Enhanced DDEEC Protocol with Adaptive Threshold for Energy Efficiency in WSNs

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Abstract: Wireless sensor networks (WSNs) are increasingly utilised in various applications, including environmental monitoring, healthcare, and military surveillance. Due to the small battery sizes of sensor nodes, energy efficiency is a critical design factor, and traditional clustering protocols attempt to manage heterogeneous energy profiles. However, the Enhanced Distributed Dynamic Energy-Efficient Clustering (EDDEEC) protocol usually leads to the premature exhaustion of more advanced nodes because they are frequently selected as cluster heads. In this work, we propose the DDEEC protocol, which is based on an adaptive threshold mechanism and a fairness coefficient. These modifications aim to balance the election process for cluster heads among heterogeneous nodes. Simulations in MATLAB show that the proposed model extends the network lifetime over EDDEEC. The results indicate improvement of the DDEEC protocol, which provides a more efficient and reliable solution for heterogeneous WSNs. Specifically, the enhanced scheme increases the number of packets delivered to the base station by up to 25%, prolongs the time until the first node dies, and ensures a more equitable distribution of energy among the nodes.

1 INTRODUCTION

Wireless Sensor Networks have become a vital technology, enabling a wide range of applications, including environmental monitoring, precision agriculture, healthcare, factory automation, and military observation [1]. The researchers are heavily focused on improvement various aspects of Wireless Sensor Networks (WSNs) to facilitate more intelligent, efficient, and secure deployments, particularly in IoT and cyber-physical systems [2], [3]. A typical WSN consists of numerous sensor nodes distributed over a geographical area to detect, analyse, and transmit environmental information to a Base Station (BS) [4].

Due to their inherent limitations, minimal battery capacity, and often non-rechargeable nature in hostile or hard-to-reach deployment environments, these nodes are highly resource-constrained. Consequently, energy efficiency is the most critical concern in WSN design, directly influencing the network’s reliability, scalability, and longevity [5].

Hierarchical clustering head protocols such as LEACH, HEED, and EEHC employ a two-level structure where nodes form clusters with a Cluster Head (CH) for communication. These cluster heads communicate with one another and the base station to relay data. Cluster heads are selected using a randomised rotation to balance energy load across WSNs [6]. The LEACH and DEEC protocols incur overhead and latency due to ineffective and redundant CH rotation in a WSNs [7]. Enhanced Distributed Energy-Efficient Clustering has been developed on top of established protocols such as LEACH and DEEC for Heterogeneous Wireless Sensor Networks (HWSNs) [8].

The improvements aim to increase network lifetime, improve energy efficiency, and enhance durability by selecting the cluster head (CH) based on multi-level energy heterogeneity (normal/advanced/super nodes) and adaptive election probabilities. This is optimized to be more dynamic and efficient based on a node's residual energy and proximity to other nodes. Enhancing energy efficiency involves various modifications to reduce energy waste during data transmission and overall network operation [9]. Recently, a modified Distance-based DDEEC based on residual energy and distance to the base station [10], [11] and an Improved DDEEC based on increasing the heterogeneity and energy levels in the network [12]. Most investigations have been enhanced by utilising metrics such as network stability, throughput, and energy efficiency in heterogeneous environments [13]. Recent results have reported improvements of 7% and 28% in stability, as well as 42% in energy efficiency [14]. However, Energy efficiency remains a fundamental principle in WSN design, influencing research across all components of the DDEEC framework: energy and data. Existing protocols, such as DDEEC, still suffer from early depletion of advanced nodes, leading to unbalanced energy usage.

In this paper, we present a modular implementation of an enhanced DDEEC protocol that integrates the adaptive threshold mechanism and a fairness coefficient to improve energy-saving strategies. The contribution offers the following benefits:

1) Long-term network stability, increased throughput, and extended lifetime through a more equitable distribution of (CH) responsibilities.
2) Significant improvements compared to traditional Distributed Energy-Efficient Clustering (DDEEC) in terms of first node death (FND), total packets delivered to the base station (BS), and remaining energy balance.
3) A robust, energy-efficient solution tailored for heterogeneous Wireless Sensor Networks (WSNs), positioning it as a strong candidate for large-scale deployments in the future.

The remainder of this paper is organized as follows: Section 2 describes the standard DDEEC protocol and reviews related work on protocols and energy efficiency in WSNs. Section 3 presents the proposed and improved DDEEC protocol, including its modular architecture and key components. Section 4 presents the simulation results, conducts a performance analysis, and discusses these results. Section 5 concludes the paper by summarizing the findings and outlining future research directions.

2 BACKGROUND STUDIES AND RELATED WORK

This section reviews the overview of wireless sensor networks (WSNs) architecture, by focusing on its structure and energy-awareness, based on models with equations and routing literature that motivated EDDEEC:

2.1 Overview of DDEEC

DDEEC is an improvement over DEEC, DDEEC, and EDEEC, all of which belong to the family of clustering-based energy-aware routing protocols for heterogeneous WSNs. A short description is as follows:

2.1.1 Developed Distributed Energy-Efficient Clustering in Wireless Sensor Networks

Sensor nodes sense and transmit data to a Base Station (BS). To save energy, nodes form clusters; each cluster has a Cluster Head (CH). CHs aggregate member data and send it to the BS.

In heterogeneous networks, energy E of nodes may be three levels:

- E_0 indicates baseline energy and is defined as a normal node;
- E_0(1+α) indicates more energy and is defined as an advanced node;
- E_0 (1+β) indicates even more energy and is defined as a super node.

Here, α and β, are energy factors ($\beta > \alpha > 0$).

2.1.2 Energy Model

Per round consumes energy due to communication, reception, and data collection, as pointed out in (1):

$$E_{round} = L \times \begin{pmatrix} 2NE_{elec} + NE_{DA} + \\ + k\epsilon_{fs} d_{toCH}^{2} + k\epsilon_{mp} d_{toBS}^{4} \end{pmatrix}. \quad (1)$$

Where:

- L: packet size (bits);
- N: number of nodes;
- E_{elec}: energy for running transmitter/receiver;
- E_{DA}: data aggregation energy;
- $k\epsilon_{fs}$, $k\epsilon_{mp}$: amplification factors (free space, multipath);
- d_{toCH}, d_{toBS}: average distances to CH and BS;
- k: number of clusters.

2.1.3 Average Energy in Round

It is calculated by considering the initial energy and the total energy consumed by all nodes in a round (r), as pointed out in (2).

$$\bar{E}(r) = \frac{1}{N} \sum_{i=1}^{N} E_{total} \left(1 - \frac{r}{R}\right). \quad (2)$$

Where:

- E_{total}: entire initial power of all nodes;

- R: entire number of rounds before network death;
- $\bar{E}(r)$: average network energy at round (r).

2.1.4 CH Selection Probability in DDEEC

DDEEC modifies the CH election probability $P_i$for node (i) dynamically based on its residual energy, as indicated in (3).

$$P_i = P_{opt} \times \frac{E_i(r)}{\bar{E}(r)}. \tag{3}$$

Here P_{opt}, is the optimal CH probability.
DDEEC implements a threshold to limit the overuse of advanced and super nodes, as indicated in (4).

$$T_{absolute} = z \times E_0, \tag{4}$$

where $0 < z < 1$(usually $z = 0.7$).

Then, the CH probability is adjusted in (5) as follows:

$$P_i = \begin{cases} \dfrac{P_{opt} \times E_i(r)}{(1 + \alpha m + \beta m_0) \times \bar{E}(r)} & \text{if } E_i(r) > T_{absolute}\, for\ normal\ node \\ \dfrac{P_{opt} \times (1 + \alpha) E_i(r)}{(1 + am + bm_0) \times \bar{E}(r)} & \text{if } E_i(r) \leq T_{absolute}\, for\ advanced\ node \end{cases} \tag{5}$$

Where $m\ and\ m_0$: fractions of advanced and super nodes and $E_i(r)$, residual energy of node i at round r.

2.1.5 Threshold Function for CH Election

Each node becomes a CH based on a threshold function as indicated in the following equation:

$$T(n) = \left(\frac{P_i}{1 - P_i \times \left(r mod \frac{1}{P_i} \right)} \right). \tag{6}$$

Equation where the set of nodes eligible to become CHs in the current round.

2.2 Related Work

The traditional protocol is a pioneering protocol designed for homogeneous Wireless Sensor Networks (WSNs). Low Energy Adaptive Clustering Hierarchy LEACH selected CHs randomly in each round and organized nodes into clusters. The use of these methods has been restricted mainly to homogeneous networks or to single-parameter analyses with limited heterogeneity. To address this, a model incorporating multiple parameters and levels of heterogeneity was introduced, featuring a cluster-head rotation method. This approach balanced energy consumption and maximized network lifetime. As a result, it achieved up to a 57% increase in throughput to the base station [15]. Still, it used a homogeneous approach, and LEACH randomly selects cluster heads (CHs).

To achieve stability and longevity in heterogeneous wireless sensor networks (WSNs), many schemes have been proposed in previous research. However, heterogeneous networks can take various forms and involve different measurable factors. Each network type exhibits its own level of heterogeneity, and no single metric performs consistently well across all of them. As a result, they often fail to maintain the same stability and lifetime as earlier heterogeneous WSNs. Some protocols are effective in WSNs where energy differences between normal, advanced, and super nodes are minimal. On the other hand, other models work well in networks with significant energy differences among these node types [16].

Stable Election Protocol (SEP) [17] is a clustering method inspired by LEACH that addresses two-tier energy heterogeneity by assigning nodes with different initial energy levels to other rounds, with the latter possessing greater resources. SEP improved energy variance management and introduced specific operational epochs for each node type. The study was designed to compare the SEP and LEACH protocols. It was observed that the LEACH protocol's first node was faster than the SEP node. The SEP protocol used a weighted cluster-head selection method, and the advanced node's initial energy increased over time. The main aim of the SEP protocol is to improve throughput and increase stability [18]. There are limitations, including a need for frequent cluster reformation in each round and a restriction to only two levels of energy heterogeneity. In addition, the SEP selection of the cluster head (CH) among sensor nodes is static, leading to nodes with less energy and farther from the center being dead first. Energy Efficient Hierarchical Routing Protocols for IoT.

Distributed Energy-Efficient Clustering (DEEC) [19] A protocol was developed to calculate probabilities and use them to select CHs based on both residual energy and average network energy, while giving higher-energy nodes a greater likelihood of becoming CHs. This approach helps to extend the network's lifetime.

Table 1: Recent studies on energy-efficient CH selection.

Protocol	Parameters	Method	Contribution	Environment	Ref.
DDEEC	Residual energy, average energy	Threshold limit for cluster head selection	Stability period and network lifetime	IoT	[24]
DDEE	Maximum distance for node-to-node	Cuttlefish optimisation algorithm	Calability, throughput, end-to-end delay	IoT	[30]
DEEC	Residual energy, transmission distance,	Article swarm optimisation-gravitational search algorithm	Prolong network life	IoT	[14]
EDDEEC	Total number of sensor nodes, Initial energy of a normal node, Energy factor for advanced nodes,	Mathematic model	Packets sent, network lifetime, through-Put, packet loss, average energy, dead nodes, cluster heads	Heterogeneous	[22]
Modified LEACH	Not specific	Mathematic model	Reduced latency	Heterogeneous	[31]
Hybrid EEDC	Packet size, Initial energy, Energy for electronics, Energy for the amplifier	Mathematic	Increase the lifetime, reliability, and stability	Heterogeneous	[32]

Some researchers [20] modified the Distributed Energy-Efficient Clustering (DEEC) approach to select a Cluster Head (CH) based on each node's remaining energy relative to the network's average energy. This adjustment resulted in a 19.30% delay, a 4.5% increase in the network's lifetime, a 5.6% increase in energy consumption, a 1.4% increase in the packet delivery ratio, and a 38% increase in throughput.

An enhanced DEEC protocol has been introduced by increasing the number of active nodes and reducing the number of dead nodes. This enhanced DEEC protocol had optimized cluster heads by aggregating data from each cluster to the base station (BS). Therefore, more data packets were sent to the BS, thereby improving network performance [21].

The DEEC suffers from high energy consumption because it is challenging to assign nodes with different initial energy levels to different CHs. It does not fully account for advanced or super nodes with greater energy [22].

The Development of DEEC [23] introduced the precise DEEC mechanism, with a slight modification regarding the threshold for residual energy. This mechanism was designed to establish energy balance by adjusting the election probability of advanced nodes. The goal of this adjustment was to ensure that the election probability of advanced nodes remained higher than that of normal nodes, even as their energy levels decreased. The study [24] evaluated a version of the DEEC protocol that aims to prolong network lifespan by adjusting node power levels and introducing a selection threshold for cluster heads in one infrastructure IoT network. Unfortunately, these changes introduce stability and throughput issues that may cause an imbalance due to shifts in the system. Furthermore, only supports two-level heterogeneity (Normal and Advanced).

The Enhanced Developed Distributed Energy-Efficient Clustering (EDDEEC) was presented with three levels and utilised to develop DDEEC by refining the CH selection probability function for heterogeneous WSNs [25]. This refinement accounts for the energy differences among nodes and categorises them as normal, advanced, and super nodes based on their residual energies. The objective is to ensure fair selection of CHs across different energy tiers to avoid the premature depletion of advanced nodes, thereby enhancing the stability and longevity of the network. There are many variants of these protocols, often named with slight modifications. The advanced nodes will usually take CH responsibilities due to their greater initial energy, which will soon exhaust them and reduce fairness [26].

To identify the Cluster Head (CH) and estimate normal energy consumption, the authors [27] employed a threshold (T) to DDEEC in the same network. In each round, nodes decided whether to become a CH by generating a random number between 0 and 1. If this number exceeded a specified threshold $T(s)$ [28], [29]. The node was designated as the CH for that round. However, throughput was increased without accounting for the current node's energy.

The Table 1 shown routing protocols such as DEEC, EDDEEC, DDEEC, and LEACH. These protocols were initially designed to maximize energy efficiency in heterogeneous or IoT networks by adjusting the probabilities of cluster head (CH) elections based on factors such as residual energy, the initial energy of normal or advanced nodes, and the network's average energy. While traditional protocols have improved cluster head selection to achieve energy balance, they still have drawbacks and need further improvement. Some drawbacks include a singular design approach to the network, suboptimal CH election processes, and the need for further reductions in energy consumption. These issues negatively affect network stability and reduce its overall lifetime. To address these limitations, this paper introduces an improved version of the Enhanced DDEEC (DDEEC) protocol. This new protocol incorporates an adaptive threshold mechanism that is adjusted over time to enhance the selection of cluster heads.

3 PROPOSED METHODOLOGY

This paper presents a new protocol, Enhanced DDEEC, that includes an adaptive threshold mechanism and a sophisticated energy consumption model to select CHs. The scheme enhances equitable energy distribution across heterogeneous nodes without disrupting network coverage or connectivity. The main contribution is the dynamic energy adjustment factor (α), which adjusts the CH selection probability according to each node's residual energy and changes over time across consecutive network rounds.

The enhanced CH possibility (P) for each node (i), it is defined as follows.

$$\mathrm{P_i} = \mathrm{P_{opt}} \cdot \frac{\mathrm{E_i(r)}}{(1+\alpha).\bar{E}(r)}. \tag{7}$$

Where $\mathrm{P_{opt}}$, is the optimal probability of CH choice. $\mathrm{E_i(r)}$ represents the residual energy of node (i), at round (r), and $\bar{E}(r)$ represents the average residual energy of the network. Equation (7), the adaptive factor (α) is dynamically updated as follows:

$$\alpha = \beta.\frac{\mathrm{E_{init}} - \mathrm{E_i(r)}}{\mathrm{E_{init}}}. \tag{8}$$

The parameter $\mathrm{E_{init}}$ is the initial energy of each node and β is an empirical control parameter that balances sensitivity and stability in the rotation of the cluster head (CH).

To prevent untimely energy exhaustion of high-energy nodes, including advanced and super nodes, the protocol has a residual energy threshold. $\mathrm{E_{th}}$ modulates the likelihood of a cluster head election when the energy of a node is less than the energy threshold:

$$\mathrm{E_{th}} = \gamma.\bar{E}(r). \tag{9}$$

Where γ is a design coefficient usually between 0.7 and 0.9, the nodes with residual energy $\mathrm{E_i(r)} > \mathrm{E_{th}}$ has a high probability of becoming cluster heads, allowing them to retain more energy and thereby increasing the overall network lifetime. Additionally, E-DDEEC has adopted a thoughtful energy rotation policy, assigning each node the role of cluster head based on its energy status. This rotation ensures minimal cluster instability and minimizes the overhead of re-clustering.

This adaptive probabilistic mechanism and threshold-based control enable the Enhanced DDEEC protocol to achieve better energy distribution, much higher packet delivery rates, and sustained network stability compared to the traditional DDEEC scheme. The effectiveness of the suggested enhancement is confirmed by simulation results, which indicate that E-DDEEC effectively delays the first node death (FND) and increases the stability duration of the WSN, Figure 1 shows the workflow diagram.

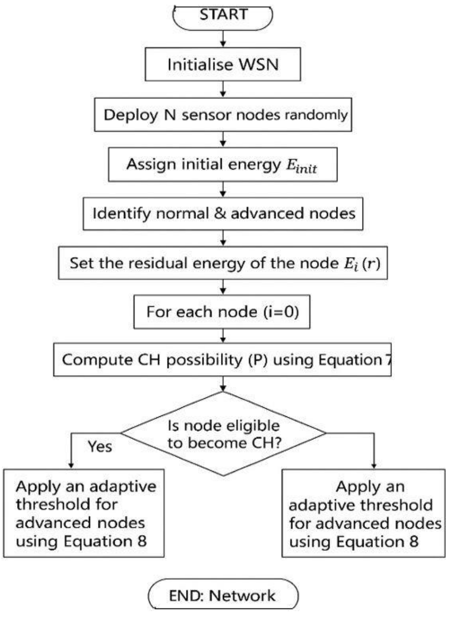

Figure 1: The workflow diagram.

Improved DDEEC refines CH selection by dynamically adjusting the threshold probability based on residual energy and average network energy.

Pseudocode of improvement DDEEC:

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▪ Step 1: START: Initialize WSN.
▪ Step 2: Deploy N sensor nodes randomly.
▪ Step 3: Assign initial energy $\mathrm{E_{init}}$;
▪ Step 4: Identify normal & advanced nodes.
▪ Step 5: Set the residual energy of the node $\mathrm{E_i(r)}$.
▪ Step 6: Compute average network energy $\mathrm{\bar{E}(r)}$ using (2).
▪ Step 7: For each node $(\mathrm{i} = 0)$ to $(\mathrm{N})$;
▪ Step 8: Compute CH possibility (P) using (7).
▪ Step 9: Apply an adaptive threshold for advanced nodes using Equation 8.
▪ Step 10: Is node eligible to become CH.
▪ Step 11: (random number < threshold) if YES, go to step 11 Else, step 12.
▪ Step 12: Node becomes CH and Broadcasts Advanced Node.
▪ Step 13: Node joins nearest, and CH based on Received Signal Strength Indicator.
▪ Step 14: CH creates TDMA schedule and Cluster members transmit data in assigned time slots.
▪ Step 15: CH aggregates received data.
▪ Step 16: CH sends aggregated data to BS.
▪ Step 17: Update residual energy of all nodes.
▪ Step 18: Check network lifetime metrics.
▪ Step 19: Next Round? (alive nodes > 0)? Yes, go to step 19. Else Step 20.
▪ Step 20: Repeat CH selection.
▪ Step 21: END: Network dies.
▪ Step 22: for next round.
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4 RESULTS AND PERFORMANCE ANALYSIS

MATLAB simulations were conducted with identical parameters for both the proposed and traditional DDEEC protocols to assess the efficiency of the proposed protocol in comparison to the traditional one. Table 2 summarizes the simulation parameters.

The enhanced DDEEC protocol was compared with the original DDEEC in terms of stability period (FND), half-node death (HND), last-node death (LND), throughput (packets sent to the BS), and the number of cluster heads per round.

Table 2: Identical parameters in traditional and enhanced of DDEEC.

Parameter	Value
Total number of sensor nodes (N)	100
Network size	100 m × 100 m
Initial energy (E_0)	0.5
Percentage of advanced nodes	20%
Percentage of super nodes	10%
P_{opt}	0.1
Data packet size	4000 bits
Energy model (E)	First-order radio

4.1 Dead Nodes over Simulation Rounds

Figure 2 illustrates the correlation between the death rates of the nodes and the simulation rounds. The Enhanced DDEEC significantly delays the first node death (FND) compared to the baseline DDEEC, where the first node dies at approximately 2000 rounds in the original protocol and at 2500 rounds in the enhanced version. Also, the last node (LND) is not immediately removed, which extends the entire network. The improvements in DDEEC help prevent high-energy nodes from being over utilized and incorporate super nodes with even greater initial energy. This results in a more stable distribution of energy consumption throughout the network.

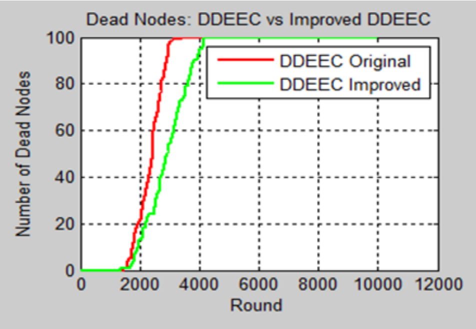

Figure 2: Number of dead nodes.

4.2 Packets Sent to Base Station

Figure 3 shows the number of packets sent to the base station. Compared to the baseline EDDEEC, the improved DDEEC sends a significantly higher number of packets, reaching a throughput of around $2.85 \times 10^5$and saturating at around 1.45×10^4. This is almost 100% throughput, confirming the effectiveness of the proposed mechanism.

4.3 Number sent to Cluster Heads per Round

Figure 4 shows the number sent to cluster heads (CHs) formed in each round. The improved DDEEC produces a more stable and balanced distribution of CHs than the original protocol, which exhibits significant swings and initial instability. Stabilized CH elections directly contribute to a more extended stability period and higher throughput.

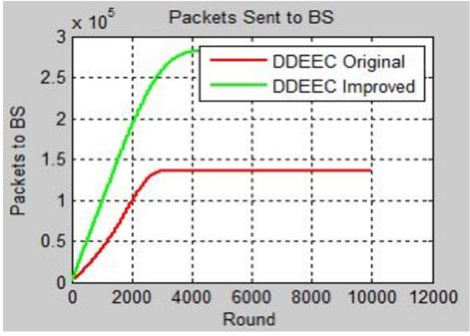

Figure 3: Number of packets sent to the base station.

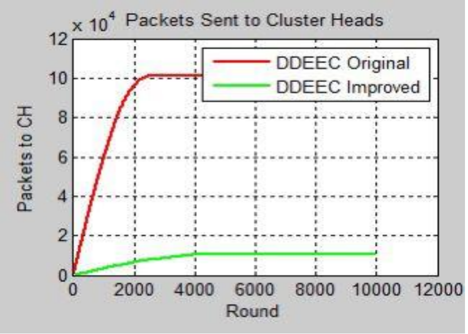

Figure 4: Number of packets sent to CHs per round.

4.4 Variation in the Number of Cluster Heads (CHs)

Figure 5 shows the change in the number of cluster heads per round for the standard DDEEC protocol and the new Enhanced DDEEC protocol. Findings indicate that the initial DDEEC shows considerable variation in CH formation, especially in the initial rounds, where CHs often exceed the ideal number. This anomaly causes overconsumption of energy, an uneven load distribution, and a shortened stability span. Conversely, the Enhanced DDEEC appears to have a more regulated and balanced CH election process; the number of CHs is closer to the optimal value, energy is used efficiently, and the network lifetime is extended. Such stability increases scalability and reliability in large-scale deployments, reduces the risk of coverage deficits, and mitigates the effects of packet loss caused by overloaded cluster heads.

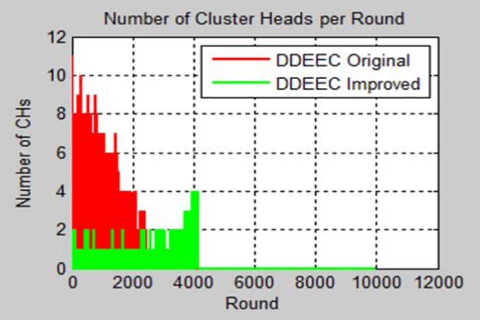

Figure 5: Variation in the number of (CHs).

4.5 Time Complexity

These results affirm that the proposed improvement effectively addresses the drawbacks of the initial DDEEC, enhancing energy efficiency, stability, and overall performance in Wireless Sensor Networks.

Reducing the number of long-range communications from cluster heads (CH) to the base station (BS) or minimising global advertisements can lead to energy savings.

The proposed DDEEC variants optimise the selection thresholds for cluster heads and reduce the frequency of global advertisements to maintain a per-round cost of $O(n)$. While previous protocols operate under the expectation of $O(n^2)$ as time complexity, our model assumes global-range broadcasts, with realistic scalability allowing for $O(n)$ message events.

5 DISCUSSION

Simulation results confirm that the proposed Enhanced DDEEC protocol effectively mitigates the major drawback of traditional DDEEC, i.e., the early demise of advanced nodes. The improved scheme is fairer, as it allocates the cluster head (CH) role more evenly across all nodes by adding an adaptive threshold and a fairness adjustment factor. The analysis of the dead nodes in Fig. 2 clearly shows the enhanced stability period. Although the original DDEEC suffers from early energy exhaustion in advanced nodes, the improved protocol will keep advanced nodes active longer, thereby increasing the time before the first and half node deaths.

This enhancement is crucial for mission-critical WSN applications, such as disaster monitoring and military surveillance, where continuous data collection is essential for as long as possible.

The throughput results are successful, as indicated in recent advancements, as shown in Figure 3. The increased number of packets sent to the base station indicates that the network under the enhanced DDEEC lasts longer and transmits more valuable information, thereby improving the quality of service. This shows that the proposed mechanism is not only energy-efficient but also improves application-level performance. The fairness of the improved protocol is confirmed by the distribution of cluster heads in Fig. 4. Stable, consistent CH numbers minimize network overhead and balance energy consumption. Conversely, the original DDEEC exhibits significant variation in CH, resulting in uneven energy consumption and a reduced network lifespan. Generally, the findings indicate that the suggested improvement offers a good trade-off between simplicity, fairness, and efficiency compared to more complex adaptive or AI-driven schemes recently proposed in [12]. This trade-off makes the Enhanced DDEEC applicable to real-world applications where energy efficiency and computational simplicity are equally crucial.

The authors [24] implemented and evaluated traditional protocols, including TDEEC and EDEEC. In the DEEC variations—specifically DDEEC, EDEEC, TDEEC, IDEEC, IoT-DEEC, and the newly proposed improved DDEECC—the initial node dies at the following round counts: 1133, 1167, 1199, 1324, 870, and 2500, respectively. Among these, the proposed protocol (DDEEC) demonstrates the best performance in terms of stability period and network lifetime.

6 CONCLUSIONS

An enhanced DDEEC protocol for heterogeneous Wireless Sensor Networks (WSN) has been introduced to address the key limitations of the conventional DDEEC approach. By incorporating an adaptive threshold mechanism and a fairness-adjustment factor, this improved protocol effectively reduces the premature failure of advanced nodes and significantly extends the stability interval. It also enhances throughput and prolongs the overall network lifetime. Experimental and simulation results demonstrate that the proposed scheme achieves substantial performance improvements, outperforming DDEEC by nearly 25% in stability compared to the original DDEEC. Notably, the time until the first node's failure is extended, the last node's failure is delayed, and the number of packets delivered to the base station is nearly doubled. This illustrates a more sustainable and resilient network operation. These findings confirm that the proposed protocol ensures a more balanced and equitable distribution of energy across all node types, helping to prevent energy holes and improve long-term performance. In addition to these quantitative enhancements, the improved DDEEC design offers a robust clustering mechanism that can adapt to heterogeneous energy conditions and dynamic operational requirements. This adaptability is essential for modern WSN applications, where reliability, longevity, and consistent data reporting are crucial. Overall, the enhanced protocol serves as a promising foundation for next-generation clustering strategies in energy-constrained networks.

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