising CH selection through adaptive thresholding and unequal clustering, this method significantly improves energy balance and network scalability compared to conventional LEACH variants. Guedmani, et al. [20] proposed a protocol designed to minimise energy consumption by reducing transmission distances and the number of communications between sensor nodes. The approach leverages a mobile base station (MBS) that dynamically moves closer to sensor nodes. The deployment area is divided into two zones, with advanced nodes located in Zone 1 and the remaining nodes in Zone 2. The protocol, referred to as ISEPSCMS, employs an SEP-based clustering scheme with MBS control, managed via a centralised software-defined network (SDN) to enable efficient mobility control and positioning near CHs. By limiting the number of CHs, communication overhead with the MBS is reduced.

Table 2
Comparison of Related and Recent Routing Approaches

Criteria/Ref No.	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[24]	[25]	[26]	**Proposed (M-GESEP)**
Contribution	Zone-based hybrid TSEP extension	TEZEM with trust & heterogeneity	Secondary CH to reduce load	Lifetime prediction model	Multi-hop CH communication	Secure path routing for body sensors	Adaptive clustering for large-scale IoT	Mobile BS with SDN control	Energy-efficient routing using small-world topology	ML-assisted optimization for heterogeneous LPWAN	Hybrid optimization-based cluster routing	Gateway-assisted multi-hop routing to enhance stability
Techniques/ Protocol	Hybrid TSEP	TEZEM	Extended SEP (SCH)	ML-based prediction	Inter-cluster multi-hop	Secure cluster routing	Unequal clustering	SEP + MBS + SDN	Small-world routing	Small-world + Machine learning	Hybrid GWO-PSO	G-MH-ESEP
Results	Improved stability & throughput	Better energy & delivery	89% improvement in stability	Proactive energy-aware routing	Lower energy & higher PDR	Enhanced medical data security	Better scalability & energy balance	Reduced energy via dynamic BS	Reduced latency & improved connectivity	Improved network performance & scalability	Improved energy efficiency & lifetime	Improved lifetime, reduced CH load, balanced energy distribution
Limitations	No mobility or gateway support	High computational overhead	Only two-level hierarchy	Not protocol-integrated	Complex CH communication	Context-specific	No mobility support	Requires mobility coordination	Designed mainly for drone networks	Requires learning models & overhead	High optimization complexity	Depends on region formation & gateway placement
Network Type	Heterogeneous WSN	Heterogeneous WSN	Heterogeneous WSN	WSN (topology-aware)	Heterogeneous WSN	WBAN	IoT-WSN	Heterogeneous WSN	Internet of Drone Networks	LPWAN	WSN	Heterogeneous WSN
BS Placement	Static, outside field	Static	Static	Static	Static	Near-body	Static	Mobile	Dynamic	Static	Static	Static, outside field
Mobility Support	No	No	No	Limited	No	Yes	No	Yes	Yes	No	No	No
Gateways Used	No	No	No	No	No	Yes	No	Yes	No	No	No	Yes
Clustering	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
#Regions	Zone-based division	Multi-level	Unspecified	Not applicable	Hierarchical	Unspecified	Unequal	Two zones	Not applicable	Not applicable	Not applicable	Multi-region (e.g., 3)

Additionally, a sleep/wake-up mechanism minimises intra-cluster communication, while nodes transmit data directly to the nearest collector, whether a CH or the BS, further reducing transmission distances.

Hoque, et al. [21] classified sensor nodes into five regions based on their placement within the network. The BS is deliberately positioned outside the sensing field, while two gateway nodes are deployed in predefined regions. Nodes located near the BS or gateway nodes transmit data via direct communication, leveraging their proximity to the destination. In contrast, nodes farther away rely on multi-hop communication to efficiently forward data to the BS or gateway nodes. This regional division, combined with the dual communication strategy, enables the EAGBRP protocol to enhance transmission efficiency and conserve energy within the network. Mohapatra, et al. [22] proposed the mobility-induced multi-hop LEACH (Mob M-LEACH) protocol for mobile heterogeneous WSNs. This protocol extends the traditional LEACH scheme by selecting CHs based on both residual energy and node mobility, thereby improving network stability and reducing link failures. Multi-hop communication to the BS is employed to minimise transmission distance and energy consumption. The authors in [23] introduced an enhanced version of the homogeneous MGEAR protocol, referred to as HMGEAR. This protocol leverages heterogeneous nodes, residual energy-based CH selection, and multi-hop routing across all regions, while incorporating energy-hole mitigation techniques to improve overall WSN performance.

Recent studies have explored advanced routing and optimisation techniques to enhance communication efficiency and energy management in wireless networks. For example, small-world network concepts have been utilised to improve routing efficiency and reduce latency in internet-of-drone networks by enhancing connectivity between nodes [24]. Similarly, machine-learning-assisted approaches have been proposed to optimise communication performance in heterogeneous LPWAN environments by dynamically adapting network parameters [25]. In addition, meta-heuristic optimisation techniques such as hybrid GWO-PSO algorithms have been applied to improve cluster-head selection and energy balancing in wireless sensor networks [26]. Although these approaches demonstrate promising results, they often rely on complex optimisation or learning mechanisms that increase computational overhead. In contrast, the proposed M-GESEP protocol adopts a lightweight region-based communication framework combined with gateway-assisted multi-hop routing to improve energy efficiency and network lifetime in heterogeneous IoT-enabled WSNs. For context, Table 2 presents a structured synthesis of related energy-efficient routing protocols for IoT-enabled WSNs. The table summarizes each protocol's key techniques, reported performance gains, and limitations that are most relevant to the design considerations of M-GESEP

2.2. Preliminaries

This subsection details the energy consumption model and the network model underpinning the proposed protocol.

2.2.1. *The energy consumption model*

The first-order radio model is employed to characterise the energy consumption of sensor nodes during data transmission, reception, and aggregation [27, 28] (see Fig. 2). Both the transmitter (E_{TX}) and receiver (E_{RX}) energy consumptions are calculated using the free-space (E_{fs}) and multipath (E_{mp}) models, depending on the distance ($dist$) between nodes [29]; specifically, if $dist < T_d$, the free-space model is applied, otherwise the multipath model is used.

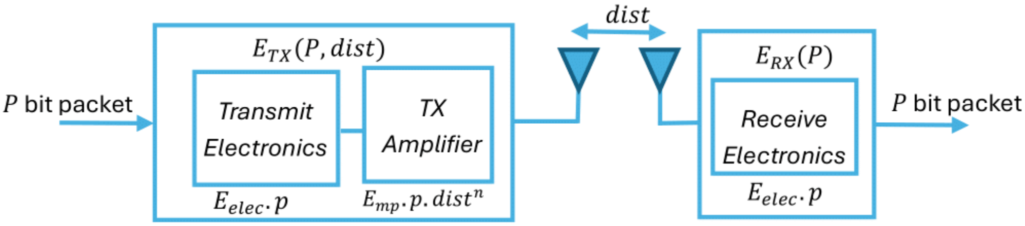

Figure 2: Radio energy dissipation model [29].

The energy required to transmit a P-bit data packet over a distance $dist$ is computed as follows.

$$E_{TX}(P, dist) = \begin{cases} P \cdot E_{elec} + P \cdot E_{fs} \cdot dist^2, & dist < T_d \\ P \cdot E_{elec} + P \cdot E_{mp} \cdot dist^4, & dist \geq T_d \end{cases} \tag{1}$$

The energy required to receive a P-bit data packet is calculated using the following expression.

$$E_{RX}(P) = P \cdot E_{elec} \tag{2}$$

where E_{elec} denotes the energy consumed by the transmitter (E_{TX}) or receiver (E_{RX}) circuitry per bit, while E_{fs} and E_{mp} are the amplification factors for the free-space and multipath models, respectively. The threshold distance T_d, which determines the switching between E_{fs} and E_{mp}, is calculated as

$$T_d = \sqrt{\frac{E_{fs}}{E_{mp}}} \tag{3}$$

2.3. The network model

In many existing protocols, sensor nodes are randomly distributed within the network, often resulting in inefficient energy utilisation. In contrast, the proposed M-GESEP protocol enhances energy efficiency by dividing the network into regions according to each node's distance from the BS or the gateway node. M-GESEP is designed as a hybrid, multi-hop heterogeneous network, effectively reducing the transmission distance between CHs and the BS. It follows a three-level heterogeneity model, comprising three types of nodes:

1. *Normal nodes:* nodes with low initial energy.
2. *Intermediate nodes:* nodes with higher energy than normal nodes.
3. *Advanced nodes:* nodes with the highest initial energy.

Let E_0 denote the initial energy of normal nodes (N), while advanced nodes possess an energy of $E_0(1 + b)$, with a fraction x of the total nodes having higher energy than normal nodes. Similarly, the energy of intermediate nodes, which constitute a fraction y of the network, is given by $E_0(1+a)$, where $a = b/2$. The total initial energy distributed among the heterogeneous WSN nodes is calculated as shown in Equations (4) and (5) [30]:

$$E_{total} = N \cdot E_o(1-x-y) + N \cdot y \cdot E_o(1+a) + N \cdot x \cdot E_o(1+b) \tag{4}$$

$$E_{total} = N E_o(1 + y \cdot a + x \cdot b) \tag{5}$$

where N represents the total number of nodes, y denotes the fraction of intermediate nodes relative to N, and x indicates the fraction of advanced nodes with higher energy compared to the other nodes.

3. The Proposed Protocol

This section presents the design and operation of the proposed M-GESEP. The protocol introduces a hybrid routing strategy that integrates region-aware direct communication with cluster-based multi-hop routing, enabling communication decisions to be dynamically adapted according to node location and residual energy. This design aims to minimise long-distance transmissions, balance energy dissipation, and prolong network lifetime in heterogeneous IoT-enabled wireless sensor networks. The M-GESEP operates in discrete communication rounds and is organised into four main phases: an initial setup phase for region assignment, followed by cluster-head selection, scheduling, and steady-state data transmission. This structured operation ensures efficient coordination between sensor nodes, cluster heads, and the gateway, while maintaining low control overhead.

3.1. The setup phase

During the setup phase of the proposed M-GESEP protocol, each node calculates its Euclidean distance to both the BS and the GW. Based on the maximum distance threshold (D_{max}), nodes are systematically assigned to distinct logical regions that determine their communication mode. Let node i at position (X_i, Y_i). The Euclidean distance between node i to BS and GW are

$$d_{i,BS} = \sqrt{(X_i - X_{BS})^2 + (Y_i - Y_{BS})^2}, \tag{6}$$

$$d_{i,GW} = \sqrt{(X_i - X_{GW})^2 + (Y_i - Y_{GW})^2}, \tag{7}$$

where $d_{i,BS}$ is the distance between node i and the BS and $d_{i,GW}$ is the distance between node i and the GW. To distinguish between direct and clustered communication, the maximum distance threshold D_{max} is given by $D_{\max} = a\sqrt{L^2 + L^2}$, where $L \times L$ is sensing area and $a \in (0, 1)$ is a control coefficient used to adjust the size of the direct communication regions.

Based on D_{max} and the relative distances to the BS and GW, nodes are assigned to the following logical regions:

1. *N-Region* 0 *(BS Region)*: This region contains normal nodes located closer to the BS than to the GW:

   $$d_{i,BS} < D_{max} \quad \text{and} \quad d_{i,BS} < d_{i,GW} \tag{8}$$

   These nodes transmit sensed data directly to the BS, minimising energy consumption due to the short transmission distance.
2. *N-Region* 1 *(Gateway Region)*: This region includes normal nodes situated closer to the GW than to the BS:

   $$d_{i,GW} < D_{max} \quad \text{and} \quad d_{i,GW} < d_{i,BS} \tag{9}$$

   Nodes in this region send their data directly to the gateway node rather than to the distant BS, thereby reducing their transmission energy.
3. $Clusteredregions(Regions2-5)$: These regions comprise intermediate and advanced nodes located farther from both the BS and the gateway node. These regions are subdivided based on node energy level and proximity to the GW:

   - *In-Region 2 and In-Region 3 (Intermediate Nodes)*: Nodes classified as intermediate energy nodes and located in the cluster region.
   - *A-Region 4 and A-Region 5 (Advanced Nodes)*: Nodes classified as advanced energy nodes and located in the cluster region.

   Intermediate nodes are partitioned into regions 2 and 3, while advanced nodes are partitioned into regions 4 and 5. Nodes in these regions participate in clustering, with cluster heads (CHs) selected using a weighted probability approach to balance energy consumption.

This hierarchical regional classification ensures a balanced distribution of nodes, reduces communication overhead, and enables energy-aware multi-hop routing through the gateway. Consequently, the setup phase establishes the foundation for efficient data aggregation, load balancing, and prolonged network lifetime in IoT-enabled WSNs. The setup procedure is summarised in Algorithm 1.

Algorithm 1 Setup Phase of M-GESEP

```
for each node $i$ in the network do
    Calculate:
        $d_{i,BS} \leftarrow$ distance(node $i$, $BS$)    ▷ Distance of node from BS
        $d_{i,GW} \leftarrow$ distance(node $i$, $GW$)    ▷ Distance of node from GW
    (Direct Communication Region)
    if $d_{i,BS} < D_{\max}$ and $d_{i,BS} < d_{i,GW}$ then
        Assign normal node $i$ to Region 0 (Base Station Region)
        Set communication mode to direct transmission to BS
    else if $d_{i,GW} < D_{\max}$ and $d_{i,GW} < d_{i,BS}$ then
        Assign normal node $i$ to Region 1 (Gateway Region)
        Set communication mode to direct transmission to GW
    (Cluster-based Regions)
    else
        Set communication mode to cluster-based routing
        if node $i$ is an intermediate node then
            if $d_{i,GW} < d_{i,BS}$ then
                Assign node $i$ to Region 2
            else
                Assign node $i$ to Region 3
            end if
        else if node $i$ is an advanced node then
            if $d_{i,GW} < d_{i,BS}$ then
                Assign node $i$ to Region 4
            else
                Assign node $i$ to Region 5
            end if
        end if
    end if
end for
```

3.2. The cluster-head selection and data transmission phase

Following the setup phase, the M-GESEP protocol operates in discrete communication rounds. Sensor nodes assigned to the base station region and gateway region follow direct data transmission rules, transmitting their sensed data directly to the BS and GW, respectively. In contrast, nodes located in the cluster region (Regions 2-5) participate in a cluster-based communication process that includes cluster-head election, cluster formation, scheduling, and steady-state data transmission, as summarised in Algorithm 2.

Algorithm 2 Cluster Head Selection and Data Transmission Phase in M-GESEP

```
Calculate CH election probabilities:
    $P_{INT}$ using Equation (10)    ▷ CH Selection for intermediate nodes
    $P_{ADV}$ using Equation (11)    ▷ CH Selection for advanced nodes
Select CHs among intermediate nodes in Regions 2 and 3 using threshold $Th(N_{INT})$ Equation (12)
Select CHs among advanced nodes in Regions 4 and 5 using threshold $Th(N_{ADV})$ Equation (13)
for each node $i$ in Region 0 (Base Station Region) do    ▷ Direct Communication
    Transmit sensed data directly to BS
end for
for each node $i$ in Region 1 (Gateway Region) do
    Transmit sensed data directly to GW
    GW forwards received data to BS
end for
    (Cluster-Based Communication)
for each non-CH node $i$ in Regions 2 to 5 do
    Transmit sensed data to the associated CH
    Sleep otherwise
end for
for each CH do
    Aggregate received data
    Forward aggregated data to GW
end for
    (Gateway Forwarding)
GW forwards all aggregated data to BS
```

$$Th\left(N_{INT}\right) = \begin{cases} \frac{P_{INT}}{1-P_{INT}\left(r \bmod \left(\frac{1}{P_{INT}}\right)\right)} \times \frac{E_{res}\times\ K_{opt}}{E_{avg}} & \text{if} \quad N_{INT} \in G \\ 0 & otherwise \end{cases} \tag{12}$$

$$Th\left(N_{ADV}\right) = \begin{cases} \frac{P_{AVD}}{1-P_{AVD}\left(r \bmod \left(\frac{1}{P_{AVD}}\right)\right)} \times \frac{E_{res}\times K_{opt}}{E_{avg}} & \text{if} \quad N_{ADV} \in G' \\ 0 & otherwise \end{cases} \tag{13}$$

3.2.1. CH election and cluster formation

In each communication round, sensor nodes operate according to their assigned regions. Normal nodes, located in the base station region, collect and transmit their sensed data directly to the base station, whereas normal nodes located in the GR forward their data directly to the gateway node. Nodes in these two regions do not participate in clustering, thereby avoiding unnecessary control overhead and long-distance transmissions. Nodes located in the Cluster Region (Regions 2-5) independently elect their cluster heads using a weighted probabilistic approach that accounts for node heterogeneity and residual energy, ensuring balanced energy consumption across the network. The probability of selecting an intermediate node as a CH as like ESEP protocol is given by

$$P_{INT} = \frac{p_{opt}(1+a)}{1+ya+xb} \tag{10}$$

where P_{INT} denotes the reference CH election probability, a and b represent the additional energy factors of intermediate and advanced nodes, respectively. In addition, x and y denote their respective fractions of intermediate and advanced nodes in the network. while the probability of selecting an advanced node as a CH is defined as

$$P_{ADV} = \frac{p_{opt}(1+b)}{1+ya+xb} \tag{11}$$

In the CH selection phase, each node generates a random number between 0 and 1. If this number is less than the threshold $T(n)$, the node will be elected as CH. To ensure fair rotation of the CH role and prevent repeated selection within the same epoch, threshold functions are applied. For intermediate and advanced nodes, the threshold functions are defined using the equations given in (12) and (13), where r is the current round, E_{res} represents the residual energy of the node, K_{opt} denotes the optimal number of cluster heads, $\boldsymbol{E_{avg}}$ is the average residual energy of alive nodes, N_{INT} and N_{ADV} denote the total number of intermediate and advanced nodes, respectively, and G and G' represent the sets of nodes that have not served as CHs in the previous round of the epoch.

3.3. The scheduling phase

After cluster-head election and cluster formation, each elected CH generates a time division multiple access (TDMA) schedule and assigns a specific transmission time slot to each member node within its cluster. Each node transmits its sensed data to the corresponding CH during its allocated time slot and remains in sleep mode during inactive periods. This scheduling mechanism reduces packet collisions, avoids idle listening, and minimises unnecessary energy consumption.

3.4. The steady-state data transmission phase

In the steady-state phase, sensor nodes begin sensing and transmitting data according to their assigned communication modes. Nodes in the BR transmit their data directly to the BS, whereas nodes in the GR transmit their data directly to the GW. Nodes located in the CR forward their sensed data to their respective CHs following the TDMA schedule. In M-GESEP, the total energy dissipated per round depends on the region-based communication strategy, which differentiates between direct transmission and clustered multi-hop transmission.

- The energy consumption of a node i in BR per-round is:

$$E^{i}_{BR} = E_{TX}\left(P, d_{i,bs}\right) \tag{14}$$

- The energy consumption of a node i in GR per-round is:

$$E^{i}_{GR} = E_{TX}\left(P, d_{i,GW}\right) \tag{15}$$

- The energy consumption of a non- CH node i to transmit its data to the associated CH in cluster region per-round is:

$$E^{i}_{CM} = E_{TX}\left(P, d_{i,CH}\right) \tag{16}$$

  where $d_{i,CH}$ is the distance between node i and its selected CH.

A cluster head receives data from its member nodes, aggregates, and forwards the aggregated packet to GW. The energy consumption of a CH (J) is:

$$E^{J}_{CH} = \sum E_{RX}(P) + N_J \cdot E_{DA} + E_{TX}\left(P, d_{J,GW}\right) \tag{17}$$

where N_J is the set of member nodes in cluster J and $d_{J,GW}$ is distance between CH (J) and GW. Thus, the total energy

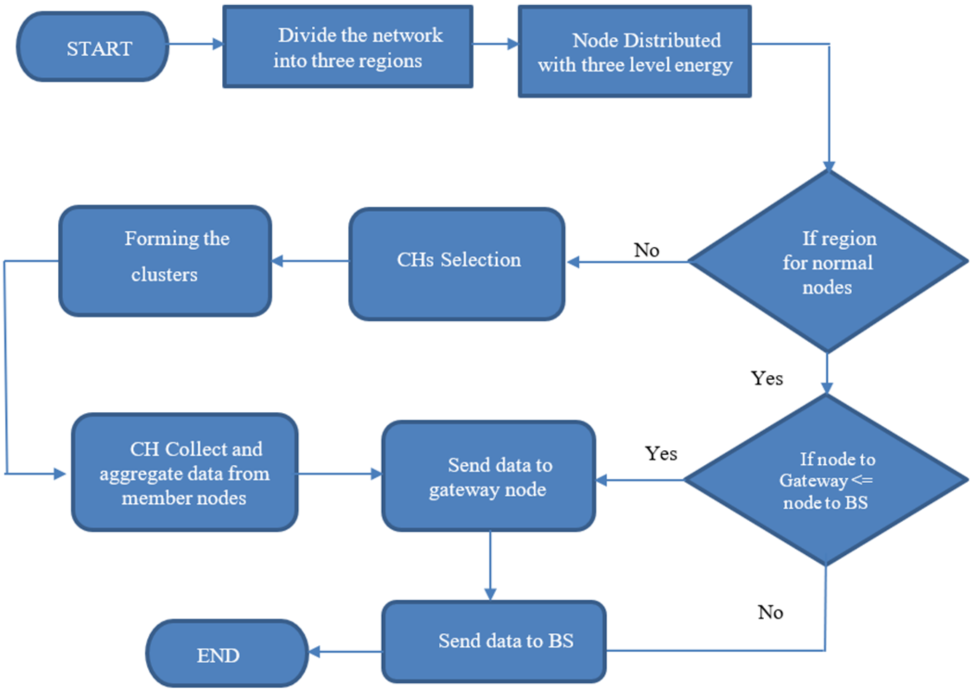

Figure 3: Flowchart of the proposed M-GESEP protocol.

consumed in one round can be calculated as:

$$E_{round} = \sum_{i=1}^{N_{BR}} E^i_{BR} + \sum_{i=1}^{N_{GR}} E^i_{GR} + \sum_{i=1}^{N_{CR}} E^i_{CM} + \sum_{J=1}^{k} E^j_{CH} \quad (18)$$

where N_{BR}, N_{GR}, and N_{CR} denote the number of alive nodes in the BR, GR, and cluster region, respectively. K is the number of elected cluster heads in the cluster region.

Each CH aggregates the data collected from its cluster members and forwards the aggregated packet to the gateway node. The gateway subsequently relays the received data to the BS. This hierarchical, gateway-assisted multi-hop communication strategy significantly reduces the communication distance between CHs and the BS, lowers transmission energy consumption, balances the forwarding load, and extends the overall network lifetime. Fig. 3 shows the flowchart of the proposed M-GESEP protocol.

3.5. Computational complexity analysis

The computational complexity of the proposed M-GESEP protocol is analysed with respect to the number of sensor nodes N. During the setup phase, each node computes its distance to the base station and the gateway to determine its assigned region, resulting in a time complexity of $O(N)$. In the cluster-head election phase, each node independently generates a random number and evaluates the corresponding threshold function. Since this operation is performed locally at each node, the overall time complexity of the election process is $O(N)$ per round. Cluster formation and TDMA scheduling involve the exchange of control messages between cluster heads and their member nodes. As each node participates in at most one cluster, these operations also incur a linear time complexity of $O(N)$. Finally, the steady-state data transmission phase involves data forwarding from sensor nodes to cluster heads, gateways, and the base station. This process scales linearly with the number of active nodes, maintaining an overall per-round time complexity of $O(N)$. Therefore, the total computational complexity of M-GESEP is linear with respect to the network size, i.e., $O(N)$ per communication round, making the protocol scalable for large-scale IoT-enabled wireless sensor networks.

4. Performance Evaluation

This section evaluates the performance of this study.

4.1. Theoretical analysis of network lifetime bound

The operational lifetime of the proposed M-GESEP protocol is fundamentally defined by the energy dissipation rate across the heterogeneous node populations and the spatial optimization provided by the regional partitioning. We define the network lifetime L as the total number of communication rounds until the residual energy of the network $E_{res} = 0$. Given the total initial energy E_{total} defined in Eq. 5, the theoretical upper bound for the lifetime L_{max} is reached only when the energy consumption is perfectly balanced across all N nodes, expressed as:

$$L_{max} \leq \frac{E_{total}}{\mathbb{E}[E_{round}]} \quad (19)$$

where E_{elec} denotes the electronic energy dissipation per bit, E_{fs} and E_{mp} represent the free-space and multipath amplifier coefficients, respectively, E_{DA} is the data aggregation energy per bit, d is the transmission distance between communicating nodes, and $T_d = \sqrt{E_{fs}/E_{mp}}$ denotes the threshold distance separating the free-space and multipath propagation models. The $\mathbb{E}[E_{round}]$ represents the expected energy consumed by the entire network in a single round. In M-GESEP, this term is minimised by optimising the characteristic transmission distance d across three logical regions (BR, GR, CR), thereby shifting the majority of nodes from the high-energy multipath fading model (d^4) to the energy-efficient free-space model (d^2).

The expected energy dissipation per round is a summation of the regional consumption: $\mathbb{E}[E_{round}] = \sum E_{BR} + \sum E_{GR} + \sum E_{CR}$. For nodes in the BR and GR, the energy consumption per node i for a P-bit packet is strictly bounded by the proximity to the receiver:

$$E_{BR,GR} = P \cdot (E_{elec} + E_{fs} \cdot d^2_{i,BS,GW}) \tag{20}$$

Since these regions are defined such that $d < T_d$, these nodes bypass the amplification penalties associated with long-range clustering. Conversely, the energy bound for a CH in the CR must account for data aggregation from m member nodes and the multi-hop relaying to the gateway:

$$E_{CH} = P\left[m(E_{elec} + E_{DA}) + E_{elec} + E_{mp} \cdot d^4_{CH,GW}\right] \tag{21}$$

where m denotes the count of cluster members. Note that m is a discrete integer determined by the cluster size, whereas x and y are fractional constants representing the network's heterogeneity configuration. Because the M-GESEP architecture ensures that $d_{CH,GW} \ll d_{CH,BS}$, the maximum energy burden on the CHs, which typically dictates the stability period, is significantly lower than in traditional SEP or LEACH-based protocols.

To ensure that the stability period (the time until the first node death) is maximised, M-GESEP utilises a weighted probabilistic threshold $T(n)$ for CH election. This threshold ensures that nodes with higher initial energy (intermediate and advanced) take on the CH role more frequently. The probability p_i for a node n to become a CH is defined based on its type $i \in \{nrm, int, adv\}$:

$$p_{nrm} = \frac{p_{opt}}{1 + x \cdot b + y \cdot a} \tag{22}$$

$$p_{INT} = \frac{p_{opt}(1 + a)}{1 + x \cdot b + y \cdot a} \tag{23}$$

$$p_{ADV} = \frac{p_{opt}(1 + b)}{1 + x \cdot b + y \cdot a} \tag{24}$$

where x and y represent the fractions of advanced and intermediate nodes, while b and a represent their respective energy enhancement factors relative to normal nodes (E_{nrm}), and p_{nrm} is the probability of a normal node becoming a CH. The election threshold $T(n)$ for a node in round r is then bounded by:

$$T(n) = \frac{p_i}{1 - p_i(r \mod \frac{1}{p_i})} \quad \forall n \in G \tag{25}$$

where G is the set of nodes that have not been CHs in the last $1/p_i$ rounds. This weighted energy-aware probability distribution, combined with the gateway-assisted reduction in d, allows M-GESEP to maintain a higher residual energy mean and a lower variance across the network, effectively delaying the "energy hole" effect and pushing the network lifetime toward the theoretical maximum L_{max}.

4.2. Energy-optimality analysis of regional multi-hop routing

The energy efficiency of the proposed M-GESEP protocol is fundamentally predicated on the minimisation of the expected energy consumption per round, $\mathbb{E}[E_{round}]$, relative to established clustering benchmarks. This optimality is achieved through the strategic optimisation of transmission distances and the equitable distribution of the communication load among heterogeneous nodes. The energy-optimality proof is established based on the following three mathematical aspects.

4.2.1. Distance-regime minimisation

The first-order radio model establishes that energy consumption is a piecewise function of the transmission distance d. Total network energy is minimised when the highest possible number of nodes transmit within the free-space distance threshold ($d < T_d$). In M-GESEP, the sensing field is partitioned into logical regions (BR, GR, CR) such that the effective transmission distance $d_{M-GESEP}$ for any node i is defined as:

$$d_{M-GESEP} = \min(d_{i,BS}, d_{i,GW}, d_{i,CH}) \tag{26}$$

Since $\min(d_{i,BS}, d_{i,GW}, d_{i,CH}) \leq d_{i,BS}$ for all $i \in N$, the protocol ensures that the amplification factor remains within the d^2 (free-space) regime more frequently than in traditional SEP-based approaches. By minimising the spatial distance to the nearest receiver, the protocol avoids the high-energy multipath fading model (d^4) common in distant cluster-to-sink communications.

4.2.2. Optimality of gateway-assisted forwarding

For a CH located at a distance D from the BS, the energy dissipated in direct transmission is $E_{dir} = P(E_{elec} + E_{mp}D^4)$. In the M-GESEP framework, the CH forwards data to a gateway at distance d_{GW}, which subsequently relays the data to the BS. The multi-hop relaying strategy is energetically optimal if the following condition is satisfied:

$$E_{CH\to GW} + E_{GW\to BS} < E_{CH\to BS} \tag{27}$$

By utilising a rechargeable (non-energy-constrained) gateway node, the energy cost $E_{GW\to BS}$ effectively becomes zero relative to the network's finite battery-powered lifetime. Consequently, the optimality condition reduces to $d_{GW} < D$, a spatial constraint guaranteed by the gateway placement and region assignment logic in the GR and CR zones.

4.2.3. *Weighted load balancing and stability equilibrium*

The preservation of the stability period (time until the first node death) relies on the maintenance of a weighted probability equilibrium. To ensure that heterogeneous nodes deplete their energy at a uniform rate, the probability of becoming a CH (p_i) must be proportional to a node's initial energy E_i. Let $w_i = E_i/E_{normal}$ denote the energy weight of node type i. The optimality of the selection strategy is achieved when the weighted threshold fulfills the following equilibrium:

$$\frac{p_{ADV}}{w_{ADV}} = \frac{p_{INT}}{w_{INT}} = \frac{p_{nrm}}{w_{nrm}} \tag{28}$$

Substituting the refined probabilities yields:

$$\frac{p_{nrm}}{1} = \frac{p_{opt}}{1 + y \cdot a + x \cdot b} \tag{29}$$

This equilibrium ensures that the variance of residual energy $\sigma^2(E_{res})$ across the network is minimised. By aligning CH election frequency with individual node capacity, M-GESEP prevents premature energy depletion in specific regions, formally satisfying the criteria for an energy-optimal routing strategy.

5. Simulation Results and Discussions

This section presents the simulation setup, network configuration, and performance evaluation of the proposed M-GESEP protocol, including stability, lifetime, throughput, residual energy, and comparative analysis with existing protocols

5.1. Simulation setup and network performance evaluation of M-GESEP

A network of 100 sensor nodes is randomly deployed within a $100 \times 100\ m^2$ sensing area. The monitoring field is divided into three logical regions based on the nodes' distance from the BS or the gateway, as illustrated in Fig. 4. The BS is positioned outside the sensing area, while the GW is deployed at the center of the sensing field. The GW remains stationary and rechargeable throughout the network operation, thereby increasing the number of active nodes and extending the network lifetime. The proposed M-GESEP protocol is implemented and evaluated using MATLAB. The simulation parameters used for performance evaluation are summarised in Table 3.

For the simulation, the network parameters are set as $x = 0.2$, $y = 0.3$, $b = 3$, and $a = b/2$. The network consists of 50 normal nodes with initial energy E_0, 30 intermediate nodes with energy $E_0(1 + a) = 1.5$ times energy more than normal nodes and 20 advanced nodes with energy $E_0(1 + b) = 3.0$. This heterogeneous energy distribution enables evaluation of the protocol's performance under multi-level energy scenarios.

Table 3
Simulation Parameters

Type of parameters	symbol	Value
Network field	- -	(100, 100)m
Number of nodes	N	100
Data Packet Length (bits)	k	4000
Energy depletion of the node's electronics circuit to transmit or receive the signal	E_{elec}	50 nJ/ bit
Data Aggregation Energy	E_{DA}	5 nJ/ bit
Transmit Amplifier Energy, if $dist < T_d$	E_{fs}	10 pJ/bit/m2
Transmit Amplifier Energy, dist ≥ T_d	E_{amp}	0.0013 pJ/bit/m4
Optimal Probability	$\mathrm{p_{opt}}$	0.1
Initial energy	E_o	0.5 J
Bas station	BS	(50, 120)
Gateway node for Proposed	G	(50, 50)
Gateway node for EAGBRP	GW1 and GW2	GW1=[25,40] GW2=[75,40]
Gateway node for HMGEAR	GW	(50, 50)
Proportion advanced node	x	0.2
Proportion intermediate node	y	0.3
Energy factors of intermediate nodes	a	1.5
Energy factors of advanced nodes	b	3.0

Stability period and network lifetime: The stability period, defined as the time from the start of network operation until the first node dies, is a critical performance metric. Simulation results show that the first node death occurs at 1158, 1304, 1361, 1235, 820 and 1484 rounds for the SEP, EDEEC, ESEP, EAGBRP, HMGEAR and the proposed M-GESEP protocols, respectively (see Fig. 5). These results demonstrate that the M-GESEP protocol extends the stability period by approximately 28%, 13.7%, 9% , 20.1% and 80.9% compared to SEP, EDEEC, ESEP, EAGBRP and HMGEAR respectively.

Network lifetime is defined as the duration from the start of network operations until the death of the last active node. Fig. 6 presents a comparison of network lifetime between the proposed M-GESEP protocol and SEP, EDEEC, ESEP, EAGBRP, and HMGEAR protocols. The last node deaths occur at 8313, 4778, 5253, 7480, 6182, and 7338 rounds for M-GESEP, SEP, EDEEC, ESEP, EAGBRP, and HMGEAR, respectively. These results indicate that M-GESEP extends the network lifetime by approximately 74%, 58.2%, 11.1%, 34.5% and 13.3% compared to SEP, EDEEC, ESEP EAGBRP, and HMGEAR, respectively. The improvement is primarily attributed to the reduced transmission distances between CHs and the BS, facilitated by the deployment of the gateway node.

Throughput: Throughput is defined as the total number of data packets received by the GW from CHs and the packets subsequently delivered the BS from the GW and nearby nodes. In the SEP, EDEEC, ESEP, EAGBRP, and HMGEAR protocols, CHs transmit data directly to the BS, resulting in higher energy consumption during data transmission. In contrast, the proposed M-GESEP protocol employs GW to reduce communication distances between transmitters and

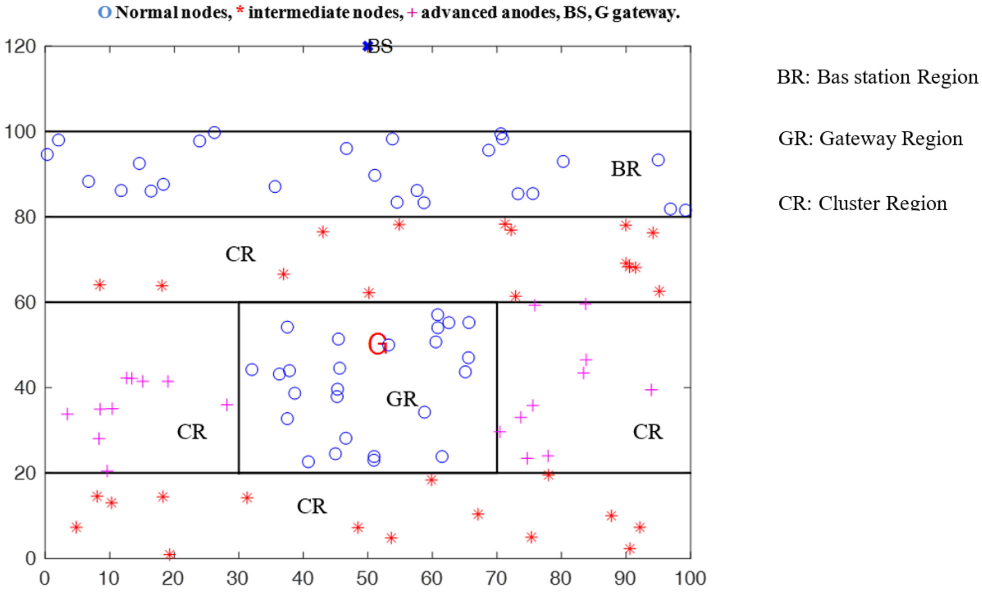

Figure 4: Nodes deployment in the network of the proposed protocol.

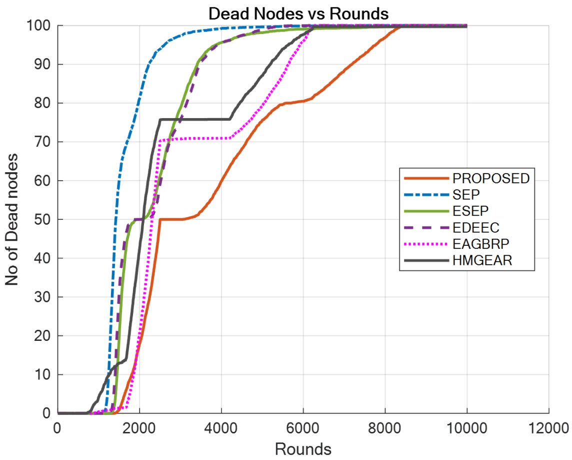

Figure 5: Number of dead nodes in the network for the proposed M-GESEP, ESEP, EDEEC, EAGBRP, HMGEAR and SEP protocols.

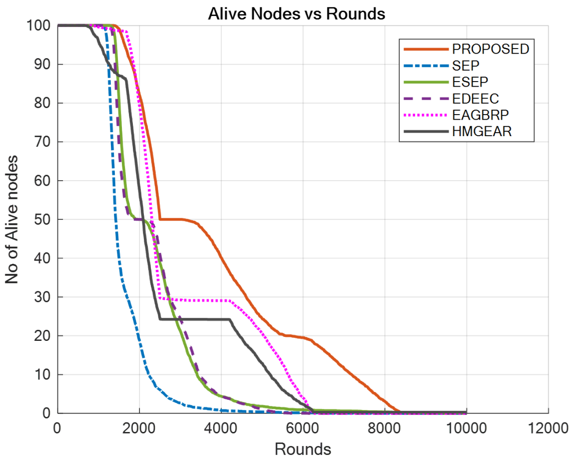

Figure 6: Network lifetime for the proposed M-GESEP, ESEP, EDEEC, EAGBRP, HMGEAR, and SEP protocols.

receivers, thereby enhancing overall network performance. Simulation results indicate that the number of packets received at the BS is higher in M-GESEP compared to SEP, EDEEC ESEP, EAGBRP, and HMGEAR protocols, as illustrated in Fig. 7.

Residual energy: Residual energy the remaining battery power of the network nodes is used to evaluate the energy consumption per round. Monitoring residual energy provides insights into the gradual degradation of network lifetime. By minimizing the transmission distance between transmitters and receivers, energy consumption is effectively reduced. Fig. 8 illustrates that the residual energy in the proposed M-GESEP protocol remains higher than that in SEP, EDEEC, and ESEP proto cols, demonstrating its superior energy efficiency.

Simulation results confirm that the proposed M-GESEP protocol outperforms single-hop and multi-hop protocols such as SEP, EDEEC, ESEP, EAGBRP, and HMGEAR in terms of stability period, network lifetime, number of data packets transmitted to the BS, and energy consumption. The obtained results are summarised in Table 4, which provides a comprehensive performance comparison for a network of 100 sensor nodes deployed over a $100 \times 100\ m^2$ sensing field. The results demonstrate the significant performance gains achieved by M-GESEP in terms of stability period, network lifetime, and throughput. These improvements are primarily attributed to the proposed hybrid region-aware architecture combined with gateway-assisted multi-hop communication,

Table 4

Performance comparison for 100 nodes deployed in a $100 \times 100\ m^2$ field (30 simulation runs, seed = 10000)

Protocol	Stability Period FND (rounds)	Standard Deviation (std) in Stability	Network Lifetime LND (rounds)	Standard Deviation (std) in Network Lifetime	Total Throughput (packets)	Avg. Throughput (packets/ round)	Stability Gain vs PROPOSED (%)	Lifetime Gain vs PROPOSED (%)
M-GESEP (Proposed)	1484.1	± 53.0	8313.9	±94.6	378,505	45.53	0.0	0.0
SEP	1158.7	± 41.4	4778.4	±1023.6	18,879	3.95	+28.1	+74.0
ESEP	1361.9	±45.3	7480.7	±1647.2	28,838	3.86	+9.0	+11.1
EDEEC	1304.8	±33.5	5253.8	±276.5	51,866	9.87	+13.7	+58.2
EAGBRP	1235.2	±300.9	6182.8	±53.8	304,205	49.20	+20.1	+34.5
HMGEAR	820.4	±69.6	7338.3	±1773.3	243,147	33.13	+80.9	+13.3

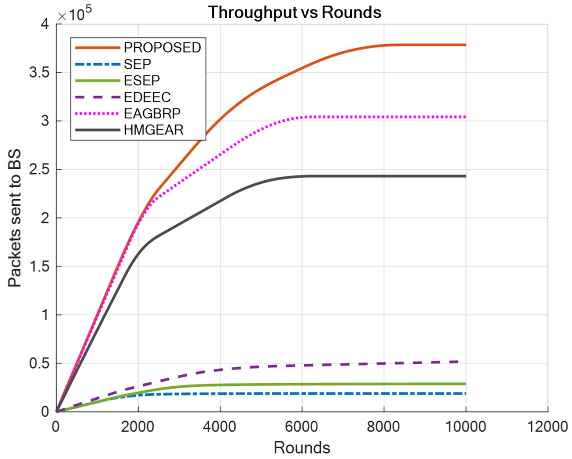

Figure 7: Number of data received by the BS for different protocols.

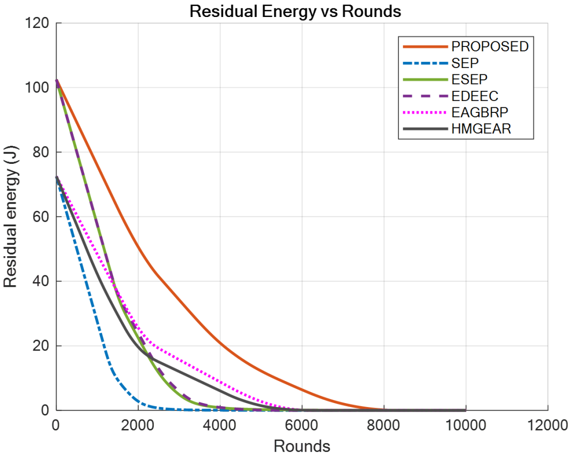

Figure 8: Residual energy of the network for different protocols.

which effectively reduces long-distance transmissions and balances energy consumption. Each reported metric represents the mean value obtained from 30 independent simulation runs, along with the corresponding standard deviation, ensuring statistical reliability and reproducibility of the results.

Comparative analysis: The comparative results illustrated in Fig. 9 substantiate the analytical insights. Prior studies [13, 14, 15, 16, 17, 18, 19, 20] that relied on clustering, zone-based hybrids, or mobility-assisted data collection exhibited inherent limitations, including overloaded cluster heads, dependence on rigid partitions, a restricted number of gateways, or the requirement for complex SDN/MDC infrastructures, thereby limiting their practicality in static IoT-WSNs. In contrast, the proposed M-GESEP protocol integrates gateway-assisted multi-hop communication with a region-aware design (BR/GR/CR). It leverages direct delivery in BR and GR regions while employing clustering in the CR, supported by a rechargeable gateway node. This design ensures superior energy balancing and prolonged network stability, achieving lifetime improvements of 74%, 58.2%, 11.1%, 34.5% and 13.3% over SEP, EDEEC, ESEP, EAGBRP, and HMGEAR, respectively, under identical conditions. The figure further demonstrates that M-GESEP not only reduces overall energy consumption and end-to-end delays but also maintains nearly perfect packet delivery, thereby validating its efficiency and robustness compared to existing approaches.

5.2. Scalability analysis with increased node density (200 nodes in a $100 \times 100\ m^2$ field)

To evaluate the scalability of the proposed M-GESEP protocol under dense network conditions, an additional simulation scenario is conducted by increasing the number of sensor nodes from 100 to 200 while maintaining the sensing area at $100 \times 100\ m^2$. This configuration represents a high-density IoT-enabled WSN deployment, where increased node contention, congestion, and energy consumption typically lead to performance degradation. To ensure a fair and consistent comparison, all protocol parameters, including the radio energy model, heterogeneity ratios, gateway placement, and cluster-head election probabilities, are kept identical to those used in the baseline 100-node scenario. The base station remained outside the sensing field, and the rechargeable gateway is positioned at the center of the network. For each evaluated protocol, 30 independent simulation runs are conducted using different random seeds. The reported results represent the mean values along with the corresponding standard deviations. Fig. 10 illustrates the

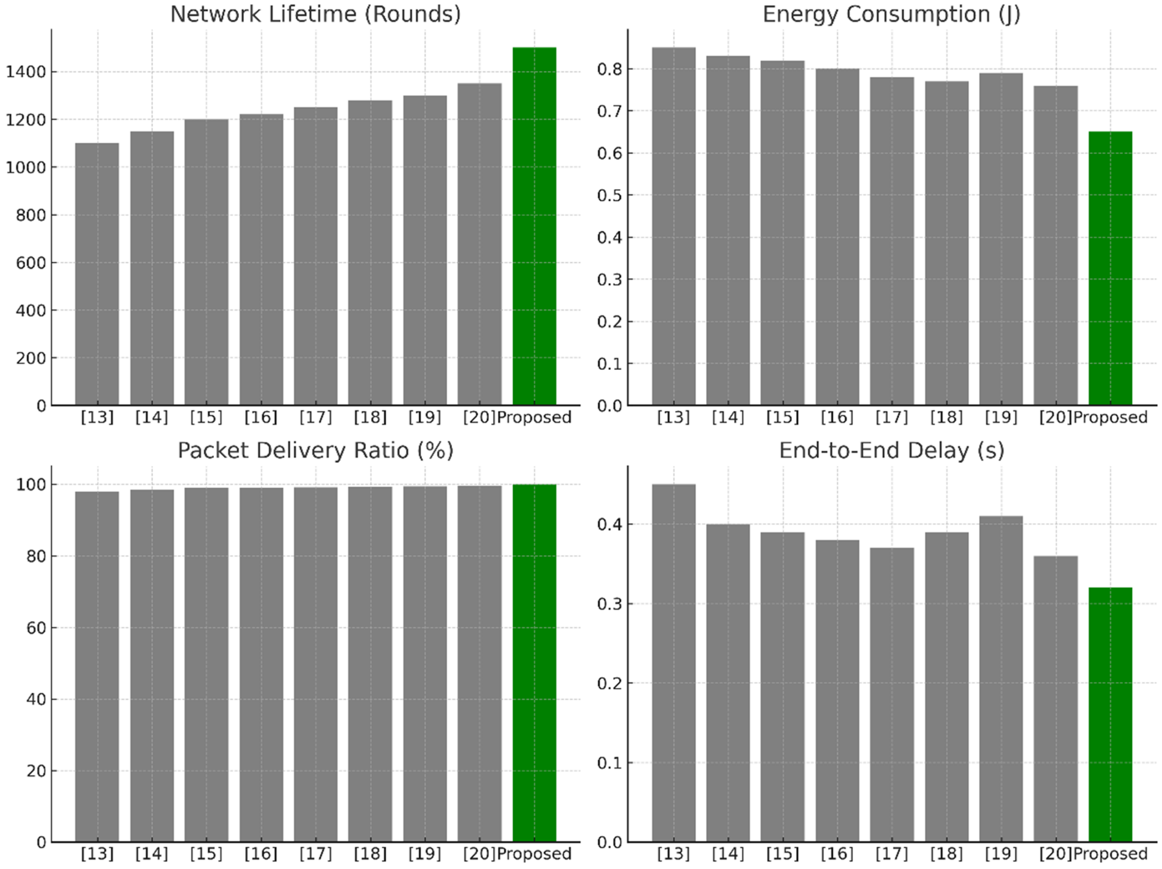

Figure 9: Comparative performance of prior protocols [13, 14, 15, 16, 17, 18, 19, 20] versus the proposed M-GESEP.

Table 5

Performance comparison for 200 nodes deployed in a $100 \times 100\ m^2$ field (30 simulation runs, seed = 10000)

Protocol	Stability Period FND (rounds)	Standard Deviation (std) in Stability	Network Lifetime LND (rounds)	Standard Deviation (std) in Network Lifetime	Total Throughput (packets)	Avg Throughput (pkt/round)	Stability Gain vs PROPOSED (%)	Lifetime Gain vs PROPOSED (%)
PROPOSED	1467.1	±39.8	10000.0	±0.0	597,391	59.739	0.0	0.0
SEP	1155.3	± 32.1	4814.5	±826.0	37,864	7.865	+26.99	+107.71
ESEP	1365.5	±34.3	7210.1	±1504.1	57,677	8.000	+7.44	+38.69
EDEEC	1356.1	±34.5	5163.9	±398.2	59,095	11.444	+8.19	+93.65
EAGBRP	1103.2	±237.9	6219.0	±27.4	608,780	97.890	+32.99	+60.80
HMGEAR	913.9	±98.1	6817.9	±1448.6	489,602	71.811	+60.53	+46.67

impact of increased node density on network performance in terms of residual energy, number of alive nodes, number of dead nodes, and throughput.

Stability period and network lifetime: As summarised in Table 5, the proposed M-GESEP protocol demonstrates strong scalability under dense network deployments. Despite the doubled node density, M-GESEP achieves a stability period of 1467 rounds, which is significantly higher than that of SEP, ESEP, EDEEC, EAGBRP, and HMGEAR. This improvement indicates that the proposed region-aware hybrid routing strategy effectively distributes the increased traffic load and mitigates early energy depletion among sensor nodes. Furthermore, M-GESEP maintains all nodes alive until the maximum simulation limit of 10,000 rounds, highlighting its capability to preserve network operability under high contention conditions. In contrast, the competing protocols experience premature node failures because of excessive long-distance transmissions or overloaded cluster heads, effects that become increasingly pronounced with higher node density. These findings confirm that the scalability gains of M-GESEP are not achieved at the expense of network stability.

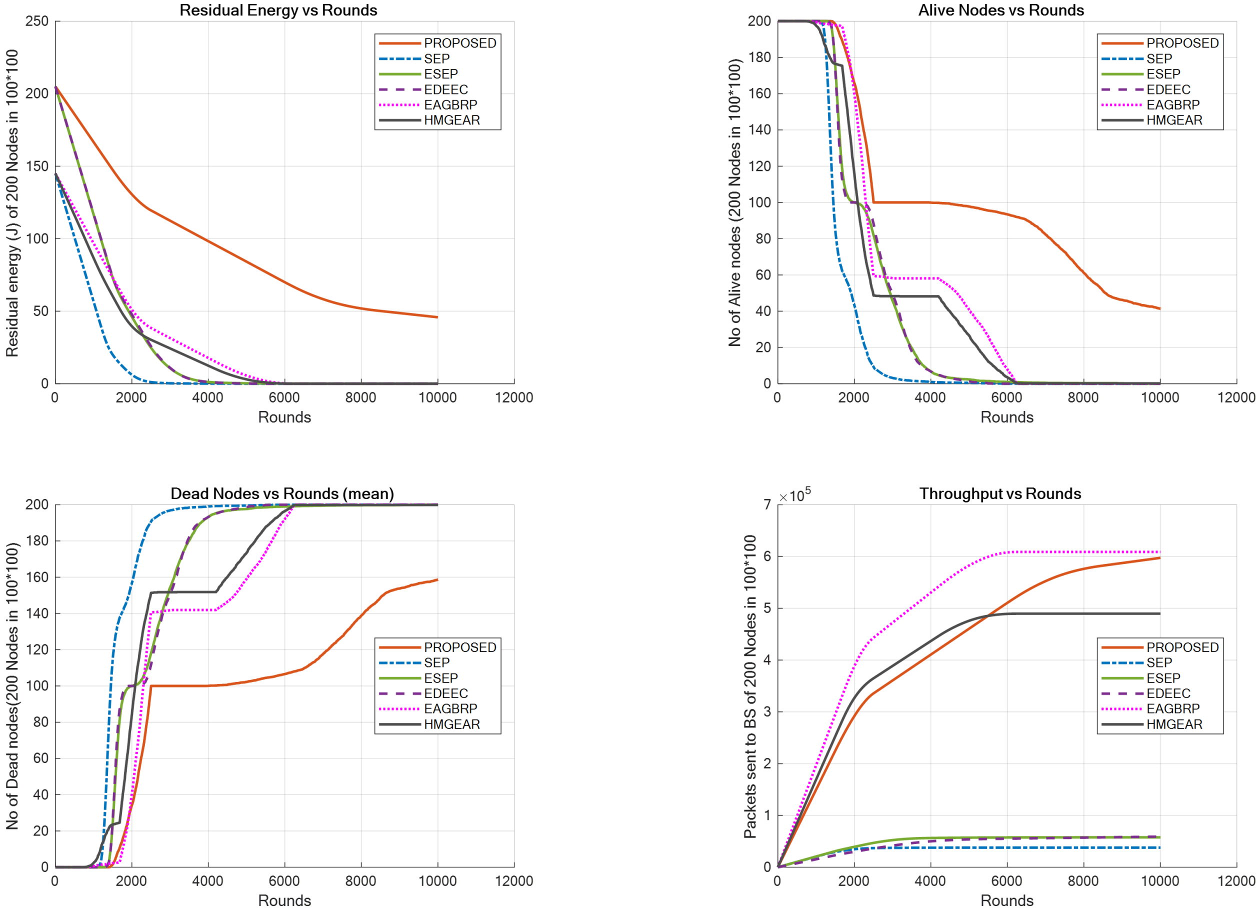

Figure 10: Scalability performance for dense deployment (200 nodes in a 100×100 m^2 area): residual energy, alive nodes, dead nodes, and throughput versus simulation rounds.

Table 6
Comparison of evaluated routing protocols and their key characteristics

Protocol	Heterogeneity Model	Node Types (Energy Levels)	CH Selection Basis	Routing Type	Gateway Used
SEP	Two-level	Normal, Advanced	Weighted probability based on initial energy	Single-hop (CH to BS)	No
ESEP	Three-level	Normal, Intermediate, Advanced	Energy-weighted probability	Single-hop (CH to BS)	No
EDEEC	Three-level	Normal, Intermediate, Advanced	Residual-energybased probability	Single-hop (CH to BS)	No
EAGBRP	Two-level	Normal, Advanced	Residual-energybased with region awareness	Hybrid (Direct and multi-hop via gateways)	Yes (2 GWs)
HMGEAR	Two-level	Normal, Advanced	Residual-energybased, hierarchical regions	Multi-hop (CH to GW to BS)	Yes (1 GW)
M-GESEP (Proposed)	Three-level	Normal, Intermediate, Advanced	Energy-aware weighted probability + regional constraints	Hybrid (Direct and Multi-hop via GW)	Yes (1 rechargeable GW)

Throughput: The throughput analysis further confirms the scalability of the proposed M-GESEP protocol. Under increased node density, M-GESEP successfully delivers a total of 597, 391 data packets to the base station, corresponding to an average throughput of 59.7 packets per round. This performance significantly exceeds that of SEP, ESEP, EDEEC, and HMGEAR, demonstrating the effectiveness of the proposed region-aware and gateway-assisted communication strategy in sustaining high data delivery rates under dense network conditions. Although EAGBRP achieves relatively high throughput by employing multiple gateway nodes, this gain is attained at the cost of reduced network stability and uneven energy dissipation, leading to earlier node failures. In contrast, M-GESEP maintains a more balanced trade-off between throughput, stability, and energy efficiency. This balanced performance highlights the suitability of M-GESEP for dense IoT-WSN deployments where both data delivery and network longevity are critical. Table 6 summarises the key characteristics of the evaluated routing protocols, including their heterogeneity models, node energy types, cluster-head selection strategies, routing mechanisms, and gateway utilisation, to facilitate a fair and transparent comparison.

6. Conclusion

This paper presents M-GESEP, a hybrid, multi-hop, and heterogeneous routing protocol designed to minimise energy consumption and enhance end-to-end performance in IoT-enabled wireless sensor networks. The sensing field is divided into three logical regions, base station region, gateway region, and cluster region, allowing communication strategies to be tailored according to node location and residual energy. Nodes in BR and GR transmit directly to the base station or the gateway, while nodes in CR utilise clustering, forwarding data through cluster heads to the gateway. Under identical simulation settings, M-GESEP improves stability period, network lifetime, throughput, and residual energy compared to conventional protocols, extending network lifetime by 45%, 35%, and 38% relative to SEP, EDEEC, and ESEP, respectively. These enhancements are primarily attributed to reduced transmission distances and balanced energy load distribution achieved through region-aware clustering and the deployment of a rechargeable gateway node. Future work will focus on incorporating gateway mobility and learning-based CH selection to further optimise energy efficiency and adaptability in dynamic network topologies and traffic conditions.

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