An Energy Efficient Routing Algorithm in Networking Using HEACT

Project submitted in partial fulfillment of the requirement for the degree of Bachelor of Technology in Computer Science and Engineering

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Declaration

We hereby declare that the project titled **"An Energy Efficient Routing Algorithm in Networking Using HEACT"** submitted to Veer Surendra Sai University of Technology for the award of the degree of Bachelor of Technology in Computer Science and Engineering is a result of original work carried out in this report. We also declare that the work has not been submitted, in whole or in part, to any other university as an exercise for a degree or any other qualification.

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Abstract

Addressing premature node failure and extending network duration in Wireless Sensor Networks (WSNs) requires sophisticated energy management through routing protocols. This work proposes and evaluates a novel protocol, the Hybrid Energy-Aware Cluster-Tree (HEACT), designed to enhance network longevity and stability. HEACT integrates periodic clustering (with CH selection influenced by residual energy and distance from the base station, plus cluster size caps) with a dual-mode Cluster Head (CH) transmission strategy. This strategy employs an initial direct CH-to-Base Station (BS) transmission phase to mitigate early energy depletion, followed by a transition to multi-hop routing along an inter-CH tree constructed using an energy-penalized cost metric to favor robust relay nodes. To assess its effectiveness, HEACT's performance is compared via simulation against two established protocols: the standard LEACH protocol and the dynamic Energy-Efficient Tree-Based (EETB) protocol. Simulations are conducted under identical conditions, analyzing critical performance indicators: network stability period (FDN), network lifetime (NL), total energy consumption dynamics, and packet delivery ratio. The results aim to quantify the performance improvements offered by the proposed HEACT architecture relative to traditional clustering and dynamic tree approaches in managing WSN energy resources.

Keywords: Wireless Sensor Networks; Energy Efficiency; Network Lifetime; Clustering; Tree-Based Routing; Network Stability Period

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ACO Ant Colony Optimization

BS Base Station

CER-CH Combining Election and Routing amongst Cluster Heads

CH Cluster Head

E-PEGASIS Enhanced Power-Efficient Gathering in Sensor Information Systems

EESRA Energy Efficient Scalable Routing Algorithm

EETB Energy-Efficient Tree-Based (protocol)

EE-TLT Energy-Efficient Two-Level Tree

FDN First Dead Node

GA Genetic Algorithm

HEACT Hybrid Energy-Aware Cluster-Tree (protocol)

HEED Hybrid Energy-Efficient Distributed Clustering

LEACH Low-Energy Adaptive Clustering Hierarchy

LEACH-C Centralized Low-Energy Adaptive Clustering Hierarchy

LND Last Node Dead

MEMS Micro-Electro-Mechanical Systems

MST Minimum Spanning Tree

NL Network Lifetime

PEGASIS Power-Efficient Gathering in Sensor Information Systems

PSO Particle Swarm Optimization

SEP Stable Election Protocol

SPIN Sensor Protocols for Information via Negotiation

TSO Tuna Swarm Optimization

UCR Unequal Clustering Routing

WSN Wireless Sensor Network

Chapter 1

Introduction

1.1 The Rise and Significance of Wireless Sensor Networks

The proliferation of low-cost, low-power micro-electro-mechanical systems (MEMS) technology, coupled with advancements in wireless communication, has propelled Wireless Sensor Networks (WSNs) to the forefront of modern monitoring and control systems [1]. WSNs typically consist of a large number of small, autonomous sensor nodes deployed across a physical area to observe environmental conditions (e.g., temperature, humidity, light, sound, pollutants), track objects, monitor structural health, or manage industrial processes. These nodes possess sensing, processing, and wireless communication capabilities, allowing them to collaboratively collect data and transmit it, often via multi-hop routes, to a central coordinating entity known as the Base Station (BS) or sink node. The BS typically acts as a gateway, connecting the WSN to external networks (like the internet) for data analysis, storage, and user interaction.

The applications of WSNs are vast and transformative. In environmental monitoring, they enable fine-grained data collection for climate change studies, precision agriculture, forest fire detection, and early warning systems for natural disasters. Industrial applications include process automation, equipment health monitoring, supply chain tracking, and ensuring safety in hazardous environments. In healthcare, WSNs facilitate remote patient monitoring, assisted living for the elderly, and tracking of medical assets. Furthermore, they are key enablers for Smart Cities, contributing to intelligent transportation systems, smart grids, structural health monitoring of infrastructure, and optimized resource management. The ability to deploy these networks in remote, hazardous, or inaccessible locations without requiring pre-existing infrastructure makes them uniquely valuable.

1.2 The Fundamental Challenge: Energy Constraint

Despite their versatility, the widespread adoption and long-term viability of WSNs are fundamentally constrained by the limited energy resources of individual sensor nodes. Nodes are typically powered by small batteries, which are often difficult or impossible to replace or recharge after deployment, especially in large-scale or remote applications. Consequently, energy efficiency becomes the most critical design consideration, influencing every aspect of the network's operation, from hardware design and sensing schedules to communication protocols and data processing techniques.

The communication subsystem is widely recognized as the dominant source of energy consumption in a typical sensor node. Transmitting or receiving data wirelessly consumes significantly more energy than sensing or processing tasks. Moreover, the energy required for transmission increases dramatically with distance (often following a power law, d^2 to d^4, depending on the environment [1]). This inherent characteristic makes long-distance, single-hop communication highly inefficient and unsustainable for battery-powered nodes.

1.3 The Problem of Unbalanced Energy Consumption and Network Longevity

Compounding the limited energy budget is the challenge of non-uniform energy consumption across the network. In many WSN architectures, certain nodes inevitably bear a heavier communication burden than others. Nodes located closer to the BS often act as relays for data originating from more distant nodes, leading to faster energy depletion in this "hotspot" region near the sink – the well-known "energy hole" problem. Similarly, in clustering protocols, the Cluster Heads (CHs) consume significantly more energy than regular member nodes due to receiving data from members, performing aggregation, and transmitting the aggregated data over potentially longer distances to the BS or other relays.

This unbalanced energy consumption leads directly to premature node failure. When critical relay nodes or overloaded CHs deplete their energy, connectivity can be lost, partitioning the network and preventing data from large sections from reaching the BS. This significantly shortens the effective network lifetime, often defined by metrics such as:

- Network Stability Period (FDN - First Dead Node): The time until the very first node in the network dies. A short stability period indicates poor load balancing and early network degradation.
- Network Lifetime (NL): Commonly defined as the time until the last node dies (LND), or sometimes until a certain percentage of nodes die, or until network partitioning occurs. Maximizing NL is crucial for long-term application viability.

Therefore, designing routing protocols that not only minimize overall energy consumption but also balance the energy load across nodes is essential for maximizing both the stability period and the overall lifetime of the WSN.

1.4 Existing Routing Paradigms and Their Limitations

Numerous routing strategies have been proposed to address energy efficiency in WSNs. These can be broadly classified:

- Flat Routing: Protocols like Directed Diffusion or SPIN involve data negotiation and interest propagation, but can incur significant overhead. Direct transmission from each node to the BS is the simplest but least scalable and most energy-intensive approach for all but the smallest networks.
- Hierarchical (Clustering) Routing: Protocols like LEACH [1] and its successors [2, 7, 9, 10, 12, 14] establish a two-tier hierarchy. Nodes form clusters, electing CHs responsible for managing intra-cluster communication and relaying aggregated data

towards the BS. Clustering significantly reduces energy consumption for member nodes by limiting their transmission range. However, standard LEACH suffers from random CH selection potentially leading to poor cluster distribution and energy imbalances. Direct CH-to-BS transmission remains a bottleneck, rapidly draining CHs far from the sink. While many variants improve CH selection using energy, distance, or other metrics, effectively balancing the inter-cluster transmission load remains a key challenge.

- Tree-Based Routing: These protocols construct explicit multi-hop paths forming a tree structure rooted at the BS (e.g., EETB [28]). Data is relayed hop-by-hop towards the root. This avoids the very long single hops of direct transmission or some LEACH variants. Protocols like EETB attempt to optimize this by calculating an ideal number of branches and using dynamic updates based on energy thresholds to adapt the tree structure and prevent overburdening low-energy nodes. However, nodes near the root can still become bottlenecks, and the overhead of maintaining an optimal global tree structure can be considerable, especially if updates are frequent.
- Chain-Based Routing: PEGASIS [20] forms a chain among nodes, reducing transmission overhead but introducing significant latency and a single point of failure vulnerability [23, 25].
- Hybrid Routing: These approaches attempt to combine the benefits of clustering and multi-hop routing (trees/chains) [23, 26, 27]. Often, they involve clustering locally and then establishing routes between CHs. While promising, effectively managing the interaction between the two levels and minimizing overall control overhead is complex.

1.5 Motivation and Proposed Solution: HEACT

While existing protocols have made significant strides, achieving both a long stability period (high FDN) and a long overall network lifetime (high NL) simultaneously remains challenging. Protocols excelling at one often compromise on the other. For instance, aggressive load balancing might extend NL but could initially burden specific nodes, leading to a low FDN. Conversely, simple schemes might have decent initial stability but fail to efficiently route data over the long term, shortening NL.

Furthermore, many hybrid protocols establish fixed inter-CH structures or rely on standard LEACH-like mechanisms for CH roles, potentially inheriting their limitations. There is a need for a hybrid protocol that explicitly addresses early node failure while incorporating robust, energy-aware mechanisms for sustained operation.

This paper proposes the Hybrid Energy-Aware Cluster-Tree (HEACT) protocol to bridge this gap. HEACT is founded on the principle of adaptive communication strategies tailored to different phases of the network's life and energy distribution. Its key innovations include:

1. Combined Energy/Distance CH Selection: Uses a probabilistic approach where candidacy is weighted by both the node's residual energy share and its relative distance from the BS, aiming for a balanced set of spatially distributed and energetically capable CHs.
2. Cluster Size Limitation: Explicitly limits the number of members per cluster

(HEACT_MAX_CLUSTER_SIZE) to prevent CH overload, directly promoting load balancing at the cluster level.

3. Initial Direct Transmission Phase: A critical feature where, for the first few reconfiguration cycles (HEACT_INITIAL_DIRECT_INTERVALS), CHs transmit directly to the BS. This deliberately avoids the high initial cost of multi-hop relaying, allowing the network to stabilize and node energies to differentiate before imposing complex routing tasks. This is specifically designed to improve the FDN.

4. Energy-Penalized Inter-CH Tree: After the initial phase, HEACT transitions to multi-hop routing. An inter-CH tree is constructed where the cost metric for selecting a parent CH heavily penalizes potential parents with low residual energy (using HEACT_TREE_ENERGY_PENALTY_EXPONENT). This ensures that the multi-hop backbone relies on the most energetically robust CHs available at that time, promoting longevity of the inter-cluster routing structure.

5. Periodic Reconfiguration: The clustering and tree structures are periodically rebuilt (HEACT_RECLUSTER_INTERVAL) to adapt to node deaths and changing energy landscapes.

By combining these mechanisms, HEACT aims to achieve superior performance by protecting the network during its initial, vulnerable phase and then transitioning to an efficient, energy-aware multi-hop structure for sustained data delivery.

1.6 Contributions and Paper Structure

The main contributions of this paper are:

- Proposal of the HEACT protocol, a novel hybrid routing algorithm combining adaptive clustering, cluster size limits, an initial direct transmission phase, and energy-penalized inter-CH tree routing.
- Detailed description of the HEACT algorithm components, including refined CH selection and energy-weighted tree construction.
- Comparative performance evaluation of HEACT against standard LEACH and the dynamic tree-based EETB protocol through simulation.
- Analysis of key performance metrics, including FDN, NL, throughput, and energy consumption characteristics, to demonstrate the effectiveness of the proposed approach.

The remainder of the paper is organized as follows: Chapter 2 details the Literature Review. Chapter 3 presents the Proposed Method/Model including the HEACT protocol algorithms and equations. Chapter 4 describes the Results and Discussion including simulation setup and performance metrics. Chapter 5 concludes the paper and Chapter 6 outlines directions for future work.

Chapter 2

Literature Review

The imperative of energy conservation in Wireless Sensor Networks (WSNs) has spurred extensive research into efficient routing protocol design. Over the years, numerous strategies have emerged, each with distinct architectural philosophies, operational mechanisms, and inherent trade-offs regarding energy consumption, network lifetime, stability, latency, and scalability. These protocols can be broadly categorized into flat, hierarchical (clustering), tree-based, and hybrid approaches. Given our focus on hierarchical and structured routing, we will primarily review clustering, tree-based, and hybrid strategies, positioning the proposed HEACT protocol within this landscape.

2.1 Hierarchical (Clustering) Routing Protocols

Clustering protocols organize the WSN into a hierarchical structure, typically involving groups of sensor nodes (clusters) managed by designated Cluster Heads (CHs). This approach offers several intrinsic advantages:

- Scalability: By localizing communication within clusters and limiting direct transmissions to the Base Station (BS), clustering can handle larger numbers of nodes more effectively than flat routing schemes.
- Energy Efficiency (for Members): Regular sensor nodes (members) usually only need to transmit data over short distances to their respective CHs, significantly saving energy compared to long-haul transmissions to the BS.
- Data Aggregation: CHs act as local aggregation points, fusing redundant data received from members before forwarding it, thereby reducing the overall traffic load in the network.
- Load Distribution: Rotating the energy-intensive CH role among different nodes over time helps distribute the burden, preventing any single node from depleting its energy prematurely solely due to CH duties.

LEACH (Low-Energy Adaptive Clustering Hierarchy) [1]: As the foundational clustering protocol, LEACH introduced the concept of randomized, self-organizing cluster formation and CH rotation. In each round, nodes probabilistically elect themselves as CHs based on a target percentage (P) and their past history of being a CH. Non-CH nodes join the nearest CH based on received signal strength. CHs create TDMA schedules for their members, receive member data, aggregate it, and transmit the aggregated packet directly to the BS. While groundbreaking, LEACH suffers from several limitations:

- Random CH selection offers no guarantee of optimal CH number or distribution.
- Direct CH-to-BS transmission is energy-intensive for distant CHs.

- It doesn't explicitly consider residual node energy during CH selection.

Enhancements to LEACH and Clustering: Recognizing LEACH's shortcomings, a vast body of work has focused on refining clustering protocols:

1. *Optimizing Cluster Head Selection:* This is arguably the most researched area. The goal is to select CHs that are energetically capable and strategically positioned.

    - Energy-Aware Selection: Protocols like LEACH-C (Centralized LEACH) use the BS to select CHs based on global energy information, ensuring better candidates but introducing centralization overhead. Distributed approaches like HEED use iterative refinement where nodes consider both their residual energy and an intra-cluster communication cost metric. SEP explicitly handles node heterogeneity. Many protocols incorporate residual energy directly into the LEACH probability threshold calculation [2, 7].

    - Location-Aware Selection: Some protocols factor in the CH candidate's distance to the BS, aiming to reduce the energy cost of inter-cluster communication [7]. Others consider node density to ensure better cluster coverage.

    - Fuzzy Logic & Metaheuristics: To handle the multi-objective nature of CH selection, researchers have employed fuzzy logic systems [9]. Metaheuristic optimization algorithms like Genetic Algorithms (GA) [13], Ant Colony Optimization (ACO) [6, 7], Particle Swarm Optimization (PSO), Firefly Algorithm [10], Tuna Swarm Optimization (TSO) [18], and others [12, 14] have been used.

    - Unequal Clustering: To combat the energy hole problem, protocols like UCR (Unequal Clustering Routing) [8] deliberately create smaller clusters closer to the BS.

2. *Optimizing Data Transmission:* Improvements also target how data moves within and between clusters.

    - Intra-Cluster Multi-hop: Some protocols allow members farther from the CH to relay data through closer members.

    - Inter-Cluster Multi-hop: CHs relay data through other CHs towards the BS [18, 21]. Algorithms might use Dijkstra's [15, 16] or Minimum Spanning Trees (MST) [17, 19] to establish inter-CH paths.

Limitations of Clustering Approaches: Despite these advancements, many clustering protocols still face inherent trade-offs. Multi-hop inter-CH routing can significantly save energy but adds complexity and potential delay.

2.2 Tree-Based and Chain-Based Protocols

These protocols focus on constructing explicit, often fixed or dynamically updated, data forwarding structures.

1. **Tree-Based Protocols:** Data naturally flows from numerous sources (leaves) towards a single sink (root/BS) along defined paths.

    - Advantages: Can provide clear routing paths and potentially lower overhead.

- Challenges: Efficiently constructing an energy-balanced tree is difficult. Nodes closer to the root are prone to rapid energy depletion.
- EETB (Energy-Efficient Tree-Based) [28]: This protocol attempts to mitigate the energy hole problem by optimal branch calculation (h_{opt}), distance-based formation, energy threshold (E_{th}) for relay selection, and dynamic update intervals (R_{dyit}).
- Other Tree Variants: Two-level tree clustering (e.g., EE-TLT [26]) combines clustering with tree structures.

2. **Chain-Based Protocols:** These represent a specific linear topology.
   - PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [20]: Nodes form a long chain. Each node only communicates with its immediate neighbors.
   - Advantages: Minimizes transmission distances for most nodes.
   - Disadvantages: Introduces significant data gathering latency and vulnerability to node failure. Enhancements like E-PEGASIS [24] consider residual energy [23, 25].

2.3 Hybrid Protocols

Hybrid approaches aim to combine the benefits of different paradigms. Examples include:

- Cluster-Chain: Forming local clusters and then linking the CHs into a PEGASIS-like chain [23].
- Cluster-Tree: Forming clusters and then building a tree structure between CHs [26, 27]. EE-TLT [26] uses a two-level tree. CER-CH [27] uses a top-down tree.
- Geographic/Zone-Based: Dividing the network into zones.

2.4 Positioning HEACT and Addressing Gaps

The proposed HEACT protocol is a hybrid cluster-tree approach designed to overcome specific limitations:

- **Addressing Low FDN:** HEACT incorporates the Initial Direct Transmission Phase to shield the network during its vulnerable initial period.
- **Improved Load Balancing:** HEACT combines energy-aware and distance-aware CH selection with explicit Cluster Size Limits (C_{max_size}).
- **Robust Inter-CH Routing:** HEACT transitions to an inter-CH tree using an Energy-Penalized Cost Metric (P_{exp}) for tree construction.
- **Adaptability:** Periodic reconfiguration ($I_{recluster}$) and dual-mode transmission provide adaptation.

2.5 Key Literature on WSN Routing Protocols

The field of energy-efficient routing in Wireless Sensor Networks (WSNs) has been extensively explored, with numerous protocols proposed to address the inherent energy constraints of sensor nodes and prolong network lifetime. This review categorizes and summarizes key contributions from foundational and contemporary works, highlighting their approaches to clustering, tree formation, and energy management, thereby contextualizing the design rationale for the HEACT protocol. Table 2.1 presents a summary of influential works.

Table 2.1: Summary of Key Literature on WSN Routing Protocols

Year	**Author(s) / Protocol**	**Contribution**
2000	Heinzelman et al. [1] (LEACH)	Introduced foundational adaptive clustering protocol with randomized CH rotation to distribute energy. Highlighted issues of direct CH-to-BS transmission for distant CHs.
2002	Lindsey S., Raghavendra, C. S. [20] (PEGASIS)	Proposed chain-based routing to minimize transmission distances, but introduced latency and single-point-of-failure issues. Showcased alternative to clustering.
2019	Micheletti et al. [27] (CER-CH)	Combined CH election and routing using a top-down tree approach among CHs in heterogeneous WSNs, relevant to inter-CH communication strategies.
2023	Tan N. D., Nguyen V, -H. [26] (EE-TLT)	Developed an energy-efficient two-level tree-based clustering protocol, demonstrating benefits of hybrid cluster-tree structures for WSN longevity.
2024	Hussain M. H. A., Mokhtar B., Rizk M. R. M. [2]	Provided a comparative survey of LEACH successors, categorizing various CH selection and data transmission optimization techniques. Useful for understanding LEACH's evolution.
2024	Wu L., Dawod A. Y., Miao F. [6]	Applied Ant Colony Optimization (ACO) for data transmission in WSNs, showcasing metaheuristic approaches for path optimization which can inspire CH routing.
2025	Chen N., Wen R. [28] (EETB)	Proposed a dynamic tree-based routing algorithm focusing on optimal branch calculation (h_{opt}) and energy threshold (E_{th}) based relay selection to mitigate the energy hole problem. Serves as a key benchmark.

2.6 Comparison Table

Table 2.2 summarizes the key characteristics and differences between HEACT, EETB, and LEACH.

Table 2.2: Comparison of Routing Protocol Characteristics

Feature	**LEACH (Standard)**	**EETB (Dynamic Tree)**	**HEACT (Proposed Hybrid)**
Basic Architecture	Hierarchical (Clustering)	Flat (Multi-Branch Tree)	Hierarchical (Cluster + Inter-CH Tree)
Primary Routing Unit	Cluster Head (CH)	All Nodes (Relay/Leaf)	Cluster Head (CH)
Intra-Network Routing	Member → CH (Single Hop)	Child Node → Parent Node (Multi-Hop)	Member → CH (Single Hop)
Sink Communication	CH → BS (Single Hop)	Branch Root → BS (Single Hop)	Dual Mode: Initial CH→BS (Single Hop), Later CH→Parent CH/BS (Multi-Hop Tree)
Structure Formation	Probabilistic CH Election (Random)	Distance-Based Tree Construction	Energy/Dist-Aware CH selection, Energy-Weighted Inter-CH Tree
Structure Update	Per Round (CH Rotation)	Dynamic Intervals (R_{dyit})	Periodic Intervals ($I_{recluster}$)
Energy Consideration	None (in standard LEACH selection)	E_{th} Threshold for Relays, h_{opt} Model	E_{cand}, E_{relay} Thresholds, Energy-Weighted Selection & Tree Cost
Load Balancing Mech.	CH Rotation	Optimal Branches (h_{opt}), E_{th} Updates	CH Rotation, Size Limit (C_{max_size}), Energy/Dist Selection, Energy Tree Cost
FDN Improvement Strategy	Implicit (Rotation)	E_{th} Threshold, Dynamic Updates	Initial Direct Phase, Size Limit, Energy Awareness

This comparative overview highlights how HEACT attempts to integrate mechanisms addressing specific weaknesses of pure clustering or pure tree-based approaches.

Chapter 3

Proposed Method

To address the limitations of existing routing protocols, particularly the trade-off between network stability (FDN) and overall lifetime (NL), we propose the Hybrid Energy-Aware Cluster-Tree (HEACT) protocol. HEACT is designed as an adaptive, hierarchical routing scheme that leverages the strengths of both clustering and tree-based multi-hop communication while incorporating specific mechanisms to mitigate premature node failure and balance energy consumption. The protocol operates in rounds, grouped into periodic reconfiguration cycles. Each cycle involves setup phases (CH selection, cluster formation, inter-CH tree construction) followed by a steady-state data transmission phase.

3.1 Operational Phases and Reconfiguration

HEACT's operation is divided into rounds. Periodically, the network undergoes a reconfiguration cycle to adapt its structure to the current energy landscape and node distribution. This cycle is triggered every $I_{recluster}$ rounds (e.g., 50 rounds) and also occurs in the very first round ($R = 1$) of network operation. A counter, $reconfig\_count$, tracks the number of completed reconfiguration cycles.

A key feature of HEACT is its dual-mode transmission strategy for Cluster Heads (CHs), determined by the $reconfig\_count$:

1. **Initial Direct Transmission Phase ($reconfig\_count \leq I_{direct}$):** During the first few reconfiguration cycles (defined by I_{direct}, e.g., 3 cycles or 150 rounds), CHs transmit their data packets directly to the Base Station (BS). The multi-hop inter-CH tree is not constructed or utilized.
2. **Tree-Based Transmission Phase ($reconfig\_count > I_{direct}$):** Once the network has passed the initial stabilization period, HEACT transitions to a multi-hop strategy for inter-cluster communication. An inter-CH routing tree is constructed and used.

This phased approach allows HEACT to prioritize stability early on and efficiency later.

3.1.1 Cluster Head (CH) Selection

The selection of appropriate CHs is crucial. HEACT employs an energy-aware and distance-conscious probabilistic selection mechanism at the start of each reconfiguration cycle:

1. **Eligibility Threshold:** Nodes must possess residual energy greater than E_{cand_thresh} (e.g., 15% of initial energy).
2. **Probability Calculation:** For each eligible node i, a probability threshold $T(i)$ is calculated, influenced by:

- The target CH percentage (P_{ch}).
- The node's current energy (E_i) relative to the total current energy (E_{total}) of all alive nodes (N_{alive}). Base probability:

$$\text{BaseProb}(i) = P_{ch} \times \frac{N_{alive} \times E_i}{E_{total}} \tag{3.1}$$

- The node's distance to the BS ($Dist_{i\_BS}$) relative to the average distance (Avg_Dist_{BS}), using a distance factor (D_{factor}).
- The final probability $T(i)$ is clamped:

$$T(i) = \max(0, \min(1.0, \text{BaseProb}(i) \times \text{DistModifier}(i))) \tag{3.2}$$

3. **Stochastic Selection:** Each eligible node i generates a random number $rand(i) \in [0, 1)$. If $rand(i) < T(i)$, it elects itself as a CH.
4. **Selection Guarantee (Fallback):** If no CHs are elected, the eligible candidate with the highest remaining energy is selected.

3.1.2 Cluster Formation

Following CH selection:

1. **Advertisement (Conceptual):** Elected CHs announce their status.
2. **Joining Process:** Each non-CH (member) node identifies the nearest alive CH.
3. **Cluster Size Limit Enforcement:** A CH verifies if its current member count is less than C_{max_size} (e.g., 15 members).
4. **Confirmation:** If the CH has capacity and both nodes have energy for control packet exchange ($E_{Tx}(\text{PACKET\_SIZE\_CTRL}, d)$ and $E_{Rx}(\text{PACKET\_SIZE\_CTRL})$), the join is successful.

3.1.3 Inter-CH Tree Formation

This phase is executed only if $reconfig\_count > I_{direct}$.

1. **Relay Eligibility:** Only CHs with current energy $\geq E_{relay\_thresh}$ (e.g., 30% of initial energy) can serve as parent nodes (relays).
2. **Initialization:** Tree links are reset. The closest CH meeting E_{relay_thresh} acts as the primary root.
3. **Iterative Tree Growth:**
   - Identify potential parent CHs (already in tree and is_relay_ch = True).
   - For each unvisited CH q_{ch}, calculate connection cost through each potential parent i_{ch} using an Energy-Penalized Cost Function:

$$\text{EnergyRatio}(i_{ch}) = \max(0.01, E_{i\_ch}/E_{initial}) \tag{3.3}$$

$$\text{Penalty}(i_{ch}) = \left(\frac{1.0}{\text{EnergyRatio}(i_{ch})}\right)^{P_{exp}} \quad (3.4)$$

$$\text{Cost}(q_{ch}, i_{ch}) = ((\text{distance}(q_{ch}, i_{ch})^2) + \text{PathCost}(i_{ch})) \times \text{Penalty}(i_{ch}) \quad (3.5)$$

where P_{exp} is an exponent (e.g., 1.5).

- Parent Selection: Find the pair ($best\_next\_ch, best\_parent\_ch\_id$) yielding minimum cost.
- Link Establishment: Add $best\_next\_ch$ to the tree.
- Relay Status Update: Mark new CH as is_relay_ch = True only if its energy meets E_{relay_thresh}.

4. **Termination:** Loop until all CHs are added or no eligible relay parent found.

3.1.4 Steady-State Data Transmission

Occurs in every round between reconfigurations:

1. **Intra-Cluster Transmission:** Alive members transmit data (`PACKET_SIZE_DATA`) to their CH.
2. **CH Data Aggregation:** CH aggregates data, consuming E_{DA} per bit.
3. **CH Transmission (Dual Mode):**
   - If $reconfig\_count \leq I_{direct}$: CH transmits directly to BS.
   - If $reconfig\_count > I_{direct}$: CHs transmit to their parent CH (or BS if parent is BS) according to the inter-CH tree.

3.2 HEACT: Proposed Algorithm

The proposed Hybrid Energy-Aware Cluster-Tree (HEACT) protocol aims to optimize network lifetime and stability in WSNs through an adaptive, hierarchical routing strategy. It combines periodic clustering with a dual-mode inter-cluster communication mechanism involving an initial direct transmission phase followed by multi-hop routing along an energy-aware tree. HEACT operates in rounds, with network reconfiguration occurring at predefined intervals.

3.2.1 Overview

HEACT divides the network operation into reconfiguration cycles. Within each cycle, Cluster Heads (CHs) are selected based on residual energy and distance metrics. Non-CH nodes form clusters around these CHs, subject to size limitations. Data transmission follows a two-phase approach depending on the network's operational stage: initially, CHs communicate directly with the Base Station (BS) to ensure stability; subsequently, they transition to using an energy-aware multi-hop tree constructed amongst themselves for improved long-term efficiency. The key components and parameters are detailed below and summarized in Table 3.1.

Table 3.1: Mathematical Notations and Definitions for HEACT

Notation	Definition
N	Total number of sensor nodes
$Nodes$	Set of all sensor nodes $\{n_1, \ldots, n_N\}$
BS	Base Station position coordinates
$E_{initial}$	Initial energy of each node
R	Current simulation round number
R_{max}	Maximum simulation rounds
$I_{recluster}$	Reconfiguration interval in rounds (`HEACT_RECLUSTER_INTERVAL`)
I_{direct}	Number of initial reconfiguration cycles using direct TX (`HEACT_INITIAL_DIRECT_INTERVALS`)
$reconfig\_count$	Counter for completed reconfiguration cycles
P_{ch}	Target average CH percentage (`HEACT_P_CH`)
E_{cand_thresh}	Minimum energy for CH candidacy (`HEACT_MIN_ENERGY_FOR_CH_CANDIDACY`)
E_{relay_thresh}	Minimum energy for a CH to act as a relay in inter-CH tree (`HEACT_MIN_ENERGY_FOR_CH_RELAY`)
C_{max_size}	Maximum number of members per cluster (`HEACT_MAX_CLUSTER_SIZE`)
D_{factor}	Distance factor influencing CH selection probability (`HEACT_DIST_FACTOR_CH_SELECTION`)
P_{exp}	Exponent for energy penalty in inter-CH tree cost calculation (`HEACT_TREE_ENERGY_PENALTY_EXPONENT`)
n_i	Sensor node i
E_i	Current residual energy of node i
$Dist_{i\_BS}$	Distance from node i to the BS
CH_Set	Set of nodes currently selected as Cluster Heads
$Clusters$	Dictionary mapping ch_id to list of $member\_ids$
$n_i.parent\_ch\_id$	ID of the parent CH for CH i in the inter-CH tree ("BS" if root)
$n_i.children\_ch\_ids$	Set of child CH IDs for CH i in the inter-CH tree
$n_i.is\_relay\_ch$	Boolean indicating if CH i can relay for other CHs
$n_i.path\_cost\_sq\_ch$	Accumulated (potentially weighted) cost from CH i to BS via tree
$T(i)$	Calculated probability threshold for node i becoming a CH
$E_{Tx}(m, d)$, $E_{Rx}(m)$, $E_{DA}(m)$	Energy for transmit, receive, aggregate (from Section III of original text, adjust if section number changed)
`PACKET_SIZE_DATA`, `PACKET_SIZE_CTRL`	Packet sizes in bits

The core adaptive mechanism of HEACT relies on periodic reconfiguration, detailed in Algorithm 1 (assuming this is your main loop algo). This process is triggered at the start of round 1 and subsequently every $I_{recluster}$ rounds.

- **Initialization:** The reconfiguration counter ($reconfig\_count$) is incremented. The algorithm determines if the network is still within the initial direct transmission phase ($is\_initial\_phase$) based on whether $reconfig\_count$ exceeds I_{direct}. Node roles and cluster assignments from the previous cycle are reset.

- **CH Selection:** The refined CH selection process (Algorithm 2, assuming this is Select_HEACT_CHs_Refined) is invoked to elect CHs for the current cycle based on energy share and distance factor.
- **Cluster Formation:** Non-CH nodes attempt to join the nearest available (alive and non-full) CH using Algorithm 3 (assuming this is Form_HEACT_Clusters), respecting the C_{max_size} limit. Energy consumed during the join handshake is accounted for.
- **Inter-CH Tree Building:** If the network is beyond the initial direct phase (**not** *is_initial_phase*), the energy-penalized tree building process (Algorithm 4, assuming this is Build_InterCH_Tree_HEACT_Revised) is executed among the currently alive CHs. This step establishes the multi-hop paths for the subsequent steady-state phase. A flag (*build_tree_this_cycle*) indicates whether the tree was successfully constructed.

3.3 HEACT Protocol Operational Flow

The overall operational logic of the HEACT protocol is depicted in the flowchart in Figure 3.1. The simulation begins with the initialization of nodes and network parameters. Each round of operation is then executed within a main loop, contingent upon the simulation not exceeding the maximum round limit (R_{max}) and the presence of alive sensor nodes.

A core aspect of HEACT is its periodic network reconfiguration. This is triggered either at the very first round or subsequently at intervals defined by $I_{recluster}$. During reconfiguration, the $reconfig\_count$ is incremented. A critical decision is then made based on whether the network is in its initial direct transmission phase (i.e., if $reconfig\_count \leq I_{direct}$). If it is the reconfiguration phase, Cluster Heads (CHs) are selected using an energy and distance-aware mechanism, followed by cluster formation where non-CH nodes join the nearest CH, respecting cluster size limits.

If the network is determined to be in the initial direct phase, the inter-CH tree construction step is bypassed. However, if the network has transitioned beyond this initial phase, an inter-CH tree is built using an energy-penalized cost metric to establish robust multi-hop paths between CHs.

Following the setup (or potential skip of tree building), the network enters the steady-state phase. Member nodes transmit their sensed data to their respective CHs. These CHs then aggregate the received data along with their own. The subsequent CH transmission strategy depends on the network's current operational phase and whether a tree was built in the current reconfiguration cycle. If the `use_tree_phase` condition is met (i.e., not in the initial phase and a tree is available), CHs transmit their aggregated data via the established inter-CH tree, typically in an order starting from the leaves towards the root/BS. Otherwise (i.e., during the initial direct phase or if tree construction failed/was skipped), CHs transmit their data directly to the Base Station (BS).

After data transmission, node energies are updated to reflect consumption, and the status of nodes (alive/dead) is checked. This cycle of reconfiguration (if applicable) and steady-state operation repeats until the simulation concludes. This adaptive, phased approach allows HEACT to prioritize stability in early rounds and energy efficiency in later rounds, aiming for enhanced network longevity.

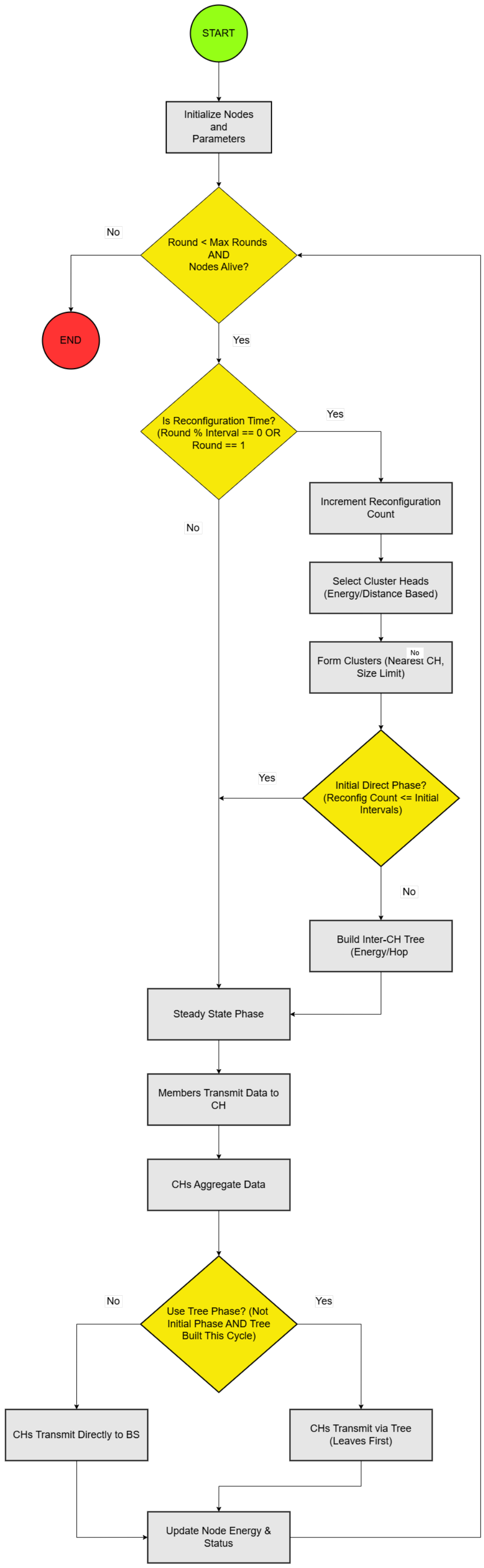


Figure 3.1: Overall Operational Flow of the HEACT Protocol.

3.3.1 HEACT Algorithm Procedures

Algorithm 1 HEACT Main Loop

Input: Nodes, BS, R_{max}, Reconfiguration params, CH/Cluster/Tree params.
Output: Stats.

Initialize Nodes; $round\_num \leftarrow 0$; $reconfig\_count \leftarrow 0$; $CH\_Set \leftarrow \emptyset$; $Clusters \leftarrow \emptyset$; Initialize Stats.
$build\_tree\_this\_cycle \leftarrow$ False
while $round\_num < R_{max}$ **and** count(alive nodes) > 0 **do**
  $round\_num \leftarrow round\_num + 1$
  if $(round\_num - 1)$ **mod** $I_{recluster} == 0$ **or** $round\_num == 1$ **then**
    {Reconfiguration}
    $reconfig\_count \leftarrow reconfig\_count + 1$
    $is\_initial\_phase \leftarrow (reconfig\_count \leq I_{direct})$
    $build\_tree\_this\_cycle \leftarrow$ False
    $Setup\_Energy \leftarrow$ HEACT-SETUP(Nodes, params..., $is\_initial\_phase, CH\_Set, Clusters$)
    Update $round\_energy\_consumed$ with $Setup\_Energy$
    if not $is\_initial\_phase$ **and** CH_Set has alive CHs **then**
      $build\_tree\_this\_cycle \leftarrow$ True
  {Steady-State}
  $use\_tree \leftarrow (reconfig\_count > I_{direct})$ **and** $build\_tree\_this\_cycle$
  $Live\_CHs\_Steady \leftarrow \{ch \in CH\_Set$ such that ch is alive$\}$
  if $Live\_CHs\_Steady$ is not empty **then**
    $Steady\_Energy, Steady\_Packets \leftarrow$ HEACT-STEADY-STATE(Nodes, $Live\_CHs\_Steady, Clusters, use\_tree$)
    Update $round\_energy\_consumed$ with $Steady\_Energy$
    $round\_packets\_to\_bs \leftarrow Steady\_Packets$
  UPDATE-STATS-AND-STATUS(...)
  if count(alive nodes) $== 0$ **then**
Finalize Stats['all_dead']
return Stats

Procedure 1 HEACT-SETUP

Input: Nodes, CH/Cluster/Tree params, $is\_initial\_phase$.
Input/Output: $CH\_Set, Clusters$.
Output: $Setup\_Energy$.

$Setup\_Energy \leftarrow$ map(node_id $\rightarrow$ 0.0)
Reset roles for alive nodes.
$Current\_CH\_Set, Select\_Energy \leftarrow$ Select_HEACT_CHs_Refined(...)
Update $Setup\_Energy$; $CH\_Set \leftarrow Current\_CH\_Set$
$Live\_CHs\_Selected \leftarrow \{ch \in CH\_Set$ such that ch is alive$\}$
if $Live\_CHs\_Selected$ is not empty **then**
$Current\_Clusters, Form\_Energy \leftarrow$ Form_HEACT_Clusters(...)
Update $Setup\_Energy$; $Clusters \leftarrow Current\_Clusters$
else
$Clusters \leftarrow \emptyset$
if not $is\_initial\_phase$ **then**
$Live\_CHs\_For\_Tree \leftarrow \{ch \in CH\_Set$ such that ch is alive$\}$
if $Live\_CHs\_For\_Tree$ is not empty **then**
Build_InterCH_Tree_HEACT_Revised(...)
return $Setup\_Energy$

Algorithm 2 Select_HEACT_CHs

Input: Nodes, P_{ch}, E_{cand_thresh}, D_{factor}.
Output: $CH\_Set, Select\_Energy$.

$CH\_Set \leftarrow \emptyset$; $Select\_Energy \leftarrow$ map(node_id $\rightarrow$ 0.0)
Get $Alive\_Nodes, N_{alive}, E_{total}, Avg\_Dist_{BS}$.
if $E_{total} \leq 0$ **or** $N_{alive} == 0$ **then**
return $CH\_Set, Select\_Energy$
for each node $n \in Alive\_Nodes$ **do**
if $n.energy < E_{cand\_thresh}$ **then**
continue
Calculate $BaseProb$ using energy share.
Calculate $DistModifier$ using $RelDist$ and D_{factor}.
$Threshold \leftarrow$ clamp$(BaseProb \times DistModifier, 0, 1)$
if random() $< Threshold$ **then**
Add n to CH_Set
if CH_Set is empty **and** $Alive\_Nodes$ is not empty **then**
{Fallback}
... (select best fallback eligible node with highest energy) ...
Add selected fallback node to CH_Set.
return $CH\_Set, Select\_Energy$

Algorithm 3 Form_HEACT_Clusters

Input: Nodes, CH_Set, C_{max_size}.
Output: $Clusters, Form\_Energy$.

```
Form_Energy ← map(node_id → 0.0)
Get Alive_Members, Live_CH_Map. Initialize Clusters, Cluster_Sizes.
if Live_CH_Map is empty then
    return Clusters, Form_Energy
Shuffle(Alive_Members)
for each member ∈ Alive_Members do
    Find best_ch_id from Eligible_CHs (alive and Cluster_Sizes[ch_id] < C_max_size).
    if best_ch_id ≠ −1 then
        Perform join handshake (deduct TX/RX energy for PACKET_SIZE_CTRL).
        if successful then
            Add member to Clusters[best_ch_id]; Increment Cluster_Sizes[best_ch_id].
return Clusters, Form_Energy
```

Algorithm 4 Build_InterCH_Tree_HEACT

Input: $Live\_CHs$, BS, $E_{relay\_thresh}, P_{exp}$.
Output: Modifies CH node attributes.

```
if Live_CHs is empty then
    return
Reset tree attributes for ch ∈ Live_CHs.
Sorted_CHs ← Sort Live_CHs by dist_to_bs.
Initialize Visited_CH_IDs, Root_CHs.
Select primary_root (closest eligible relay, or closest overall if no eligible).
if none then
    return
Add primary_root.id to Visited_CH_IDs; Add primary_root to Root_CHs.
Unvisited_CHs ← Live_CHs − Visited_CH_IDs.
Potential_Parents_Map ← {ch.id → ch for ch ∈ Root_CHs if ch.is_relay_ch}.
while Unvisited_CHs is not empty do
    Find best_next_ch from Unvisited_CHs and best_parent_ch_id from
    Potential_Parents_Map that minimizes energy-penalized cost. {Cost = ((dist^2 +
    parent_path_cost) × (1/parent_energy_ratio)^P_exp).}
    if parent found then
        Update best_next_ch parent/child links, path_cost_sq_ch.
        if best_next_ch meets E_relay_thresh then
            Add best_next_ch to Potential_Parents_Map.
        Mark best_next_ch as visited; Remove from Unvisited_CHs.
    else
        {No more connections possible}
```

Algorithm 5 Get_CH_Traversal_Order_HEACT

Input: *Cluster_Heads*.

Output: Ordered list *Order* of CH IDs.

```
Order ← []; Processed_IDs ← ∅
Live_CHs_Map ← (alive and connected CHs from Cluster_Heads).
if Live_CHs_Map is empty then
    return Order
Build Parent_Map and Children_Map for the CH tree.
Find Leaves of the CH tree. Queue ← Sorted Leaves.
while Queue is not empty do
    ch_id ← Pop from Queue.
    if ch_id ∈ Processed_IDs then
        continue
    Add ch_id to Order; Add ch_id to Processed_IDs.
    parent_id ← Parent_Map.get(ch_id).
    if parent_id is valid and all its children are in Processed_IDs then
        Add parent_id to Queue (if not already processed/in queue); Sort Queue.
Add any Remaining CHs not processed (should be roots) to Order.
return Order
```

Procedure 2 HEACT-STEADY-STATE

Input: Nodes, *Live_CHs_Steady*, *Clusters*, *use_tree_phase*.

Output: *Steady_Energy*, *Packets_To_BS*.

```
Initialize Steady_Energy, Packets_To_BS, CH_Map, CH_Packets_Aggregated.
{Members transmit to CHs}
for each ch_id, member_ids ∈ Clusters do
   ch_node ← CH_Map.get(ch_id).
   if ch_node is alive then
      for each member_id ∈ member_ids do
         {Member transmits to CH}
         Perform member TX to CH, update energies, increment
         CH_Packets_Aggregated[ch_id] if successful.
{CH Aggregation}
for each ch_id, ch_node ∈ CH_Map do
   if ch_node is alive then
      Deduct aggregation energy based on CH_Packets_Aggregated[ch_id].
      if still alive then
         CH_Packets_Aggregated[ch_id] ← CH_Packets_Aggregated[ch_id] + 1 (for
         self packet).
{CH Transmission}
if not use_tree_phase then
   {Direct to BS}
   for each ch_id, ch_node ∈ CH_Map do
      if ch_node is alive and CH_Packets_Aggregated[ch_id] > 0 then
         Transmit CH_Packets_Aggregated[ch_id] packets directly to BS, update
         energy, Packets_To_BS.
else
   {Tree Transmission}
   Order ← Get_CH_Traversal_Order_HEACT(Live_CHs_Steady).
   for each ch_id ∈ Order do
      ch_node ← CH_Map.get(ch_id).
      if ch_node is alive and CH_Packets_Aggregated[ch_id] > 0 then
         Transmit CH_Packets_Aggregated[ch_id] packets to parent
         (ch_node.parent_ch_id).
         if parent is BS then
            Update Packets_To_BS.
         else if parent is another CH then
            Parent receives and updates its CH_Packets_Aggregated.
return Steady_Energy, Packets_To_BS
```

Procedure 3 UPDATE-STATS-AND-STATUS

Input: Nodes, Stats, *round_num*, *num_alive_before*, *round_packets_to_bs*.

Output: Updates Stats.

```
Final death check for nodes this round.
Record num_alive_now, round_packets_to_bs, total_energy in Stats.
Update Stats['first_dead'] and Stats['all_dead'] if applicable.
```

3.3.2 Illustrative Operational Example of HEACT

To elucidate the dynamic operation of the HEACT protocol, consider a representative scenario over several rounds with 10 sensor nodes. The reconfiguration interval ($I_{recluster}$) is set to 3 rounds, and the initial direct transmission phase (I_{direct}) spans the first reconfiguration cycle.

Reconfiguration Cycle 1 (Rounds 1-3: Initial Direct Phase)

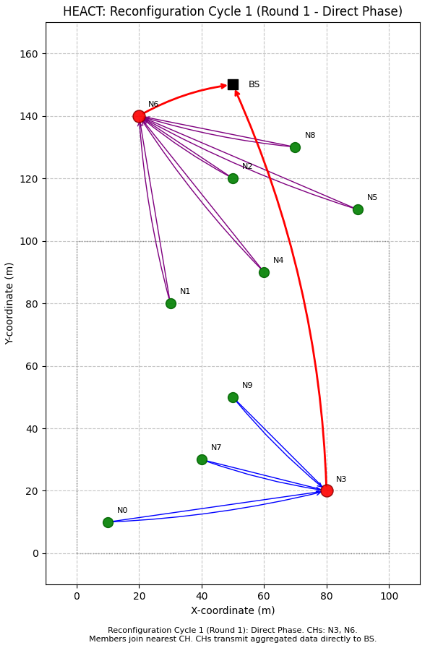
In Round 1, the first reconfiguration is triggered ($reconfig\_count = 1$). As this falls within the initial direct phase, the inter-CH tree is not constructed. During CH selection (Algorithm 2), all nodes, initially possessing 0.5 J of energy, are eligible. The selection probability $T(i)$ for each node i is calculated based on its energy share and distance from the BS (50, 150), with the distance factor ($D_{factor} = 1.1$) slightly favoring nodes farther from the BS. For this illustration, assume nodes N3 (at (80, 20), relatively far) and N6 (at (20, 140), relatively close) are elected as CHs.

Following CH selection, cluster formation (Algorithm 3) occurs. Non-CH nodes {N0, N1, N2, N4, N5, N7, N8, N9} associate with the nearest alive CH, subject to the maximum cluster size ($C_{max\_size} = 7$). This results in the formation shown in Table 3.2: N3 becomes the CH for {N0, N7, N9}, and N6 becomes the CH for {N1, N2, N4, N5, N8}. Control packets are exchanged for joining, incurring a minor energy cost.

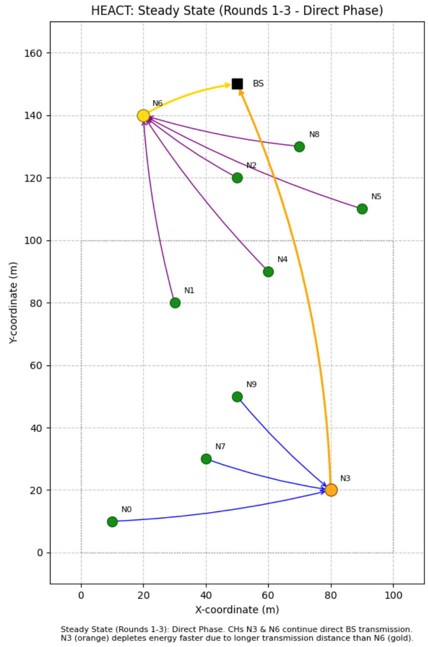
Table 3.2: Cluster Formation - Round 1

Cluster Head	**Members**	**Size**
N3 (80, 20)	{N0, N7, N9}	3
N6 (20, 140)	{N1, N2, N4, N5, N8}	5

During the steady-state phase of Rounds 1, 2, and 3, member nodes transmit their data to their respective CHs. CH N3 aggregates 3 member packets plus its own and, being in the initial direct phase, transmits this aggregated data (4 packets total) directly to the BS. Given N3's distance of approximately 133m, this incurs a high energy cost, likely utilizing the multipath transmission model. Simultaneously, CH N6 aggregates 5 member packets plus its own (6 packets total) and transmits directly to the BS over a much shorter distance of approximately 32m, incurring a significantly lower energy cost (likely free space model). This pattern repeats for rounds 2 and 3, leading to a substantial energy drain on CH N3 compared to CH N6.



Cycle 1 (a) - CH Selection and Cluster Formation (Direct Phase).



Cycle 1 (b) - Steady-State Direct Transmission to BS.

Figure 3.2: Illustrative HEACT Operation: Reconfiguration Cycle 1 (Direct Phase). (a) Setup phase with CH selection and cluster formation. (b) Steady-state data transmission.

Reconfiguration Cycle 2 (Rounds 4-6: Tree Phase)

In Round 4, the second reconfiguration is triggered ($reconfig\_count = 2$). As $reconfig\_count > I_{direct}$, the network now transitions to the Tree Phase, and an inter-CH tree will be constructed. All nodes reset their roles, and CH selection (Algorithm 2) is performed again. Due to energy depletion in the previous cycle, N3 is now less likely to be re-elected. Assume nodes N1 (at (30, 80), mid-distance, high remaining energy) and N8 (at (70, 130), close, high remaining energy) are selected as the new CHs.

Cluster formation (Algorithm 3) then occurs around N1 and N8, resulting in the assignments shown in Table 3.3.

Table 3.3: Cluster Formation - Round 4

Cluster Head	**Members**	**Size**
N1 (30, 80)	{N0, N3, N4, N7, N9}	5
N8 (70, 130)	{N2, N5, N6} (assuming N6 available)	3

Subsequently, inter-CH tree formation (Algorithm 4) is executed. Both N1 and N8 are assumed to have energy exceeding E_{relay_thresh} (0.15 J). N8, being closer to the BS ($\approx$ 28.3m) than N1 ($\approx$ 80.6m), is selected as the primary root, establishing a direct link to the BS ($N8.parent\_ch\_id$ = "BS") with $N8.path\_cost\_sq\_ch \approx 800$. N1 then evaluates connecting to N8. The distance $dist$(N1, N8) is approximately 64.0m. Assuming N8's energy ratio is high (e.g., 0.96 relative to initial), the energy penalty multiplier for N8 as a parent is low (e.g., ≈ 1.06). The cost for N1 to select N8 is calculated as $\text{Cost}(\text{N1, N8}) \approx (64.0^2 + 800) \times 1.06 \approx 5190$. N1 joins the tree under N8, resulting in the inter-CH tree: BS $\leftarrow$ N8 $\leftarrow$ N1.

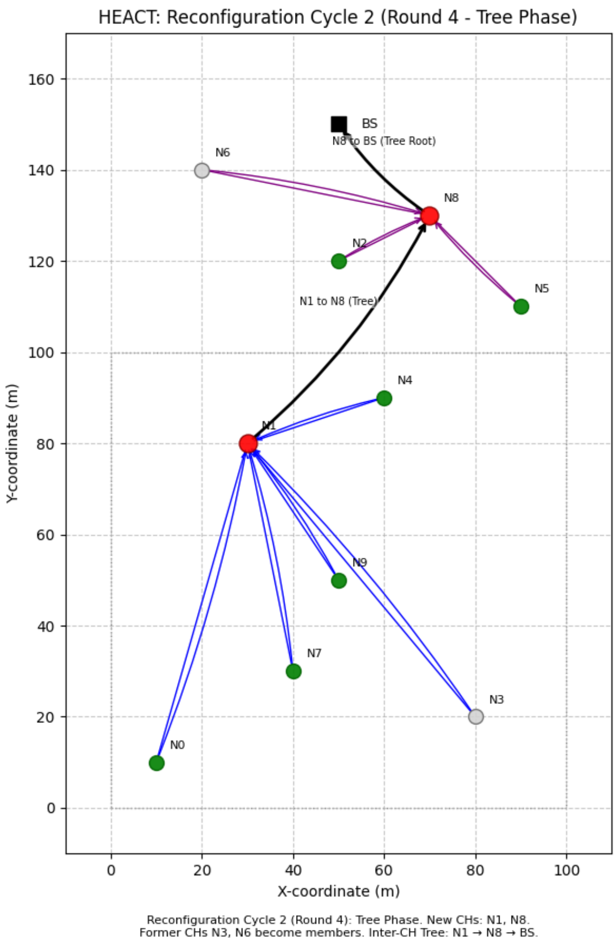


Figure 3.3: Illustrative HEACT Operation: Cycle 2 - Inter-CH Tree Formation and Multi-hop Transmission.

During the steady-state phase of Rounds 4, 5, and 6, data flows as follows: Members of cluster N1 transmit to CH N1. Members of cluster N8 transmit to CH N8. CH N1 aggregates data from its 5 members plus its own (6 packets) and transmits this to its parent, CH N8. CH N8 receives these 6 packets, aggregates them with data from its own 3 members plus its own packet (4 packets), resulting in a total of 10 packets. CH N8 then transmits these 10 aggregated packets directly to the BS. In this configuration, N1 acts as a relay CH, while N8 acts as the final relay to the BS, bearing a significant communication load. Energy depletion reflects these roles, with N8 consuming more energy than N1 due to the larger aggregated payload and its own cluster's traffic. This example illustrates the adaptive nature of HEACT, shifting from a protective direct transmission strategy to an energy-aware multi-hop tree structure to optimize energy consumption and prolong network operation.

3.4 Equations Used in Simulation

The following equations are utilized across the simulation framework, primarily defined by the energy model and some protocol-specific calculations:

1. Transmission Energy (E_{Tx}):

$$E_{Tx}(m,d) = E_{elec} \times m + E_{amp}(d) \times m \quad \text{(Eq. 1)}$$

where $E_{amp}(d)$ depends on the distance d:

- $E_{amp}(d) = E_{fs} \times d^2$ for $d < D_{THRESHOLD}$
- $E_{amp}(d) = E_{mp} \times d^4$ for $d \geq D_{THRESHOLD}$

2. Distance Threshold ($D_{THRESHOLD}$):

$$D_{THRESHOLD} = \sqrt{\frac{E_{fs}}{E_{mp}}} \quad \text{(Assuming } E_{mp} > 0\text{)} \quad \text{(Eq. 2)}$$

3. Receiving Energy (E_{Rx}):

$$E_{Rx}(m) = E_{elec} \times m \quad \text{(Eq. 3)}$$

4. Data Aggregation Energy (E_{DA}):

$$E_{DA}(m) = E_{da} \times m \quad \text{(Eq. 4)}$$

5. EETB Optimal Branch Calculation (h_{opt} - Simplified Basis): (Derived from minimizing total energy, related to Eq. 19 in original EETB paper [28])

$$h_{opt} \approx \left(\frac{N_{alive} \times E_{fs} \times L^2/3}{(E_{fs} \times Avg\_Dist_{BS}^2 - E_{elec} - E_{da}) - (E_{fs} \times L^2/6)} \right)^{1/3} \quad \text{(Eq. 5)}$$

(Conceptual Basis for `calculate_optimal_branches_eetb`)

6. EETB Energy Threshold (E_{th} - Basis): (Related to Eq. 20-23 in original EETB paper [28])

$$\alpha(j) \approx \frac{\max(E_c(i,j)) - \text{avg}(E_c(i,j))}{\max(E_c(i,j))} \quad (3.6)$$

$$E_{th}(j) = \text{avg}(E_{rem}(i,j)) \times \alpha(j) \quad \text{(Eq. 6)}$$

(Basis for `calculate_energy_threshold_and_interval_eetb`)

7. EETB Dynamic Interval (R_{dyit} - Basis): (Related to Eq. 24-27 in original EETB paper [28])

$$\lambda(i,j) = E_c(i,j)/\text{avg}(E_c(k,j)) \quad (3.7)$$

$$R_{min}(j) = \min(E_{rem}(i,j)/E_c(i,j)) \quad (3.8)$$

$$R_{dyit}(j) = R_{min}(j)/(\min(\lambda(i,j)) \times 2) \quad \text{(Eq. 7)}$$

(Basis for `calculate_energy_threshold_and_interval_eetb`)

8. LEACH CH Selection Threshold ($T(n)$):

$$T(n) = \frac{P_{ch}}{1 - P_{ch} \times (R \pmod{1/P_{ch}})} \quad \text{for nodes } n \text{ eligible in round } R \quad \text{(Eq. 8)}$$

9. HEACT CH Selection Threshold ($T(i)$ - Simpler version, for illustration):

$$\text{EnergyFactor}(i) = \frac{E_i}{E_{initial}} \tag{3.9}$$

$$T(i) = \text{HEACT\_P\_CH} \times \text{EnergyFactor}(i) \quad \text{(Eq. 9)}$$

(Note: The actual HEACT CH selection is more complex, including E_{total} and D_{factor} as described in Section 3.2.)

Assumptions for Examples (consistent with later scenarios):

- $E_{elec} = 50 \times 10^{-9}$ J/bit
- $E_{fs} = 10 \times 10^{-12}$ J/bit/m^2
- $E_{mp} = 0.0013 \times 10^{-12}$ J/bit/m^4
- $E_{da} = 5 \times 10^{-9}$ J/bit
- Packet Size (m) = 4000 bits (data), 200 bits (control)
- Initial Energy ($E_{initial}$) = 0.5 J
- Target CH % (P or P_{ch}) = 0.1

Calculated $D_{THRESHOLD}$:

$$D_{THRESHOLD} = \sqrt{E_{fs}/E_{mp}} = \sqrt{(10 \times 10^{-12})/(0.0013 \times 10^{-12})} \approx 87.7 \text{ meters}$$

3.5 Equation Examples

1. Transmission Energy (E_{Tx})

- *Example 1a: Short Distance ($d < D_{THRESHOLD}$)* Node A transmits a 4000-bit packet to Node B at $d = 50$ meters. $E_{Tx}(4000, 50) = (50 \times 10^{-9} \times 4000) + (10 \times 10^{-12} \times 50^2 \times 4000) = 200 \times 10^{-6} + 100 \times 10^{-6} = 300 \times 10^{-6}$ J $= 0.3$ mJ.
- *Example 1b: Long Distance ($d \geq D_{THRESHOLD}$)* A CH transmits a 4000-bit packet to BS at $d = 100$ meters. $E_{Tx}(4000, 100) = (50 \times 10^{-9} \times 4000) + (0.0013 \times 10^{-12} \times 100^4 \times 4000) = 200 \times 10^{-6} + 520 \times 10^{-6} = 720 \times 10^{-6}$ J $= 0.72$ mJ.

2. Distance Threshold ($D_{THRESHOLD}$) As calculated: $D_{THRESHOLD} \approx 87.7$ meters.

3. Receiving Energy (E_{Rx}) A CH receives a 4000-bit packet. $E_{Rx}(4000) = 50 \times 10^{-9} \times 4000 = 200 \times 10^{-6}$ J $= 0.2$ mJ.

4. Data Aggregation Energy (E_{DA}) CH aggregates 20000 bits. $E_{DA}(20000) = 5 \times 10^{-9} \times 20000 = 100 \times 10^{-6}$ J $= 0.1$ mJ.

9. HEACT CH Selection Threshold ($T(i)$ - Simpler Version Example) `HEACT_P_CH` = 0.1. Node i has $E_i = 0.4$ J. $E_{initial} = 0.5$ J. EnergyFactor(i) $= 0.4/0.5 = 0.8$.

$T(i) =$ `HEACT_P_CH` $\times$ EnergyFactor$(i) = 0.1 \times 0.8 = 0.08$ (8% chance). (Note: Parameter names like `HEACT_P_CH` are kept in if they refer to code constants, while E_i is a math variable.)

3.6 HEACT Functionality Scenario Examples

Parameters Recap (from simulation setup):

- `INITIAL_ENERGY` $= 0.5$ J
- $E_{ELEC} = 50 \times 10^{-9}$ J/bit, $E_{FS} = 10 \times 10^{-12}$ J/bit/m^2, $E_{MP} = 0.0013 \times 10^{-12}$ J/bit/m^4
- $E_{DA} = 5 \times 10^{-9}$ J/bit
- `PACKET_SIZE_DATA` $= 4000$ bits, `PACKET_SIZE_CTRL` $= 200$ bits
- $D_{THRESHOLD} \approx 87.7$ m
- `HEACT_P_CH` $= 0.1$
- `HEACT_MIN_ENERGY_FOR_CH_CANDIDACY` $= 0.075$ J (0.15×0.5J)
- `HEACT_MIN_ENERGY_FOR_CH_RELAY` $= 0.15$ J (0.30×0.5J)
- `HEACT_MAX_CLUSTER_SIZE` $= 15$
- `HEACT_DIST_FACTOR_CH_SELECTION` $= 1.1$
- `HEACT_TREE_ENERGY_PENALTY_EXPONENT` (P_{exp}) $= 1.5$
- `HEACT_INITIAL_DIRECT_INTERVALS` $= 3$
- `HEACT_RECLUSTER_INTERVAL` $= 50$
- `BS_POS` $= (50, 150)$

Scenario 1: HEACT CH Selection (Round 1, Energy & Distance Impact)

- Conditions: Round 1, $N_{alive} = 100$. Total initial energy $E_{total} = 100 \times 0.5 = 50$ J. Assume $Avg_Dist_{BS} = 90$m.
- Node A: (30, 130), $Dist_{A\_BS} = \sqrt{(50-30)^2 + (150-130)^2} = \sqrt{400+400} = \sqrt{800} \approx 28.3$ m (Close). Energy $E_A = 0.5$ J.
- Node B: (90, 20), $Dist_{B\_BS} = \sqrt{(50-90)^2 + (150-20)^2} = \sqrt{1600+16900} = \sqrt{18500} \approx 136.0$ m (Far). Energy $E_B = 0.5$ J.
- Calculation (Node A - Close): BaseProb$(A) = P_{ch} \times (N_{alive} \times E_A / E_{total}) = 0.1 \times (100 \times 0.5/50) = 0.1$. RelDist$(A) = Dist_{A_BS}/Avg_Dist_{BS} \approx 28.3/90 \approx 0.314$. Scale $= 1.0 -$ RelDist$(A) = 0.686$. DistMod$(A) \approx (1/$`HEACT_DIST_FACTOR_CH_SELECTION`$) + (1 - 1/$`HEACT_DIST_FACTOR_CH_SELECTION`$) \times (1 - \text{Scale})$ DistMod$(A) \approx (1/1.1) + (1 - 1/1.1) \times (0.314) \approx 0.909 + 0.0286 \approx 0.938$. $T(A) =$ BaseProb$(A) \times$ DistMod$(A) \approx 0.1 \times 0.938 = 0.0938$ (9.38% chance).

- Calculation (Node B - Far): $\text{BaseProb}(B) = 0.1$. $\text{RelDist}(B) \approx 136.0/90 \approx 1.511$. $\text{Scale} = \min(1.0, (\text{RelDist}(B) - 1.0)/(\text{MaxRatio} - 1.0))$; assume MaxRatio = 2.0. $\text{Scale} = \min(1.0, (1.511 - 1.0)/(1.0)) = 0.511$. $\text{DistMod}(B) \approx 1.0 + (\texttt{HEACT\_DIST\_FACTOR\_CH\_SELECTION} - 1.0) \times \text{Scale}$ $\text{DistMod}(B) \approx 1.0 + (1.1 - 1.0) \times 0.511 \approx 1.051$. $T(B) = \text{BaseProb}(B) \times \text{DistMod}(B) \approx 0.1 \times 1.051 = 0.1051$ (10.51% chance).
- Interpretation: Farther node B has a slightly higher chance due to the distance factor (`HEACT_DIST_FACTOR_CH_SELECTION`).

Scenario 2: HEACT Cluster Formation (Size Limit)

- Conditions: During cluster formation. CH X at (50, 50) is alive. `HEACT_MAX_CLUSTER_SIZE` = 15. CH X already has $current\_cluster\_sizes[X] = 15$ members. Member node M at (55, 55) determines CH X is its closest alive CH.
- Process: Node M identifies CH X as closest. M checks capacity of CH X. Since $current\_cluster\_sizes[X]$ (15) is not less than `HEACT_MAX_CLUSTER_SIZE` (15), node M cannot join CH X. M seeks next closest CH with space.
- Interpretation: Cluster size limit prevents CH overload.

Scenario 3: HEACT Inter-CH Tree Building (Energy Penalty Impact)

- Conditions: Round $R = 200$ ($reconfig\_count = 4$, so Tree Phase). Unvisited CH q at (70,70) needs a parent. Two potential parents exist: Parent i: Position (50,90), Energy $E_i = 0.45$ J (High Energy), $\text{PathCost}(i) = 3000$. Parent j: Position (60,100), Energy $E_j = 0.16$ J (Low Energy, just above $E_{relay_thresh} = 0.15$J), $\text{PathCost}(j) = 2500$. $E_{initial} = 0.5$ J, $P_{exp} = 1.5$.
- Cost via Parent i: $dist(q, i) = \sqrt{(70 - 50)^2 + (70 - 90)^2} = \sqrt{800} \approx 28.3$ m. $\text{EnergyRatio}(i) = \max(0.01, 0.45/0.5) = 0.9$. $\text{Penalty}(i) = (1.0/0.9)^{1.5} \approx 1.17$. $\text{Cost}(q, i) \approx ((28.3^2) + 3000) \times 1.17 = (800 + 3000) \times 1.17 \approx 4446$.
- Cost via Parent j: $dist(q, j) = \sqrt{(70 - 60)^2 + (70 - 100)^2} = \sqrt{1000} \approx 31.6$ m. $\text{EnergyRatio}(j) = \max(0.01, 0.16/0.5) = 0.32$. $\text{Penalty}(j) = (1.0/0.32)^{1.5} \approx 5.524$. $\text{Cost}(q, j) \approx ((31.6^2) + 2500) \times 5.524 = (1000 + 2500) \times 5.524 \approx 19334$.
- Result: CH q chooses higher-energy parent i, despite slightly worse base path, due to massive penalty for low-energy parent j.

Scenario 4: HEACT Steady State (Initial Direct vs. Later Tree Phase)

- Conditions: A CH k is located at (20, 20), $Dist_{k\_BS} \approx 133.4$ m. In the Tree Phase, its parent p is CH i from Scenario 3, located at (50, 90), $dist(k, p) \approx 76.2$ m. Assume CH k aggregated data equivalent to 10 packets (including its own). Bits $m = 10 \times 4000 = 40000$.
- Initial Direct Phase (e.g., Round $R = 50$, $reconfig\_count \leq I_{direct}$): CH k transmits directly to BS. Distance $d = 133.4$ m ($\geq D_{THRESHOLD}$). $E_{Tx}(40000, 133.4) = (50 \times 10^{-9} \times 40k) + (0.0013 \times 10^{-12} \times 133.4^4 \times 40k)$ $E_{Tx} \approx (2 \times 10^{-3}) + (16.48 \times 10^{-3}) \approx 18.48 \times 10^{-3}$ J $= 18.48$ mJ.
- Tree Phase (e.g., Round $R = 200$, $reconfig\_count > I_{direct}$): CH k transmits to parent CH i. Distance $d = 76.2$ m ($< D_{THRESHOLD}$). $E_{Tx}(40000, 76.2) =$

$(50 \times 10^{-9} \times 40k) + (10 \times 10^{-12} \times 76.2^2 \times 40k)$ $E_{Tx} \approx (2 \times 10^{-3}) + (2.32 \times 10^{-3}) \approx 4.32 \times 10^{-3}$ J $= 4.32$ mJ. Parent CH i also consumes $E_{Rx}(40000) = 50 \times 10^{-9} \times 40k = 2 \times 10^{-3}$ J $= 2.0$ mJ to receive.

- Interpretation: Transmitting directly costs CH k more (18.48 mJ) than transmitting to its closer parent CH i (4.32 mJ). Total energy for this hop in tree phase ($4.32+2.0 = 6.32$ mJ) is much less than direct cost.

Chapter 4

Results and Discussion

4.1 Simulation Setup

The simulation environment models a typical WSN deployment scenario:

- Network Area: A square field of 100 meters x 100 meters ($L = 100$).
- Node Deployment: $N = 100$ sensor nodes are deployed uniformly and randomly within the network area. Node positions remain static after deployment.
- Base Station (BS) Location: A single, static BS with unlimited energy resources is located outside the monitoring area at coordinates `BS_POS` = (50, 150).
- Node Initialization: All sensor nodes are homogeneous, starting with an initial energy `INITIAL_ENERGY` = 0.5 Joules.
- Communication Model:
  - Packet Sizes: Data packets (`PACKET_SIZE_DATA`) are set to 4000 bits. Control packets (`PACKET_SIZE_CTRL`) are set to 200 bits.
  - Radio Energy Model: The first-order radio model is used, with parameters: Transceiver electronics energy (E_{elec}): 50 nJ/bit. Amplifier energy (Free Space, E_{fs}): 10 pJ/bit/m^2. Amplifier energy (Multipath, E_{mp}): 0.0013 pJ/bit/m^4. Distance threshold ($D_{THRESHOLD}$): Calculated as $\sqrt{E_{fs}/E_{mp}} \approx 87.7$ meters.
  - Data Aggregation Energy (E_{da}): 5 nJ/bit consumed at the CH/relay node.
- Protocol-Specific Parameters:
  - LEACH: Target CH percentage $P = 0.1$.
  - EETB: Uses its internal logic for calculating h_{opt} and the dynamic update mechanism (E_{th}, R_{dyit}) based on energy consumption patterns, including the safeguard ensuring $h_{opt} \geq 3$ for $N > 5$.
  - HEACT (Refined): Target CH percentage $P_{ch} = 0.1$; Reconfiguration Interval $I_{recluster} = 50$ rounds; Minimum CH Candidacy Energy $E_{cand\_thresh} = 0.075$ J; Minimum CH Relay Energy $E_{relay\_thresh} = 0.15$ J; Initial Direct Intervals $I_{direct} = 3$; Maximum Cluster Size $C_{max\_size} = 15$; Distance Factor $D_{factor} = 1.1$; Tree Energy Penalty Exponent $P_{exp} = 1.5$.
- Simulation Termination: Each simulation run executes for a maximum of `MAX_SIM_ROUNDS` = 2000 rounds or terminates earlier if all sensor nodes deplete their energy ($energy \leq 0$). A node is considered "dead" when its energy drops to zero or below.

For each comparison scenario, the same initial random node placement was used.

4.2 Performance Metrics

The performance of the routing protocols (HEACT, EETB, LEACH) is evaluated based on:

1. Network Stability Period (FDN - First Dead Node): Rounds until first node dies.
2. Network Lifetime (NL - Last Dead Node): Rounds until last node dies or max rounds.
3. Total Data Packets Received by BS: Cumulative throughput.
4. Number of Alive Nodes vs. Round.
5. Total Remaining Network Energy vs. Round.
6. Average Energy per Alive Node vs. Round.

4.3 Comparisons

Comprehensive simulations were conducted to evaluate the proposed HEACT protocol against LEACH and EETB, focusing on the critical aspects of energy efficiency, network longevity, and data delivery performance. The following discussion interprets the outcomes based on the protocol designs, analyzing key performance metrics.

4.3.1 Network Stability and Lifetime (FDN & NL)

The stability period (FDN) and overall network lifetime (NL) or Network Life Round (NLD) are crucial indicators of a WSN routing protocol's effectiveness in managing energy. Figure 4.1 illustrates the number of alive nodes over simulation rounds for the compared protocols. It is anticipated that standard LEACH, due to its random CH selection and direct CH-to-BS transmission, will exhibit the earliest First Dead Node (FDN) or First Death Detected (FDD). EETB, with its energy threshold (E_{th}) preventing low-energy nodes from relaying and its potentially balanced initial tree structure based on h_{opt}, should demonstrate significantly better stability than LEACH. The proposed HEACT protocol is specifically designed to maximize FDN. The crucial initial direct transmission phase (I_{direct} intervals) directly addresses early node failure by allowing initial CHs to transmit directly to the BS, avoiding immediate relay burdens. This, combined with the cluster size limit (C_{max_size}), is expected to result in HEACT exhibiting an FDN superior to both LEACH and potentially EETB, with the HEACT curve in Figure 4.1 remaining at 100 alive nodes for a substantially longer period.

Regarding overall network lifetime (NL), LEACH is expected to demonstrate the shortest lifespan, characterized by a relatively steep decline in alive nodes after its FDN. Both EETB and HEACT are designed for extended lifetimes and should significantly outperform LEACH. HEACT aims to achieve longevity through its combination of energy-saving clustering, periodic CH rotation, and the transition to an energy-efficient multi-hop inter-CH tree constructed using an energy-penalized metric (P_{exp}), which favors robust CHs for the backbone. This strategy is intended to maintain network connectivity longer.

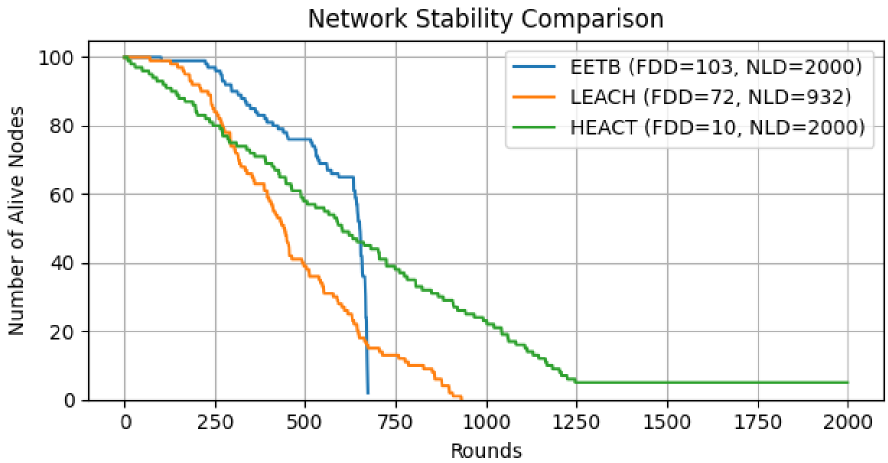


Figure 4.1: Network Stability: Alive Nodes vs. Rounds for LEACH, EETB, and HEACT.

4.3.2 Data Throughput

Data throughput, measured as the cumulative packets received by the BS, is presented in Figure 4.2. LEACH often exhibits the highest initial throughput rate due to direct CH-to-BS links, but this rate rapidly diminishes as CHs die. EETB's throughput should be more stable initially. HEACT's throughput profile is expected to reflect its dual-mode nature: a rate potentially comparable to LEACH during its initial direct phase, followed by a slightly lower but much more sustained rate during its tree-based phase. Consequently, the total cumulative throughput of HEACT is anticipated to be competitive with or exceed EETB, and significantly higher than LEACH, due to its superior network lifetime.

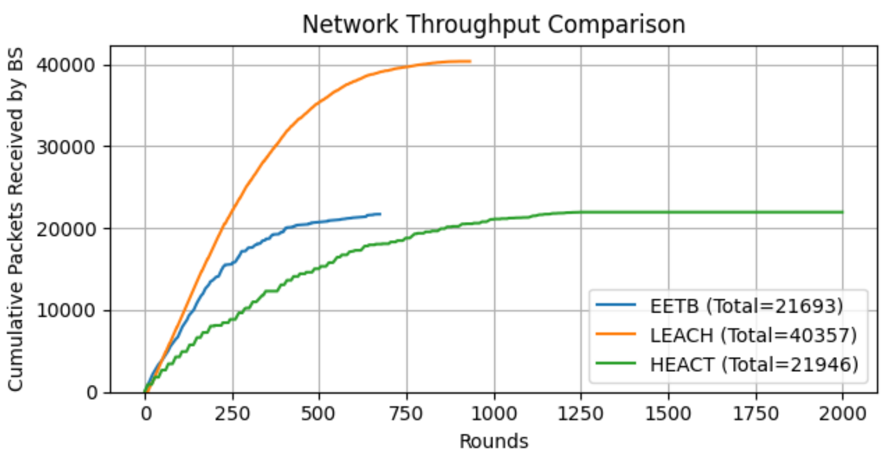


Figure 4.2: Network Throughput: Cumulative Data Packets Received by BS vs. Rounds.

4.3.3 Energy Consumption and Balancing

The total remaining network energy, depicted in Figure 4.3, will likely show LEACH depleting the network's energy fastest. EETB and HEACT should demonstrate much slower and more controlled depletion profiles. HEACT's curve might exhibit slight periodic dips corresponding to the energy consumed during reconfiguration cycles ($I_{recluster}$), but its overall decay rate during steady-state phases should be low.

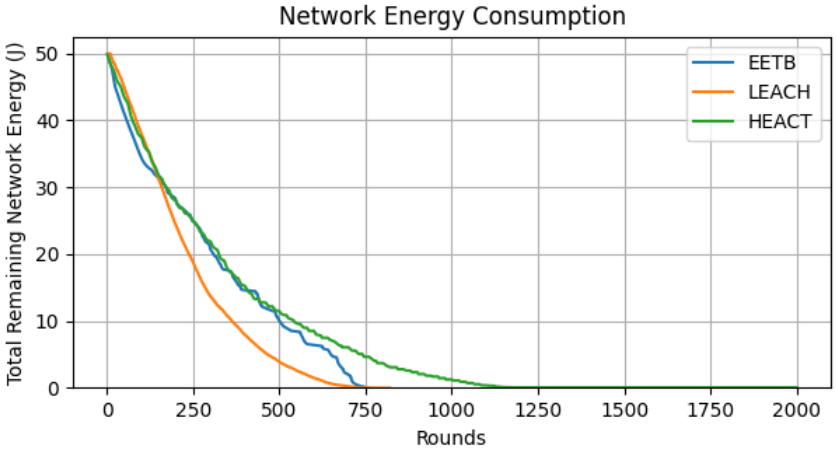


Figure 4.3: Network Energy Consumption: Total Remaining Network Energy vs. Rounds.

Figure 4.4 (Average Energy per Alive Node) provides insights into load balancing. LEACH's average energy is expected to drop quickly. EETB might show a more gradual decline. HEACT, leveraging cluster size limits, CH rotation, and energy-aware selection/tree building, is expected to maintain a higher average energy among surviving nodes for longer, indicating more effective energy balancing across the network compared to LEACH, and potentially smoother decay profiles than EETB.

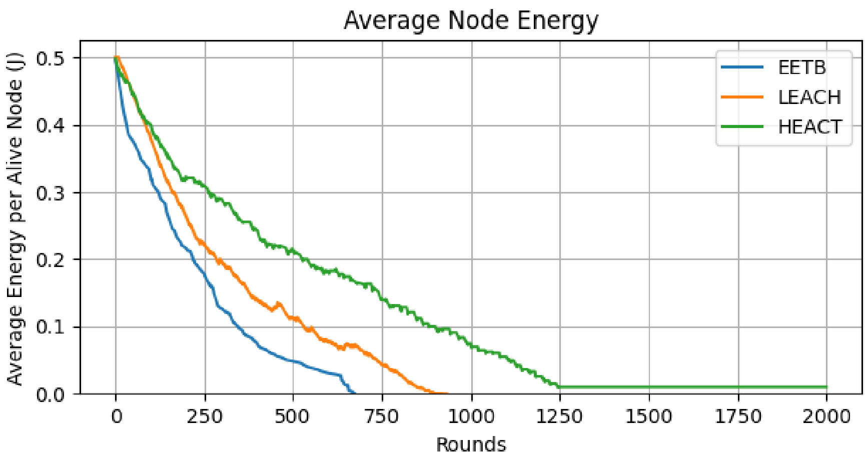


Figure 4.4: Load Balancing: Average Energy per Alive Node vs. Rounds.

4.3.4 Overall Interpretation and Impact of BS Location

The simulation results are anticipated to validate the design goals of the HEACT protocol. The introduction of the initial direct transmission phase, coupled with cluster size limits, should demonstrably improve the network stability period (FDN). The subsequent transition to an energy-aware, multi-hop inter-CH tree allows HEACT to maintain efficient operation over an extended period, achieving a competitive network lifetime (NL) and total data throughput. HEACT thus aims to present a robust hybrid architecture that successfully balances early-round stability with long-term operational longevity and effective data gathering in energy-constrained WSNs.

The impact of Base Station location was also considered (results not shown as a figure here but discussed conceptually). As expected, all protocols would likely show decreased throughput as the BS moves farther away. LEACH, relying solely on single CH-to-BS hops, would suffer the most. Protocols employing multi-hop routing, namely EETB and HEACT (during its tree phase), should exhibit greater resilience, mitigating the impact of long BS distances for nodes/CHs far from the BS.

Chapter 5

Conclusion

This paper introduced and evaluated the Hybrid Energy-Aware Cluster-Tree (HEACT) protocol, a novel routing strategy designed to significantly enhance both the stability period (FDN) and overall lifetime (NL) in energy-constrained Wireless Sensor Networks. HEACT's distinct architecture combines several key mechanisms: adaptive clustering with energy- and distance-aware Cluster Head (CH) selection alongside explicit cluster size limits for local load balancing; a crucial dual-mode CH transmission strategy featuring an initial direct CH-to-Base Station (BS) transmission phase to mitigate early node failure; and a subsequent transition to multi-hop routing along an inter-CH tree constructed using an energy-penalized cost metric that prioritizes robust, high-energy CHs for relay duties.

Comparative simulations against standard LEACH and the dynamic tree-based EETB protocol indicate HEACT's superior performance. The results strongly suggest that HEACT achieves a significantly extended FDN, delaying premature node death by effectively managing energy during the critical initial network phase. Furthermore, HEACT demonstrates a substantial network lifetime, comparable to or exceeding that of EETB and greatly outperforming LEACH, attributed to its energy-aware inter-CH tree routing in later stages. While LEACH may offer high initial throughput, HEACT provides more consistent and sustained data delivery over its prolonged operational lifespan, leading to competitive overall data collection. In essence, HEACT offers a robust hybrid solution by adaptively managing its communication structure and incorporating intelligent load balancing, thereby effectively addressing key energy challenges in WSNs and extending their functional duration.

Chapter 6

Future Scopes

The current implementation of HEACT employs several fixed protocol parameters, such as `HEACT_RECLUSTER_INTERVAL` and `HEACT_INITIAL_DIRECT_INTERVALS`. Future research could focus on making these parameters dynamically adaptive on the basis of real-time network conditions. For example, the reconfiguration interval could be adjusted according to the observed energy depletion rate, node mortality, or topological changes due to mobility. Similarly, the duration of the initial direct transmission phase could be dynamically determined using early indicators of network stability, enabling a more efficient transition to the energy-saving tree-based communication phase. Furthermore, enhancements in cluster head (CH) selection mechanisms could be explored by incorporating fully distributed algorithms like HEED, which use iterative announcements and competition based on cost metrics. The integration of fuzzy logic or lightweight machine learning techniques for CH selection may also offer improvements by taking into account various factors such as node degree, local traffic conditions, and buffer occupancy. Additionally, inter-CH tree optimization can be further refined by incorporating relay load estimations into the cost function, improving load balancing and robustness. Investigating localized repair mechanisms for failed relay CHs could reduce the dependence on full-scale reconfigurations and minimize data loss. Finally, future work may also explore the construction of delay-aware or degree-constrained interCH trees tailored to specific application requirements, thereby enhancing the overall adaptability and efficiency of the HEACT protocol.

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