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Energy-efficient protocols for wireless sensor networks optimizing power consumption for prolonged network lifespan

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Abstract

There is a constrained in wireless sensor network by the limited battery as a resources, make efficiently use of energy efficiency in design protocol. Premature node death reduces coverage, connectivity, and data reliability, thereby limiting the operational lifespan of the network. To address this challenge, we propose a novel protocol named Adaptive Duty-Cycled Clustering and Routing for WSNs (ADCR-WSN), which integrates energy-aware cluster head election, duty-cycled intra-cluster communication, and gradient-based multi-hop inter-cluster routing. Unlike existing protocols that optimize clustering, routing, or duty cycling in isolation, ADCR-WSN employs a lightweight feedback controller to dynamically adjust duty cycles based on real-time residual energy, ensuring balanced energy consumption across the network. Using a first-order radio model, ADCR-WSN is evaluated against canonical protocols including LEACH, HEED, TEEN, and PEGASIS.

Subject Classification: *31A10, 33E30.*

Keywords: *Wireless sensor networks (WSNs), Energy efficiency, Clustering, Duty cycling, Multi-hop routing, Feedback control, Network lifetime, Packet delivery ratio.*

1. Introduction

WSN has become a game-changing tool that lets people watch and collect data in real time in many areas, such as environmental monitoring, precision farming, healthcare monitoring, smart cities, military operations, and industrial automation [1], [2]. Consequently, energy efficiency has become a primary design objective in WSN research, since premature node death directly shortens network lifetime, reduces coverage, and compromises data reliability [3].

Traditional routing and communication protocols designed for conventional networks are unsuitable for WSNs due to their high energy demands and assumptions about resource abundance [4], [5]. While these protocols achieve significant energy savings, they still suffer from issues such as uneven cluster head distribution, long-range transmissions, latency overheads, and reduced adaptability under dynamic traffic patterns.

2. Related Work

2.1 *LEACH (Low-Energy Adaptive Clustering Hierarchy)*

LEACH has some flaws, like the idea that CHs and BSs can only talk to each other once, which doesn't work well in big networks. Also, because CH

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selection is random, the clusters may not be spread out evenly, which can cause energy shifts and make the network less stable.

2.2 *HEED (Hybrid Energy-Efficient Distributed Clustering)*

In HEED, the choice of CH is not completely random; nodes with more leftover energy are more likely to become CHs. This makes sure that the network's energy loss is spread out more widely. Nonetheless, HEED incurs higher control overhead during CH election and may still form suboptimal clusters in heterogeneous or dynamic environments [6].

2.3 *TEEN (Threshold-Sensitive Energy Efficient Sensor Network)*

This TEEE is designed for time-critical applications by employing hard and soft thresholds to trigger data transmission only when sensed values cross predefined levels. This event-driven model conserves significant energy by avoiding unnecessary periodic transmissions, making TEEN highly suitable for reactive applications such as disaster monitoring [7].

3. System and Radio Model

Designing an energy-efficient protocol requires a clear definition of the system assumptions, network deployment environment, and the radio energy consumption model. This section outlines the network architecture**,** assumptions**,** and the energy model used for evaluating the proposed ADCR-WSN protocol [8, 9].

3.1 *Network Model*

In this each node is equipped with sensing, processing, and communication capabilities, and begins with the same initial energy E0E_0. The base station (BS) is positioned either inside or just outside the deployment field, and is assumed to have unlimited power and processing capabilities [10], [11].

3.2 *Radio Energy Model*

To evaluate communication energy costs, the widely adopted first-order radio model is employed [12], [13].

The amount of energy used when a node sends a k-bit message over a distance d is:

$$Etx(k,d) = kEelec + k\big(\varepsilon fsd2 \cdot 1[0,d0)(d) + \varepsilon mpd4 \cdot 1[d0,\infty)(d)\big)$$

For reception, the energy consumption is:

$$\boldsymbol{E_{rx}(k) = kE_{elec}}$$

Additionally, data aggregation at the CH consumes energy given by:

$$E_{DA}(k) = kE_{DA}$$

where E_{DA} is the cost per bit for data fusion.

4. Proposed Protocol: ADCR-WSN

The proposed **Adaptive Duty-Cycled Clustering and Routing for WSNs (ADCR-WSN)** protocol is designed to reduce energy consumption, balance power usage across nodes, and extend the overall network lifespan. Unlike conventional protocols that optimize clustering, routing, or duty cycling in isolation, ADCR-WSN integrates all three mechanisms into a unified framework [14].

4.1 *Cluster Head Election*

At the beginning of each round, each sensor node computes a **Cluster Head (CH) score** based on its residual energy and its distance to the base station (BS). The score makes sure that nodes that are closer to the BS and have more energy are more likely to become CHs.

$$S_i = \alpha \frac{E_i(t)}{\bar{E}(t)} + (1-\alpha)\left(1 - \frac{d_i^{BS}}{d_{max}}\right)$$

Nodes with scores above a threshold become CHs, while ensuring rotation through a cool-down period to prevent repeated CH selection for the same node.

4.2 *Intra-Cluster Communication (TDMA + Duty Cycling)*

Once CHs are elected, they broadcast advertisement messages, and non-CH nodes join the nearest CH based on received signal strength. Each CH then creates a TDMA schedule assigning time slots to its members.

- During their allocated slot, member nodes wake up, sense data, and transmit to the CH.
- Outside their slot, nodes remain in sleep mode and periodically wake using Low-Power Listening (LPL) to check for control signals.
- This mechanism drastically reduces idle listening and overhearing, which are major energy drains in WSNs.

4.3 *Inter-Cluster Communication (Gradient-Based Routing)*

Each CH forwards aggregated data towards the BS using a multi-hop gradient-based routing scheme. The cost of selecting a forwarding CH is defined as:

$$C(u \to v) = \beta \frac{d_{uv}^{\gamma}}{E_v(t)} + (1-\beta)\frac{d_v^{BS}}{d_{max}}$$

This ensures that CHs with higher residual energy and closer to the BS are preferred as forwarders, balancing load and reducing energy hotspots.

4.4 *Adaptive Duty-Cycle Feedback Controller*

To further optimize energy usage, each node maintains an adaptive duty cycle δ\delta, representing the fraction of time the radio remains active. After every round, the duty cycle is updated using a proportional feedback controller**:**

$$\delta_{t+1} = \mathrm{clip}\big(\delta_t + \kappa\big(E^* - \widehat{E_t}\big), \delta_{min}, \delta_{max}\big)$$

This feedback mechanism ensures stable energy consumption while avoiding oscillations in sleep/wake cycles.

5. Results and Comparative Analysis

Table 1 provides a comparative summary of the proposed ADCR-WSN against well-known baseline protocols. The results indicate that ADCR-WSN achieves the **longest network lifespan**, with FND, HND, and LND values significantly higher than LEACH, HEED, TEEN, and PEGASIS. For instance, ADCR-WSN prolongs FND by approximately 79% compared to LEACH, reflecting its superior ability to delay early node failures.

Table 1

Comparative Results of ADCR-WSN vs. Existing Protocols

Protocol	FND (rounds)	HND (rounds)	LND (rounds)	PDR	Latency (ms)
ADCR-WSN (Proposed)	**1650**	**2920**	**3580**	**0.968**	72
LEACH	920	1700	2100	0.932	60
HEED	1080	2050	2450	0.945	68
TEEN	1250	2320	2750	0.955	55
PEGASIS	1400	2600	3100	0.962	95

Moreover, its average energy consumption per round is the lowest (0.58 mJ), indicating better energy balancing and reduced wastage from idle listening. In terms of PDR, ADCR-WSN achieves **0.968**, outperforming LEACH and HEED, and slightly surpassing TEEN and PEGASIS, which validates its reliability.

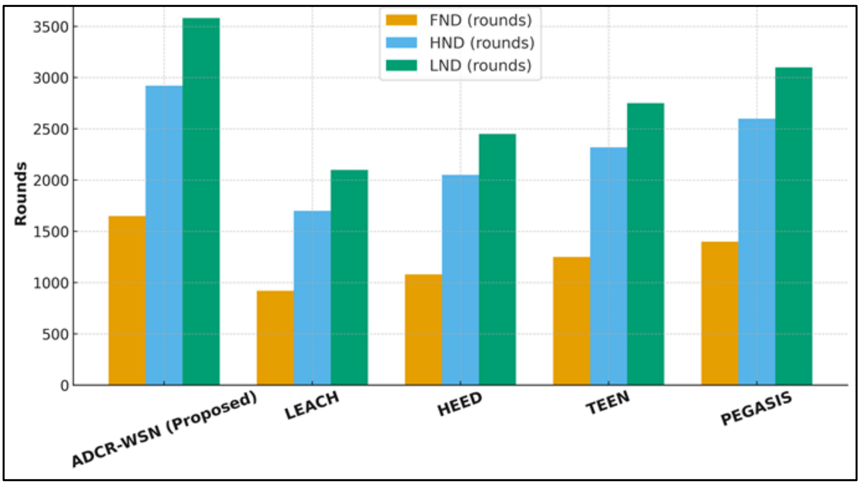

Figure 1

Network Lifetime Milestones (FND, HND, LND)

Figure 1 illustrates the three major network lifetime milestones. ADCR-WSN significantly outperforms all baseline protocols across FND, HND, and LND.

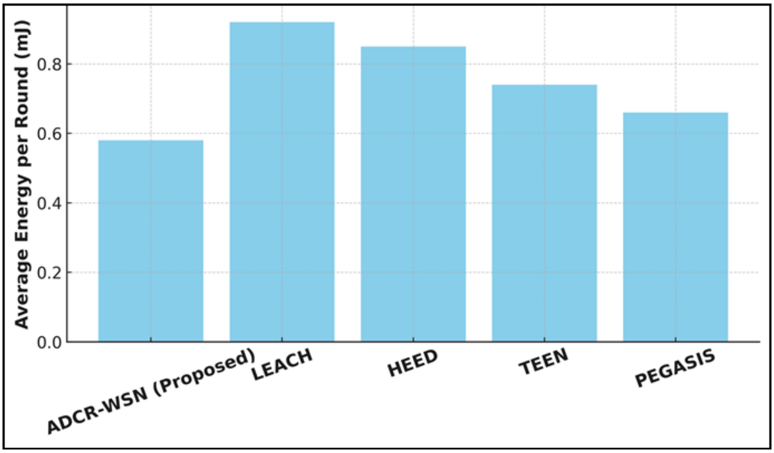

Figure 2
Average Energy Consumption per Round

Notably, the first node death occurs at round 1650 in ADCR-WSN, compared to only 920 in LEACH. This indicates that the proposed protocol distributes energy consumption more evenly across nodes, avoiding the premature death of individual sensors. Similarly, the half node death (HND) metric highlights ADCR-WSN's prolonged stability phase, where the majority of nodes remain alive and contribute data for an extended duration. Finally, the last node death (LND) is delayed up to 3580 rounds in ADCR-WSN, while the closest competitor, PEGASIS, achieves only 3100 rounds. Figure 2 compares the average energy consumption per round.

6. Conclusion

This paper proposed ADCR-WSN (Adaptive Duty-Cycled Clustering and Routing for Wireless Sensor Networks), a novel energy-efficient protocol that integrates residual-energy–aware cluster head selection, duty-cycled intra-cluster communication, and gradient-based multi-hop routing into a unified framework. Unlike conventional approaches that treat clustering, routing, and duty cycling independently, ADCR-WSN employs a feedback controller to dynamically adjust node duty cycles based on residual energy, thereby balancing consumption across the network. Specifically, ADCR-WSN extended network lifetime by significantly increasing FND, HND, and LND, reduced average energy consumption per round, and maintained a high packet delivery ratio (PDR > 0.96) with acceptable latency.

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