DYNACEEP: A Dynamic and Energy-Efficient Clustering Protocol for Wireless Sensor Networks with Mobile Base Station

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***Abstract*—Collecting data by balancing energy consumption in wireless sensor networks (WSN) is an important problem for which energy-aware cluster-based routing protocols with mobile sinks have been proposed especially for the last decade. Our primary objective is to address uneven energy depletion—an issue where a few nodes bear most of the communication load and being depleted early, causing network partitioning. To overcome this problem, we present dynamic and energy-efficient clustering protocol (DYNACEEP) for wireless sensor networks with a mobile base station. DYNACEEP integrates adaptive cluster-head (CH) election, load-aware clustering, Time-To-Live (TTL)-based packet management, and periodic base station mobility. CHs are selected by using a composite fitness metric based on normalized residual energy, proximity to the base station, and local node density. Ordinary nodes join clusters through a two-pass mechanism: prioritizing nearby, high-energy CHs and fallback assignments for outliers. Energy-aware data transmission probabilities prevent low-energy nodes from premature depletion. A hybrid CH-to-CH multi-hop and direct BS delivery mechanism, regulated by TTL and retry counts, ensures reliable packet forwarding. Over 1,000 rounds of MATLAB simulations, DYNACEEP achieved a Packet Delivery Ratio (PDR) exceeding 84%, with nearly complete energy utilization and robust operation until the final rounds. Our results demonstrate that DYNACEEP offers a practical and scalable solution for sustainable communication in next-generation WSNs targeting 5G/6G IoT deployments.**

***Index Terms*—Wireless Sensor Networks, Energy Efficiency, Clustering, Mobile Base Station, Multi-hop Routing, Packet Delivery Ratio.**

I. Introduction

WSNs are key enablers for IoT applications [1], [2], [3] yet often suffer from unbalanced energy consumption: nodes near the base station (BS) or frequently serving as cluster heads (CHs) die early, causing coverage holes, partitioning [4], [14].

We propose *DYNACEEP*, a dynamic, energy-efficient clustering protocol for WSNs with a mobile BS. It rotates CHs using energy/location metrics, adapts transmission probability by residual energy, applies TTL-based packet handling, and periodically relocates the BS to spread load [3], [15]-[19].

A. Motivation

Traditional clustering methods such as LEACH and its variants offer basic energy-saving mechanisms but suffer from random CH rotation and static BS assumptions [7], [8]. These methods lead to unbalanced energy usage and limited protocol lifetime, especially in large-scale or latency-sensitive deployments targeted by 5G/6G-enabled WSNs [5], [6], [20]. In addition, most prior approaches lack packet-level reliability features and fail to integrate BS mobility or adaptive routing behaviors under energy constraints [13], [12].

In real-world scenarios, sensor nodes are often deployed in harsh environments and expected to operate for extended periods without maintenance. Fixed base stations result in energy hotspots near the sink, where nodes quickly die due to frequent forwarding duties. This creates coverage holes and network partitions [14], [4]. Moreover, randomly rotating CHs can cause low-energy nodes to be selected, reducing transmission success and accelerating node deaths. These challenges are more significant in heterogeneous WSNs, where energy levels and connectivity vary among nodes.

There is also a growing need for protocols that consider both energy and delivery reliability. Many studies overlook packet drops due to buffer overflow, retransmission failure, or unresponsive nodes. Techniques such as Time-To-Live (TTL) and retry counters are rarely implemented in lightweight protocols, although they are essential for maintaining consistent data delivery in lossy networks [9], [21]. Similarly, BS mobility is often ignored despite its ability to balance load distribution and extend network lifetime [13], [12]. These gaps point to the need for a practical, adaptive solution that can address energy imbalance, packet loss, and protocol sustainability in a single unified framework.

B. Main Contributions

We implement DYNACEEP in MATLAB over 1,000 rounds with heterogeneous nodes and realistic traffic:

- Adaptive CH election via energy, BS proximity, and density with fairness constraints [8], [22].

- Two-pass, load-aware clustering with sleep fallback for isolated/low-energy nodes [23], [24].
- Hybrid CH-to-CH/direct-BS forwarding bounded by TTL and retries [9], [21].
- Periodic micro-mobility of the BS to prevent regional energy holes [13], [12].

DYNACEEP attains PDR >84%, high energy utilization, and long operation vs. static baselines [20], [3].

II. Related Work

Clustering protocols have been widely explored to improve energy efficiency in WSNs, particularly for 5G/6G IoT deployments. Among hierarchical approaches, LEACH and its variants periodically rotate CH roles to reduce transmission cost [3], [7]. However, random CH selection and static BS assumptions cause uneven energy use and early node deaths. LEACH-C leverages residual energy for CH selection but requires centralized control and infrastructure such as GPS, which limits scalability [8].

Enhanced versions like LEACH-DCS improve cluster stability by considering node history and energy [3], yet most still assume a fixed BS and ideal conditions. Geographic routing and aggregation schemes such as GBR and Directed Diffusion reduce redundancy but lack packet-level reliability [4]. Multi-hop LEACH variants lower transmission cost for distant CHs but rarely adapt to real-time energy variation or include TTL/retry control.

Learning-based protocols have also been proposed. CEERP applies reinforcement learning through the Multi-Objective Improved Seagull Algorithm (MOISA) to select CHs and routing paths dynamically [5]. It achieves higher throughput and delivery ratios but increases computational complexity, making it less suitable for low-power sensors. AI techniques such as fuzzy Q-learning, DQN, PSO, and ACO [10], [11], [8] further optimize clustering but often exceed sensor memory and processing limits.

Mobility-aware studies show that controlled node or BS movement can balance network load. Gures *et al.* explored mobility robustness optimization in 5G HetNets [12], while Wang *et al.* introduced the Equivalent Sensing Radius (ESR) for mobile nodes to enhance coverage and energy fairness [13]. Despite these benefits, dynamic BS relocation remains largely absent from clustering designs.

Recent research also investigates energy-harvesting and RL-based access policies for harsh environments. Eriş *et al.* [28], [29] proposed a TDMA policy using cooperative multi-agent reinforcement learning to improve efficiency in underwater networks. Similar RL-based routing strategies for energy management are reported in [30], [31].

From this literature, four main gaps persist:

- **Static CH Selection:** Inflexible rotation under dynamic energy conditions.
- **Lack of Packet-Level Control:** Few include TTL, retry, or acknowledgment logic.
- **Limited BS Mobility:** Mobility rarely integrated to prevent regional energy holes.
- **Heavy AI Dependence:** High computational cost unsuitable for WSN nodes.

By combining energy-aware CH rotation, TTL-regulated multi-hop forwarding, and periodic BS repositioning in a decentralized design, **DYNACEEP** directly addresses these limitations and enhances network sustainability for large-scale IoT deployments.

III. System Model and Problem Definition

A. System Model

We deploy $N = 220$ nodes randomly in a $1000 \times 1000\,\mathrm{m}^2$ field with heterogeneous initial energy (0.05–0.10 J). The BS starts at the center and moves slightly every 10 rounds. Each round includes CH election, clustering, data generation/forwarding, BS mobility, and metric logging. Nodes maintain only local state (position estimate, residual energy, role, buffers). Transmission uses the first-order radio model [9]:

$$E_{tx}(k,d) = \begin{cases} kE_{elec} + kE_{fs}d^2, & d < d_0 \\ kE_{elec} + kE_{mp}d^4, & d \geq d_0 \end{cases}, \quad E_{rx}(k) = kE_{elec}.$$

B. Problem Definition

Design a decentralized clustering protocol that maximizes PDR, balances energy to delay deaths/partitions, and bounds overhead. Required: (i) CH selection using residual energy, BS proximity, and density; (ii) TTL/retry-limited routing to avoid loops/loss [21]; (iii) periodic BS repositioning to mitigate spatial energy holes.

IV. Proposed Method: DYNACEEP Protocol

DYNACEEP operates in discrete rounds: CH election, clustering, data generation, forwarding, BS mobility, and tracking (Fig. 1). Design choices (adaptive CH rotation, TTL/retry, periodic BS moves) directly target common gaps in clustered WSNs.

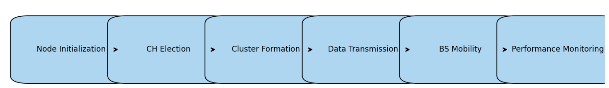

Fig. 1: Round cycle of the DYNACEEP protocol.

A. Node Initialization and State Machine

Nodes start at random positions with 0.05–0.10 J, and switch between active/sleep/dead based on residual energy and clustering outcomes.

B. Adaptive Cluster-Head Election

Every 5–12 rounds (adaptive to average energy), nodes are scored by normalized residual energy, BS distance, and local density; recently served CHs or high drop-rate nodes are penalized. Top scorers become CHs.

C. Cluster Formation and Load Balancing

Regular nodes join nearby, high-energy CHs under size limits (first pass); a relaxed fallback (second pass) improves coverage. Isolated or critical-energy nodes enter sleep.

D. Energy-Aware Data Transmission

Data generation probability scales with residual energy. Each packet at the CH has TTL$=5$ and max 3 retries. If BS is within threshold and energy permits, transmit directly; otherwise forward to a viable CH; else rebuffer or drop at limits (Alg. 1).

Algorithm 1 Energy-Aware Data Transmission with TTL and Retry

Input: Set of CH nodes with packet buffers; base station location; energy parameters.
for all CH node i with buffered packets **do**
    for all packet p in buffer **do**
        $p.ttl \leftarrow p.ttl - 1$
        if $p.ttl = 0$ **then**
            Attempt forced delivery to BS or drop.
            continue
        end if
        if i is within threshold distance to BS **and** has enough energy **then**
            Transmit p directly to BS
        else if Next-hop CH exists and both nodes have energy **then**
            Forward p to next-hop CH
        else
            for all Other CHs j **do**
                if j has energy and buffer space **then**
                    Forward p to CH j
                    break
                end if
            end for
            if no CH found **then**
                $p.retries \leftarrow p.retries + 1$
                if $p.retries >$ MAX_RETRY **then**
                    Drop p and update metrics
                else
                    Buffer p again for next round
                end if
            end if
        end if
    end for
end for

E. CH-to-CH Multi-hop and Direct BS Delivery

CHs forward (i) directly to BS if feasible, (ii) to next-hop CH when beneficial, or (iii) to any CH with buffer room. TTL prevents loops; retries cap overhead.

F. Mobile Base Station Model

The BS moves slightly within bounds every 10 rounds to increase direct deliveries, spread load, and avoid regional energy holes. The mobility model is random, lightweight, and decentralized.

V. Simulation Setup

We simulate 1,000 rounds on a $1000 \times 1000\,\mathrm{m}^2$ field with 220 nodes (0.05–0.10 J). The BS starts centered and moves every 10 rounds.

1) Energy and Radio Model: We use the first-order model [9] with threshold d_0 as usual. Reception energy is $E_{rx}(k) = kE_{elec}$.

2) Traffic Generation and Packet Control: Each node generates data probabilistically depending on residual energy. Packets are 4096 bits with TTL=5 and retry limit 3.

TABLE I: Simulation Parameters

Parameter	Value
Number of nodes	220
Simulation area	1000×1000 m^2
Initial energy per node	0.05–0.10 J (random)
Packet size	4096 bits
E_{elec} (TX/RX)	50 nJ/bit (TX), 20 nJ/bit (RX)
E_{fs}	10 pJ/bit/m^2
E_{mp}	0.0013 pJ/bit/m^4
Threshold distance d_0	$\sqrt{E_{fs}/E_{mp}}$
Sleep energy loss	0.5 μJ per round
CH reselection interval	Adaptive (5–12 rounds)
BS mobility interval	Every 10 rounds
Packet TTL	5
Max retries	3

VI. Numerical Results and Analysis

We report PDR, energy consumption, node-death progression, overhead, and qualitative topology snapshots.

1) Packet Delivery Ratio (PDR): DYNACEEP achieves 84.18% PDR over 1,000 rounds (Fig. 2), due to hybrid forwarding, adaptive CH rotation, and energy-scaled traffic.

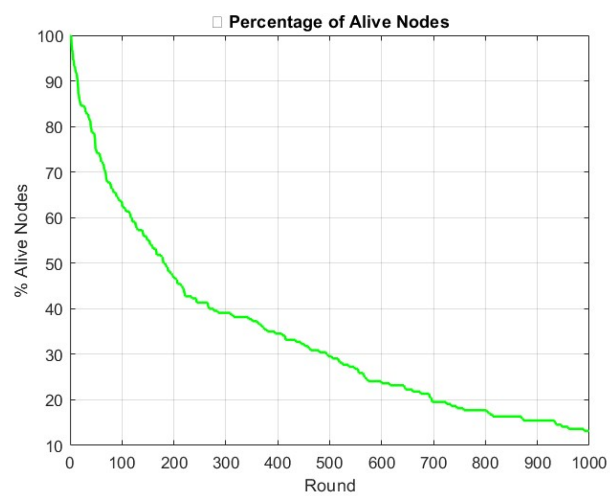

Fig. 2: Percentage of alive nodes over time. First node death at round 3; HND at round 180.

2) Energy Consumption and Network Lifetime: Total energy usage is 99.59%; the decline accelerates after round 300 under higher routing load. The network remains functional nearly until round 1,000 (Fig. 3).

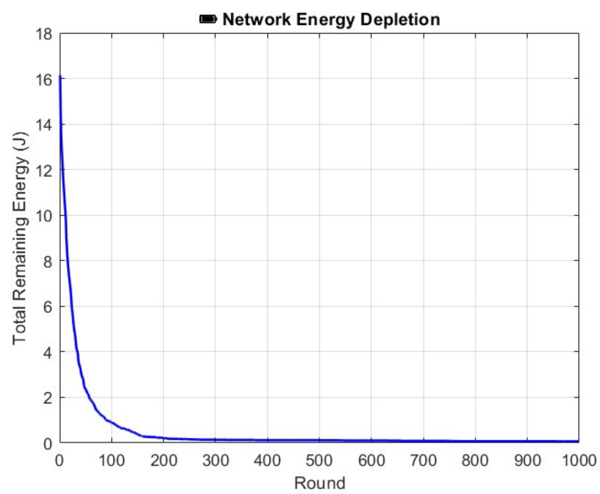

Fig. 3: Total remaining energy over simulation rounds.

3) Node Death Progression (FND, HND, LND): FND at round 3, HND at 180, and LND near 1,000 indicate graceful degradation (Fig. 4).

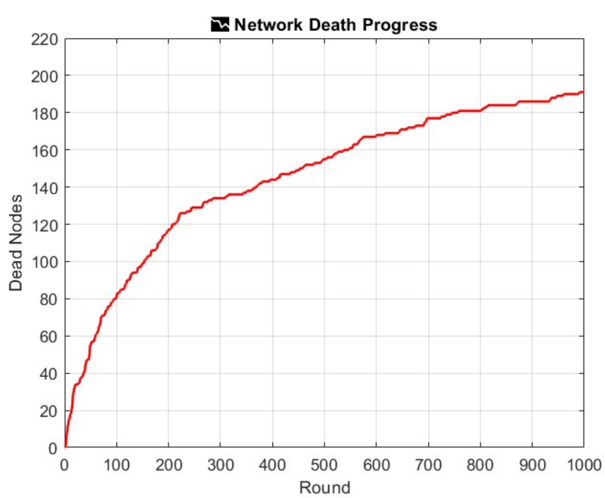

Fig. 4: Cumulative node death progression.

4) Routing Overhead and Throughput: TTL/retry bounds limit drops to 343 (11.54% overhead). Throughput averages 4.88 packets/round. Topology snapshots show adaptive clustering and viable paths (Figs. 5–6).

A. Comparative Evaluation and Simulation Assumptions

TABLE II: Simulation Parameters Across Compared Protocols

Parameter	DYNACEEP	LEACH [25]	LEACH-C [26]	CEERP [27]
Simul. Area	1000×1000	100×100	100×100	500×500
Node Count	220	100	100	100
Initial Energy	0.05–0.10 J (het.)	2 J (hom.)	0.5 J (hom.)	1 J (hom.)
BS Position	Mobile	Fixed (corner)	Fixed (corner)	Fixed (corner)
CH Selection	Adaptive, Decent.	Random	Centralized	MOISA (AI)
Rotation	5–12 rounds	Every round	Every round	History-based
Packet Size	4096 bits	2000 bits	4000 bits	4000 bits
TTL / Retry	5 / 3	None	None	Limited
Energy Model	1st-order+sleep	1st-order	1st-order	1st-order
Rounds	1000	500–800	500	800

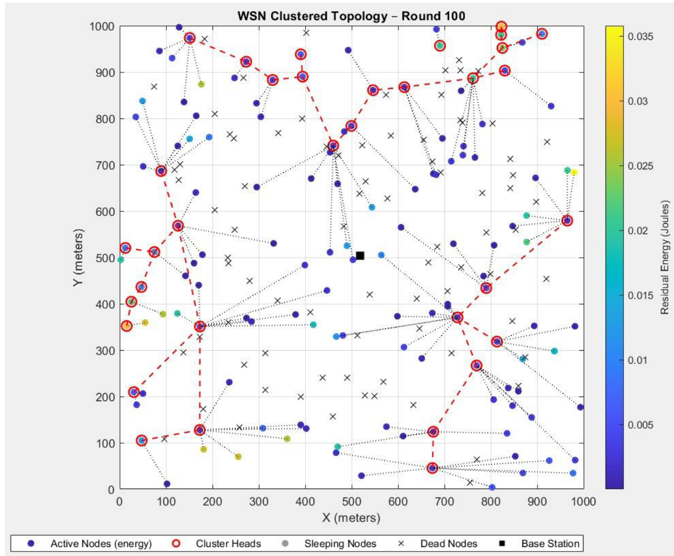

Fig. 5: Clustered topology and energy distribution at round 100.

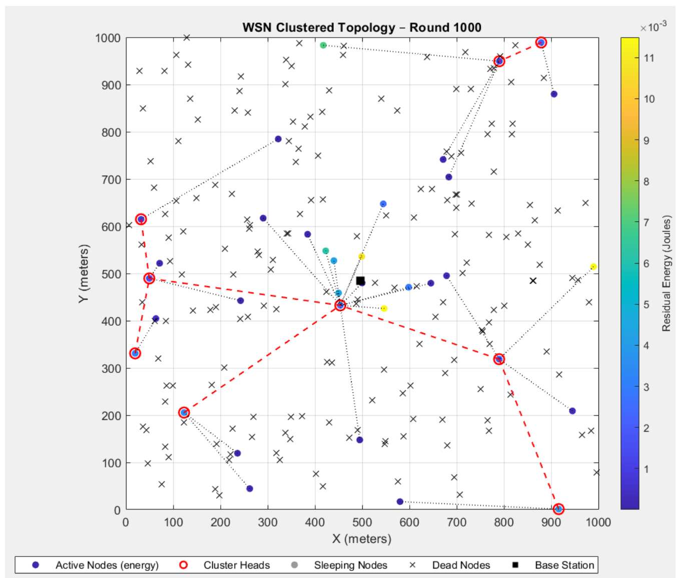

Fig. 6: Clustered topology at round 1000—residual structure still functional.

Parameter misalignments reflect different scenarios; DYNACEEP targets a larger, heterogeneous field with BS mobility and TTL/retry for realism.

B. Comparative Summary with Other Protocols

TABLE III: Quantitative Comparison with Existing Protocols

Protocol	PDR	Lifetime	Energy	Overhead	Mob./Retry
LEACH [25]	60–70%	<600	∼85%	>25%	No / No
LEACH-C [26]	70–75%	<700	∼88%	>20%	No / No
CEERP [27]	75–85%	∼850	∼90%	<15%	No / Partial
DYNACEEP	**84.18%**	**1000**	**99.59%**	**11.54%**	Yes / Yes

VII. Conclusion and Future Work

DYNACEEP integrates adaptive CH rotation, energy-aware transmission, TTL-bounded forwarding, and periodic BS mobility to mitigate hotspots and premature deaths. Simulations show >84% PDR, near-full energy use, and operation to ∼1,000 rounds with modest overhead. Future work: testbed validation, lightweight AI for CH selection, advanced adaptive transmissions, hybrid energy sources, and security hardening for next-generation IoT.

ACKNOWLEDGMENT

This work is funded through a TÜBİTAK 2209-A project with ID 8855, entitled "Collaborative Energy-Efficient Routing Protocol for Sustainable Communication in 5G/6G WSNs". The publication has also been supported by the project "Increasing the knowledge intensity of Ida-Viru entrepreneurship in Estonia" co-funded by the European Union. The publication has also been supported by ITU BAP Office via HIZDEP project with ID FHD-2025-45868, entitled "Mobil Baz İstasyonlu Kablosuz Sensör Ağları için Dinamik ve Enerji Verimli Bir Kümeleme ve Bilişsel Radyo Etkinleştirilmiş Araç Ağında Kusurlu Kanal Algılama Yoluyla Eniyiye Yakın Fırsatçı Spektrum Erişimi".

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