

An Elastic Clustering Framework for Large-Scale WSNs Maximizing Network Lifetime

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Abstract—Large-scale Wireless Sensor Networks (WSNs) are applied in multiple domains, notably Precision Agriculture, Intelligent Traffic Management and Smart Hospital. A key task for these applications, long-term environment monitoring, relies on periodic data collection via network clustering. In applications like precision agriculture, large networks require frequent topology updates to avoid hotspot issues at Cluster Heads (CHs), balance energy consumption, and meet QoS demands. Centralized topology maintenance at the Base Station ensures global energy efficiency but incurs costly network-wide control overhead in larger deployments. This undermines existing LEACH-derived and even recent protocols using tree-based approaches, in terms of scalability. We propose PECEE, a framework combining centralized CH selection with local routing coordination, enabling elastic clustering for raw data collection. Simulations show that PECEE extends network lifetime from 50% to 90% compared to some notable solutions including GSTEB [11] in raw data collection simulations, and up to 200% when data aggregation is used.

I. INTRODUCTION

Large-scale wireless sensor networks (WSNs) have been widely deployed worldwide, delivering remarkable results in various practical applications. Notable examples include precision agriculture and intelligent transportation management. For instance, the DEMETER project has deployed over 38000 devices including sensor for agricultural monitoring across 18 countries in 25 pilot sites in Europe [1]. Similarly, the Caltrans Performance Measurement System (PeMS) by the California Department of Transportation (USA) provides real-time traffic monitoring on major highways and urban areas with the use of nearly 40,000 individual detectors across California [2]. In these large-scale applications, the central base station not only collects locally aggregated or processed data but also substantial volumes of raw data, such as images of crop diseases or traffic incidents.

Over the past two to three decades, the problem of continuous and periodic data harvesting in WSNs has garnered significant attention from the research community, with typical solution approaches relying on clustering-based processing. However, traditional protocols such as LEACH [3] and PEGASIS [9] are ill-suited for large-scale networks (typically limited to around 100 nodes or fewer), as they fail to provide efficient solutions for data transmission from distant clusters to the base station. Recent solutions for large networks still adhere to clustering paradigms but require deep data

aggregation from clusters (and even lower tiers) to minimize the volume transmitted to the base station. The most critical challenge in large-scale networks is the rapid energy depletion of hotspot nodes (those near the base station or cluster heads), where traffic is concentrated, severely impacting network lifetime.

Recently, solutions leveraging mobile sinks, including Unmanned Aerial Vehicles (UAVs or drones), have attracted considerable interest. For example, in precision agriculture, UAVs can be dispatched to continuously fly to Cluster Heads to directly collect data via wireless channels before returning to the base station for offloading. This approach completely alleviates the network transmission burden from CHs to the base station. To ensure load balancing and prevent energy exhaustion at CHs, cluster head rotation techniques are commonly employed. Nevertheless, prior studies suffer from a major limitation: CH rotation incurs substantial overhead due to the complete reconstruction of network topology at each round, thereby negatively affecting network lifetime.

Typically, proposed schemes focus on selecting new CHs for each round using intelligent heuristics that prioritize healthier nodes distributed evenly across the network. However, this is followed by rebuilding clusters and internal data collection structures from scratch in each cluster, resulting in considerable communication overhead. Thus, for data harvesting tasks in clustering-based WSNs, a core challenge persists: how to enable CH rotation while avoiding excessive overhead. In other words, after generating a list of CH changes (additions and removals), the system must efficiently re-establish network linkages to minimize overhead comprehensively.

To address this core challenge, we designed an efficient solution that provides a platform for the continuous reconfiguration of clusters and their internal connection structures whenever CH rotation is required. This platform offers services to the upper layer, which submits reconfiguration requests along with a new CH list (generatable by any pre-selected rotation algorithm). The key innovation of our solution lies in maximizing the inheritance and reuse of existing network connection components from the previous round. Our approach is highly generalizable, serving as a platform for most prior important schemes, which primarily focus on new CH placement, thereby creating the most efficient overall system through optimal integration of infrastructure and upper-layer components.

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We propose PECEE¹, a novel framework for optimizing cluster reconfiguration and energy efficiency in large-scale WSNs. Simulations show that PECEE extends network lifetime from 50% to 90% compared to some notable solutions, including GSTEB.

II. RELATED WORKS

Research on Wireless Sensor Networks (WSNs) has centered on two technical pillars: *Cluster Head (CH) selection* and *routing*. These determine network lifetime and scalability, the main concerns for applications such as precision agriculture, where thousands of nodes must transmit raw data.

A. Cluster-Head Selection

LEACH established clustering as the foundation for energy-efficient communication through distributed CH rotation [3]. It required no central control but often ran into the problem of selecting low energy CHs. Later, HEED [4] and DEEC [5] incorporated residual energy and node degree for energy-aware CH election while adopting the distributed execution mode.

Centralized CH selection emerged with LEACH-C [6], where the Base Station (BS) used global energy and node location data to optimize CH placement. This improved energy distribution and network lifetime but incurred control overhead. Metaheuristic nature-inspired optimizations further refined CH placement for heterogeneous or larger networks [7].

Recent work integrates CH selection with application-level objectives. In UAV-assisted WSNs, for example, CH placement is jointly optimized with UAV trajectories to balance load and extend lifetime [8]. While efficient, these centralized schemes incur high reconfiguration costs whenever CHs change.

B. Routing in Clustered Networks

Routing governs data flow between nodes, CHs, and the BS. In LEACH, routing follows the star topology, nodes transmit directly to the CH, which aggregates and forwards data directly to the BS. This quickly becomes inefficient when clusters size scaled due to long single-hop links. PEGASIS [9] replaced this with a chain structure to reduce long-distance links, while GSTEB [11] introduced a tree-based model to distribute forwarding load and enhance scalability. These chain and tree structures remain key alternatives for intra-cluster routing.

In scaled networks where CH can not reach the BS in a direct manner, hierarchical routing was introduced. MHEACH [10] added multi-hop paths among CHs, improving network scalability and balancing energy across CHs. Cluster-based Routing Protocol (CRP) family expanded on this multi-hop idea for large-scale networks [12]. Later UAV-aided WSN generation alleviated the problem of inter-cluster routing [8].

However, *most clustered routing protocols rely on data aggregation to limit transmissions*, unsuitable for applications

requiring high-fidelity raw data collection such as precision agriculture or multimedia sensing. They demand routing schemes that preserve data fidelity while remaining energy-efficient. GSTEB proposed an algorithm for these applications [11]. Recently, HTC-RDC revisited this demand and proposed a load-balanced tree-construction strategy [13].

C. Emergence of the Elastic Cluster

Centralized CH selection offers effective global energy management, but frequent CH reassignment each round incurs costly network-wide updates from the BS, particularly in large scale networks. Existing approaches are insufficient for large, long-lived networks that support raw data collection. This paper tackles the challenge of combining the efficiency of centralized CH selection with the flexibility of localized routing to achieve *Elastic Clustering*: adaptive clusters formation and routing for raw data collection, while minimizing coordination overhead and extending network lifetime.

III. PECEE: PLATFORM FOR ELASTIC CLUSTERING AND ENERGY EFFICIENCY

This section describe our system model, the main idea of PECEE, and then elaborate on the key issues and technical details

A. System Model

Wireless transmissions: Wireless Sensor Nodes utilize the radio spectrum to transmit and receive data packets. We assume the unit disk transmission model in this paper, with an uniform *transmissionRange* amongst all Nodes.

Network Model: The size of large scale monitoring WSNs can span between hundreds to thousands of Sensor Nodes, deployed in a grid-like manner to ensure the sensing coverage.

We assume several key characteristics of this network:

- **Sparse Spacing:** Nodes are sparsely spaced at approximately their *transmissionRange*
- **Raw Data Collection:** Data packets travelling from all of the Nodes, up the CFT is not modified, each Parent Node simply relays its children's packets.
- **Node Homogeneity:** All Nodes have the same hardware specification: energy amount, radio transmission range and computation power.²

B. Main Idea

The core idea of PECEE is to conduct an *initial network setup* phase prior to data harvesting, establishing a cellular network composed of autonomous cells, each with a topology designed for long-term utilization. Concurrently, a cell coloring mechanism is implemented to ensure that cells sharing the same color (i.e., communicating simultaneously) are free from mutual radio interference. During this phase, “pending links” between adjacent cells are established and configured for reuse in subsequent operations as required.

²These assumptions simplify the model to evaluate PECEE’s core operation; heterogeneous nodes, irregular deployments, and unstable links will be addressed in future extended work.

¹Platform for Elastic Clustering and Energy Efficiency

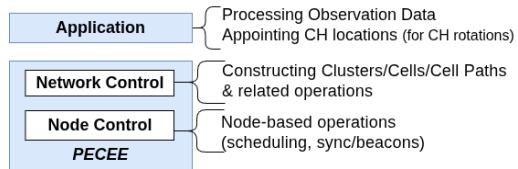


Fig. 1. Architecture of our WSN system.

The data collection process is then organized into rounds, each comprising two phases: the *Setup Phase* and the *Steady Phase*, inspired by the LEACH approach. During the Setup Phase, clusters are formed by grouping cells based on their self-selected affiliations. *Cell Paths* are generated to define straightforward data transmission routes toward the *Cluster Head* (CH), leveraging pre-established “pending links” at the boundaries of neighboring cells. In the Steady Phase, operating cyclically based on color schedules, cells of a given color forward data toward their respective CHs along the predetermined Cell Paths.

From a system perspective, the network is organized into three layers. The highest layer, the Application, hosts a service that enables users to utilize the network. This layer defines mechanisms for selecting CHs during each round (CH rotation) and application-specific criteria and Quality of Service (QoS) requirements (e.g., criteria for prioritizing which cluster each node should join), which will be discussed further in Section 4. The second layer, Network Control, provides mechanisms for establishing the cell grid and forming clusters. The lowest layer, Node Control, manages direct communication between neighboring nodes, scheduling transmissions to avoid interference.

C. The Cellular Overlay

PECEE organizes the network as a set of autonomous cells based on a regular hexagonal grid. Using GPS, nodes determine their coordinates and identify their corresponding cell within the hexagonal grid³. A node closest to the cell's center is designated as the *Cell Leader* (CL). The topology connecting nodes within a cell is constructed by the CL, utilizing node updates on their positions and neighbors (nodes communicate with neighbors via a standard beacon mechanism). The establishment of the cell grid, CLs, and local cell topologies occurs during the initial Network Setup Phase. Simultaneously, the CL designates nodes at the cell boundaries as *Cell Gateways* (CGs), which serve as connection points for data transmission to neighboring cells. These CGs act as “pending links” to establish cell paths connecting to CH in the future. With each CG as the root, a *Cell Forwarding Tree* (CFT) and transmission schedule are established, enabling other nodes in the cell to forward data to the CG when needed.

Due to page constraints, we refrain from elaborating on the detailed procedures for the network setup; comprehensive

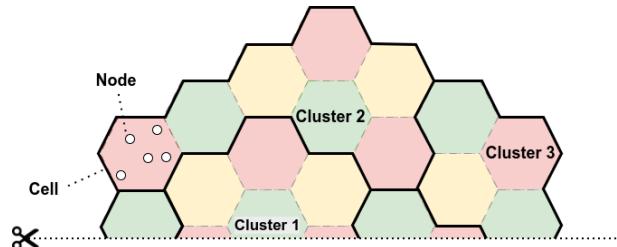


Fig. 2. The Cellular Overlay

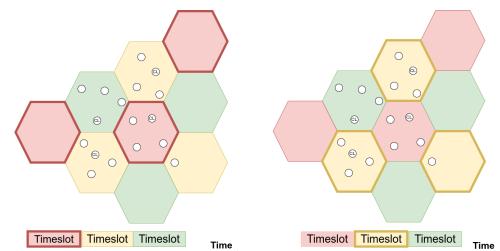


Fig. 3. Example of constraining transmissions with the Cellular Overlay over the time axis (TDMA)

algorithmic pseudocode will be provided in the extended version of this paper. Instead, illustrative figures (Fig. 2, Fig. 4, and Fig. 6) are included to elucidate the nature and significance of these steps.

To prevent mutual radio interference between non-adjacent cells, the edge length of each hexagonal cell is designed to exceed the transmission radius, with the ratio ($\varepsilon > 1$) serving as a configurable network parameter. A minimum of three colors is required to color the cell grid, ensuring that no two adjacent cells share the same color. For visualization, we adopt three distinct colors: Red, Green, and Yellow. As shown in Fig. 2, cells are arranged in a hexagonal pattern, with each pair of adjacent cells assigned different colors to avoid interference. Fig. 3 illustrates the transmission schedule, where cells of each color take turns transmitting in designated time slots, ensuring that only nodes in cells of the active color communicate with their neighbors during a given slot.

Fig. 4 illustrates the role of CG nodes: each CG serves as a “pending link” connecting a cell to its adjacent neighbor at the boundary, with a Cell Forwarding Tree rooted at the CG to define how nodes within the cell forward data toward the CG

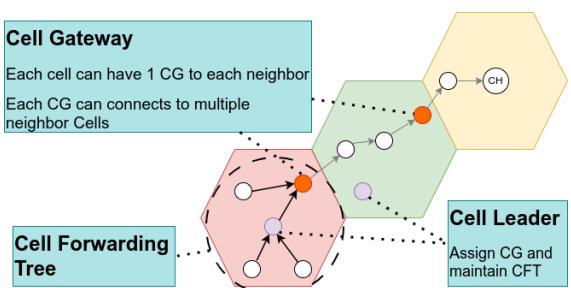


Fig. 4. Cell coordination and routing.

³We assume node locations are available; GPS is used as an example technique, but PECEE also applies with low-cost anchor-based localization (e.g., RSSI-based ranging) that provides sufficiently accurate coordinates.

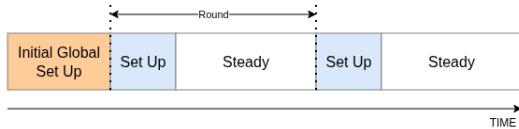


Fig. 5. Main Phases

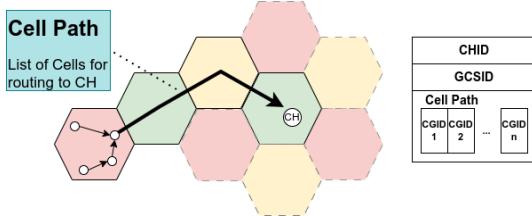


Fig. 6. Cell Path and CHA Packet

for subsequent transmission to the corresponding neighboring cell.

D. Main Phases

During the Setup Phase of each round, newly rotated CHs broadcast Cluster Head Advertisement (CHA) packets containing their location. Each CHA is forwarded across neighboring cells with an updated Cell Path (CP) field recording traversed cell IDs. Fig. 6 illustrates CP construction via interconnected CGs. After a timeout period, Cell Leaders (CLs) will have received multiple CHAs and autonomously select a CH (by selecting a CHA) based on Application Layer policies. The selected CHA defines the CP to the chosen CH, along with the corresponding Cell Gateways (CGs).

Through the topology setup steps in the Setup Phase, data collection in the Steady Phase becomes straightforward: each cell accumulates data via the CFT (following the associated transmission schedule), and the CG forwards the accumulated data to the next cell along the CP. Below, we provide a more detailed description of the setup steps in the Setup Phase.

When a CL receives multiple CHA packets from various new CHs, it updates its environmental state, including information about existing clusters (identified through old and new CHs it has interacted with), distances, and energy consumption levels. Based on the selection criteria and procedures specified by the Application Layer, CLs choose the most suitable cluster to join and establish corresponding technical parameters. A common criterion is to prioritize distance, where the CL simply selects the CH with the shortest cell-path. However, alternative criteria may be imposed by the Application Layer, such as minimizing the energy cost of transmitting each packet to the CH.

Our proposed PECEE solution serves as a platform that provides flexible algorithmic mechanisms to support various data harvesting applications with diverse objectives and Quality of Service (QoS) requirements. To achieve this, the framework incorporates modular optimization slots that function as callbacks for application-specific algorithms (e.g., for cluster construction or selection of CLs/CGs). These

algorithms are referred to as *Global Clustering Strategies* (GCS). The general mechanism for cluster construction is described through algorithmic pseudocode in Algo , where line 9 specifies the invocation of an appropriate GCS based on the application-specific context. The subsequent Section 4 provides specific application examples.

Algorithm Cluster Formation (executed by each CL)

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1: State:
2:  $CH\text{Aset} \leftarrow$  all received CH Advertisements (CHA)
3: if node is Cluster Head ( $CH_i$ ) then
4:   Broadcast CHA( $CH_i$ ) to all neighboring Cells
5: Upon receiving CHA( $CH_i$ ) from neighbor  $CL_k$ :
6:    $CH\text{Aset} \leftarrow CH\text{Aset} \cup \{\text{CHA}(CH_i)\}$ 
7:   Rebroadcast CHA( $CH_i$ ) to all neighbors except  $CL_k$ 
8: After CHA flood timeout  $T_f$ :
   {Determine best CH according to selection policy}
9:  $CH \leftarrow \text{CHSelect-GCS } (CH\text{Aset})$ 
10: if CH in Cell then
11:    $CG \leftarrow CH$ 
12:    $CFT \leftarrow \text{calculateAndCacheCFT}(CG)$ 
13: else
14:    $nextCell \leftarrow$  next Cell to  $CH$  (from  $CHA.\text{CellPath}$ )
      {Reuse cached topologies from Initial Network Setup}
15:    $CG \leftarrow \text{getCachedCG } (nextCell)$ 
16:    $CFT \leftarrow \text{getCachedCFT } (CG)$ 
17: end if
   {Synchronize routing state locally}
18: Update CFT info for all Cell Members
19: Result: Each CL selects next round CH, Cell Path, CG and CFT.

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IV. TYPICAL SCENARIOS IN USING PECEE

In this section, we discuss several typical applications where our proposed solution provides a robust platform to support critical real-world use cases.

Precision Agriculture. In this scenario, on-top applications may consist of services that continuously monitor and control the agricultural environment, equipped with a centralized optimization algorithm for CH selection. PECEE accepts requests with a list of CHs as input for each round (computed by the BS using the aforementioned centralized optimization module), then configures the network accordingly and manages the underlying system to collect and forward data to the CHs. The mechanism for relaying data from CHs to the BS, which is pre-selected by the application (e.g., using drones for data collection), is outside the scope of PECEE.

With the provided WSN platform, nodes periodically forward observation data to their respective Cluster Head (CH), which subsequently relays the data to the Base Station (BS) via hop-to-hop communication or through UAVs/drones. Alongside domain-specific agricultural data, information about the remaining energy levels of nodes is also transmitted. This enables the BS to maintain a comprehensive overview of the network and make optimal decisions for

designating CHs in subsequent rounds, replacing those that have operated for extended periods and exhibit significantly reduced energy levels compared to the network average. The designated CHs receive notifications from the BS and broadcast them within their local area, allowing nodes in the region to join an appropriate cluster based on defined selection criteria. These criteria may be application-specific, such as prioritizing the closest geographical distance to the CH or minimizing energy consumption for hop-to-hop communication to the CH. A third, more complex option involves balancing the energy consumption of a CH (dependent on cluster size) proportionally to its remaining energy. While this criterion is more challenging to satisfy, it helps facilitate load balancing and effectively extends network lifetime. To meet these criteria, PECEE incorporates pre-implemented modular algorithms (i.e., GCSs mentioned earlier) within the platform, which are activated based on the requirements of specific applications.

Intelligent Traffic Management. In an intelligent traffic management scenario, vehicles moving to a new region may re-register with a different cell and cluster. To navigate efficiently, each vehicle can connect to the CH to obtain updated intra-cluster traffic information. In the event of a traffic incident, nodes within a cell promptly report updates to the CH. Nodes equipped with cameras can proactively capture footage and send it to the CH for potential forwarding to the BS. Data from the CH can be relayed to Roadside Units (RSUs) for processing by AI systems, leveraging edge computing and fog computing capabilities. For complex traffic incidents generating large streaming data volumes, data can be transmitted via multiple cell paths to RSUs in neighboring clusters, enabling rapid delivery to a central processing unit with sufficient AI computational resources.

Smart Hospital IoT Network. Through the network of cells, CHs continuously collect information about hospital pathways, corridors, crowded patient areas, and emergency incident locations. This enables the system to coordinate and route Automated Guided Vehicles (AGVs) for transporting equipment, supplies, and medications to their destinations according to scheduled timelines.

V. SIMULATION AND EVALUATION

A. Settings

We evaluate the performance of PECEE through simulation-based experiments. Two simulation scenarios are considered: the Raw Data (RD) Scenario and the Data Aggregation (DA) Scenario, with a focus on the former due to its greater challenge in fully relaying data to the Base Station (BS). In the DA Scenario, data received at each intermediate node is aggregated into a single packet for forwarding. In both scenarios, we compare PECEE against a prominent baseline, GSTEB. Additionally, in the RD Scenario, we include HTC-RDC, a recent state-of-the-art method supporting RD, for comparison. Since existing solutions for RD often focus on building energy-efficient trees and lack clustering, we augment them with a cluster construction procedure using

TABLE I
SIMULATION PARAMETERS

Parameter	Setting
Node Type	Homogeneous
Node Density	4×10^{-4} nodes/m ²
Radio Model	Unit Disk Model
Transmission Radius	80 m
Sensing Rate	1 pkt/round

Voronoi-based spatial clustering method. All simulations employ the same CH rotation algorithm, which selects new CHs per round based on higher residual energy probabilities. Experiments are conducted using the OMNET++ simulation platform, integrated with the Castalia framework [14] for MAC-layer communication. We employ GSTEB [11] model of energy consumption. Common simulation parameters are detailed in Table I.

B. Results

1) *Network Lifetime:* We ran simulations on 3 networks sizes, to observe the performance of each solution for large-scale networks. Network Lifetime is defined as the round in which the first node depletes its energy (First Node Death).

TABLE II
NETWORK LIFETIME FOR RAW DATA SCENARIO IN ROUNDS

Network Settings	Routing Algorithm		
	PECEE	GSTE	HTC-RDC
Size 100 CHs count 3	340	152	253
400 6	174	61	92
400 12	190	88	163
400 24	195	158	173
900 27	178	125	130

TABLE III
NETWORK LIFETIME FOR DATA AGGREGATION SCENARIO IN ROUNDS

Network Settings	Routing Algorithm	
	PECEE	GSTE
Size 100 CHs count 3	480	357
400 12	901	281

2) *Node Energy over lifetime:* The long-term stability of the network is evaluated using node residual energy. We collect minimum and average residual energy value of nodes at end of each round. See Fig 7

3) *Cumulative Control Overhead:* The Cumulative Control Overhead (CCO) at round i represents the total network-wide energy spent for control transmissions up to that round, computed as $CCO_i = \frac{\sum_{r=1}^i \text{Transmitted Control Bits}_r}{\sum_{r=1}^i \text{Total Transmitted Bits}_r}$. Lower CCO indicates higher energy saving in control operations.

C. Analysis

In smaller networks, PECEE performs comparably to GSTEB and HTC-RDC but excels in larger networks, achieving 30-90% longer lifetime (see Table II, Fig 7). Table II also showed that **for 400-node networks with large individual**

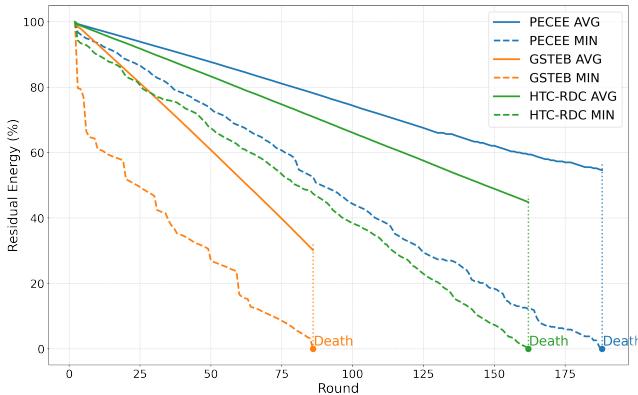


Fig. 7. Node residual energy over time for raw data scenario in a network of 400 nodes divided into 12 clusters.

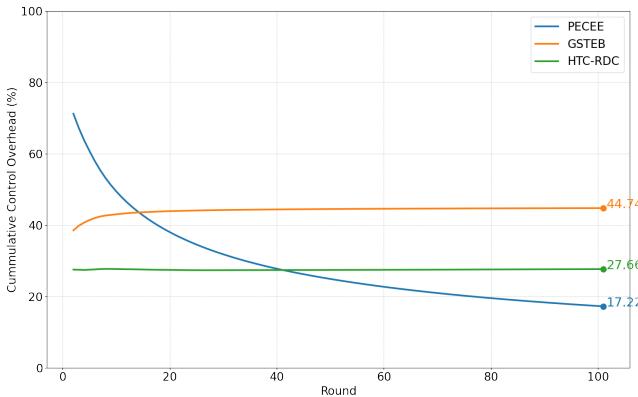


Fig. 8. Cumulative Control Overhead at round i .

clusters, PECEE nearly triples the lifetime of GSTEB and doubles that of HTC-RDC⁴. Initially, PECEE's high initialization cost (71%) reduces early performance, but control overhead drops (to 5.3%) by round 100, outperforming HTC-RDC (27%) and GSTEB (45%). This highlights a key insight: PECEE incurs substantial cost during initialization, however, once CGs and CFTs are fully established and reused intensively, the per-round overhead becomes negligible (as observed in Fig 8), enabling PECEE to extend network lifetime effectively.⁵ Table III shows that **with data aggregation, PECEE outperforms GSTEB, maintaining 200% network lifetime improvement in 400-nodes network**, and 30% in the smaller one.

VI. CONCLUSION

PECEE's Cellular Overlay reuses precomputed local topologies after each CH rotation, reducing control energy and avoiding full network reconfiguration. Though the initial Network Setup Phase incurs notable overhead, this cost yields long-term gains and realizes PECEE's philosophy of

⁴Line 2, Table II.

⁵In one example simulation: 43,470 packets in total for Initial Network Setup phase, and drops to 700 (2–7 per node) packets per round

topology reuse: trading early setup cost for sustained efficiency and stability. PECEE's Cellular Overlay reuses local topologies after CH rotation, reducing control energy and avoiding full network reconfiguration. Despite high initial setup costs, topology reuse ensures long-term efficiency. The framework scales effectively across network sizes, excelling in raw data applications like Precision Agriculture. Replacing simple heuristics with edge-AI could enable adaptive cluster optimization, supporting dynamic QoS demands while maintaining PECEE's scalability and energy efficiency for next-generation WSNs.

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