Journal of Intelligent Systems and Internet of Things
Vol. 17, No. 02, PP. 133-151, 2025
DOI: https://doi.org/10.54216/JISIoT.170210

An Efficient Wireless Sensor Network Developed Election Protocol for Extendable Lifetime

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Abstract

Wireless sensor networks (WSNs) are made up of thousands of sensor nodes that are distributed in an area where their energy is limited. To overcome the issue of energy consumption. This paper study different deployment configuration as well as evaluating the two different clustering-based routing protocols. This work describes a hybrid distance, energy, and zonal SEP (HDEZ-SEP), which combines the strengths of the Distance and Energy-Aware Stable Election Routing Protocol (DE-SEP) and Zone-Based Stable Election Protocol (Z-SEP) to improve WSN energy efficiency and longevity. The suggested HDEZ-SEP was executed and compared to other protocols, including DE-SEP and Z-SEP. Using the MATLAB R2022b simulator; we assess the suggested protocol and contrast it with the others. According to the simulation results, the overall performance is improved. This study shows how hybrid techniques can effectively optimize data transmission and energy use in WSNs.

Received: January 01, 2025 Revised: March 01, 2025 Accepted: May 24, 2025

Keywords: Base Station; Wireless Sensor Networks; Routing protocols; LEACH; SEP; Cluster head

1. Introduction

WSNs have become an essential part of contemporary pervasive computing systems, making it possible for a broad spectrum of applications that depend on real-time and autonomous surveillance of physical space. A WSN is often composed of numerous small, low-power, spatially distributed sensor nodes that work together to sense, process and transmit data to an endpoint Base Station (BS) or sink node at the center [1]. The sensor nodes have very stringent resource limits, especially in terms of energy, processing capability, memory, and bandwidth. Of these, the most significant is energy limitation; since nodes are typically battery-operated and often located in remote or inaccessible areas, battery replacement (or recharging) is not feasible. It follows that to extend the life of the network and to guarantee the delivery of reliable data; it is a significant requirement to design protocols that optimize energy consumption.WSNs may be classified into homogeneous and heterogeneous designs. In a homogeneous WSN, the nodes are all the same, both in hardware and in terms of energy capacity. Homogeneous networks are relatively easier to operate and deploy. However, they can experience uneven energy usage (mostly in multi-hop communication situations where nodes closer to the BS are overloaded, leading to premature energy exhaustion and potential network partitioning). It is a more realistic energy-aware architecture that utilizes heterogeneous nodes, i.e., nodes that differ in their energy capacity, transmission range, or processing power. In this example, more nodes that are complex could be more energized and super nodes could be more energized, in addition to covering a greater range of transmission. This type of heterogeneous node can be strategically utilized to perform energy-intensive tasks, such as Cluster Head (CH) functions and data aggregation, and thus be used to achieve an energy consumption-versus-long network life cycle equilibrium [2].Clustering is one of the most popular and effective techniques developed as part of the strategies intended to maximize energy consumption in WSNs. The network is divided into manageable clusters of nodes, which are headed by a CH, through clustering. The CH will centralize data at its member nodes and relay the compressed data to the BS, resulting in a significant reduction in redundant transmissions and increased scalability [3]. The choice of CHs, however, is a fragile one. When CHs are often selected as low-energy nodes, energy depletion can occur quickly, reducing the network lifetime. Thus, a wise choice of CH with respect to energy-conscious and distance-conscious measures is essential. Clustering-based routing protocols not only minimize communication overhead in large-scale networks, but also minimize path loss and interference incurred during direct transmissions to the BS.

Due to the flexibility of the WSNs, they have found applications in many critical and commercial sectors. They have been used in environmental monitoring (e.g., temperature, air quality, and soil condition monitoring), in healthcare systems (e.g., remote patient monitoring), in precision agriculture, in military surveillance, in disaster detection and early warning systems, and in smart infrastructure management in cities. Such applications typically require a long-term operating mode, continuous data transmission, and network performance adjustments in response to changing environmental conditions and varying traffic loads. It has been noted, however, that dynamic changes in topology, variable node density, long-distance transmissions, as well as the requirement for effective energy management, challenge such deployments in preventing network degradation. To cope with these complex demands, a range of energy-efficient routing protocols have been proposed in recent years [4], [5]. LEACH (Low Energy Adaptive Clustering Hierarchy) was the first to propose a probabilistic model of CH selection and periodically rotate roles to redistribute the energy consumption among all nodes evenly. LEACH is effective in saving energy in small-scale and homogeneous networks, but not in large-scale or non-homogeneous networks, as the one-hop flow of messages in a large-scale network can locally congest nodes far away, leading to rapid energy depletion.The Stable Election Protocol (SEP) responded by introducing node heterogeneity through the use of weighted probabilities when selecting CHs based on initial energy levels; that is, more sophisticated nodes could be elected as CHs [6], [7]. Although SEP is more robust in a heterogeneous environment than LEACH, it does not completely address the problems of uneven distribution of CH and the hotspot issue around the BS. To improve further on CH selection, Distance and Energy-Aware SEP (DE-SEP) was proposed, which uses not only residual energy but also proximity to the BS to elect CHs. Similarly, Zone-Based SEP (Z-SEP) separates the network into spatial zones and adopts the hybridization communication strategies where ordinary nodes can only communicate with the BS, and advanced modules apply clustering. Although they have been developed, the protocols continue to have limitations, including zone imbalance, inefficient multi-hop communication, and suboptimal CH positioning. Hybrid and adaptive routing mechanisms are gaining popularity in the literature to address these shortcomings. These methods build upon the synergistic benefits of today's protocols, combining residual energy measurements, zone awareness, and network distance issues to achieve better load balancing, energy consumption, and network reliability, particularly in large-scale and other demanding deployment environments. We present in this work a Hybrid Distance-Energy-Zone-Based Stable Election Protocol (HDEZ-SEP), a new protocol that combines the advantages of DE-SEP and Z-SEP synergistically. The protocol presents a multi-metric CH selection scheme that considers residual energy, distance between nodes and sinks, zone selection and communication cost. Additionally, to enable data from remote zones to be forwarded via middle CHs, multi-hop communication is employed, thereby significantly reducing the energy load on remote nodes. The targeted protocol should achieve balance in energy consumption, stability in the network over a long period, and improve the throughput. A significant amount of simulation was conducted in MATLAB R2022b to evaluate the effectiveness of HDEZ-SEP. Findings show that the suggested protocol achieves significant gains over DE-SEP and Z-SEP in the primary performance metrics, including network lifetime, preservation of residual energy, node survival rate, and total data throughput. The improvements listed above confirm the applicability of the protocol to massive, long-term WSN implementations, particularly when energy efficiency and adaptability are key considerations.

2. The main contributions

The following is a presentation of the research's most significant contributions:

- Development of HDEZ-SEP, a hybrid clustering protocol that unifies energy-aware, distance-based, and zone-based strategies for optimal CH selection and energy-efficient routing.
- Formulation of a hybrid CH selection metric, incorporating residual energy, communication cost, and node proximity to the BS.
- Integration of multi-hop communication, enabling more efficient data forwarding and reducing energy expenditure for distant nodes.

- Implementation of zone-based deployment, improving spatial load distribution and minimizing intra-cluster communication costs.
- Demonstrated enhancement of network lifetime, with the proposed protocol sustaining a greater number of active nodes over time.
- Improved energy sustainability, with balanced consumption across heterogeneous nodes, making the protocol suitable for critical and resource-constrained WSN applications.

The rest of this paper is organized as follows: Section 2 reviews related work on routing protocols in WSNs. Section 3 presents the system and energy models. Section 4 elaborates on the proposed HDEZ-SEP protocol. Section 5 details the simulation environment and performance analysis. Finally, Section 6 concludes the paper and outlines future research directions.

3. Related works

A number of authors have conducted studies to develop efficient routing for WSNs. Some of the most significant results and achievements made by these researchers in that field are shown in this section.

A significant protocol in routing WSNs is LEACH, proposed in [8]. This version incorporates rank-based CH selection using node coverage, energy consumption rate, and the distance features of the base station to maintain the random number generation. However, each node has an equal chance of becoming the cluster head. Meanwhile, because the assignment of cluster head nodes is performed randomly, it is possible to choose the nodes with low energy as cluster head nodes, resulting in an unbalanced energy consumption that eventually lowers the network's longevity.

Panchal, Singh, and Singh [9] developed the RCH-LEACH method to optimize energy efficiency in Wireless Sensor Networks. This approach is an upgraded version of the classic (LEACH) procedure. The technique accounts for node residual energy to prevent premature node death and increase network lifespan. Simulations highlight the effectiveness of energy-constrained situations. The EOCGS approach, which was first described in Panchal and Singh's [10] publication, optimizes Grid Heads and Cluster Heads in Wireless Sensor Networks (WSNs) to improve energy efficiency. This technique ensures long-term WSN operations by maintaining strong communication structures and balancing energy consumption across the network, resulting in lower total energy usage.

A single-hop homogeneous network was introduced as a novel extension in [11]. The initial and residual energy of the sensor node, along with its distance from the BS, were taken into consideration when selecting the CH. The resulting energy efficiency and network longevity are similar to those of LEACH. Another related protocol is Modified LEACH (MODLEACH), which is demonstrated in [12]. It is a different modified version of LEACH. This protocol introduces an efficient cluster head replacement scheme and dual transmitting power levels. Which then improved in Enhanced MODLEACH (EMODLEACH) [13]. EMODLEACH performs better than MODLEACH in terms of network lifetime and packets sent to the base station. However, it has a problem of lower energy efficiency and the number of packets sent to BS.

In Sectored LEACH (S-LEACH) [14], throughput is higher and network lifetime is longer. Despite using a multi-hop communication mechanism to restrict the energy consumption of remote nodes, S-LEACH does not alleviate the energy gap issue. For heterogeneous WSN, SEP is proposed [15] with two levels of heterogeneity. A subset of nodes with higher energy levels than regular nodes is referred to as advanced nodes. While advanced nodes have a higher likelihood of becoming cluster heads than standard nodes, both categories of nodes in SEP are assigned weighted probabilities to ascend to cluster headship. This means that efficient node deployment is not guaranteed by the stable region in SEP, particularly when the base station is positioned outside of the sensing field.

A proactive strategy called modified-SEP (MSEP) for two-level heterogeneous WSNs was proposed in [16]. By taking into account the residual energy in the CH selection criterion, MSEP outperformed SEP in terms of performance. However, MSEP does not take distance into account when choosing a CH; therefore, there's a chance that a far-off node could be chosen as a CH, increasing energy consumption. A hybrid approach of distance-aware residual energy-efficient SEP (DARE-SEP) is described in [17]. It is an integration of Direct Transmission (DT) and Distance-Based Protocol (DP) with Residual Energy Efficient SEP (REE-SEP) characteristics. However, it still consumes high energy, so it cannot prolong the lifetime of the network.

A reactive procedure called Threshold-sensitive SEP (TSEP) [18] employs three levels of heterogeneity: normal, advanced, and super nodes. The super nodes have a substantially larger beginning energy than the advanced nodes. TSEP, however, is unable to effectively save energy to provide a balanced load distribution. But even with effective energy conservation, TSEP is unable to guarantee a load distribution that is balanced. The modified version of TSEP called Enhanced Threshold Sensitive SEP (ETSSEP) [19] considers both the node's leftover energy during threshold computation and the minimal number of clusters every round.

A dynamic energy-efficient routing protocol called DE-SEP explained is in [20]. It takes into account the position and energy of the nodes in the CH selection process. Therefore, closer nodes to BS have a significant role in becoming a CH. However, this routing protocol does not consider the mobile sensor node at a constant speed. A protocol with the same cluster formation of SEP is Z-SEP, which was created in [21]. Where the principle of network node zonal deployment is explained. However, it does not consider the consumption energy to choose the CH. So, the limited energy sensor nodes have a high chance of being selected as a CH.

An Advance Z-SEP (AZ-SEP) is proposed in [22], which is an improvement of the Z-SEP protocol. It introduces multi-hop communication with the BS, and CH will use a multi-hop technique for communication. Therefore, it uses less energy, extending the sensor network's lifespan and stability period. However, there are still certain problems, like the connection between normal nodes and the BS, which would be fascinating to investigate further. In order to get around this restriction, the Extension of Z-SEP (EZ-SEP) is suggested [23]; it does this by capping the total number of CHs for three-level heterogeneous WSNs. In order to extend the network lifetime, the EZ-SEP protocol takes into account the nodes' remaining energy during the CH selection phase. However, it overlooks the density of sensor nodes, which is another crucial factor in choosing the CH in the network.

An optimized forwarding candidate set selection technique is proposed by a cross-layer routing protocol based on channel quality (CLCQ) [24], which speeds up the convergence speed of the reinforcement learning algorithm and improves the routing protocol's overall performance and efficiency. For a multi-heterogeneity routing protocol, [25] introduces a new entropy-based clustering algorithm for WSNs, which is an effective energy technique. It takes into account energy efficiency in CH selection and inter-cluster routing. Nevertheless, limitations arise in highly dynamic environments or scenarios with frequent node mobility.This approach effectively reduces packet loss and improves network longevity. However, it still faces limitations, such as increased computational overhead due to the fuzzy inference system, fixed fuzzy rule sets that may not adapt well to rapidly changing network conditions, and a lack of real-world deployment validation methodology.

Salim El Khediri et al. [27] to increase search efficiency and lower total energy usage in WSNs introduced a hybrid approach combining ABC and ACO. The best CH may be chosen from a collection of terminals with the use of this procedure. ACO determines the most effective route between the CH and the BS by taking into account variables such node degrees, distance, and remaining power.

The MFO with historical flame archive (MFO-HFA) has been proposed as the best approach to engineering problems [28]. In order to enhance convergence, a top flame randomly matching technique is suggested, which mainly guards against network intrusion detection. EEMFO offers a potential remedy for the problems with energy usage in WSNs but cannot avoid energy loss because of malevolent attacks or security lapses.

This study [30] used three strategies to increase the network's lifespan: (i) sleep scheduling methods; (ii) path length reduction through reinforcement learning; and (iii) data transmission limitation based on variations in received data rates. The use of deep neural networks based on whale optimization to improve spectral and energy efficiency has attracted a lot of attention due to the growth of Internet of Things (IoT) networks that depend on Wireless Sensor Networks (WSN)[31],[32]. Optimal resource allocation is used to the multi-hop network to improve quality of service (QoS) and energy efficiency.

Although several clustering-based routing protocols such as LEACH, SEP, DE-SEP, and Z-SEP have contributed significantly to improving energy efficiency in WSNs, they each exhibit critical limitations. These include fixed CH selection probabilities, lack of zone-awareness, and limited support for multi-level energy heterogeneity. Optimization-based methods, like the Modified Ant Colony Optimization Protocol and KNN-assisted clustering, offer performance improvements but often introduce high computational costs and impracticality in resource-constrained deployments.

a. *The system model*

i. *Energy Model*

The energy model is based on three types of nodes classified according to their initial energy levels: normal, advanced, and super nodes, with energy heterogeneity playing a key role in optimizing network performance.

- Normal Nodes: have a baseline energy level denoted as E_0

- Advanced Nodes: possess an energy level α times higher than normal nodes, giving them an initial energy of $E_0(1+\alpha)$.
- Super Nodes: have the highest energy level, γ times greater than normal nodes, so their initial energy is $E_0(1+\gamma)$.

Where α and γ represent the additional energy levels of advanced and super nodes, respectively, E_0 represents the initial energy of normal nodes, m represents the fraction of advanced nodes, and υ represents the fraction of super nodes in the network.

This results in the remaining $1-m-\upsilon$ fraction of nodes being normal. The total initial energy E_{total} can be represented by

$$E_{total} = (1-m-\upsilon).E_0 + m.E_0(1+\alpha) + \upsilon.E_0(1+\gamma). \qquad (1)$$

In addition to the residual energy (E_{res})of nodes being important to ensure the energy efficiency, it is also considered in determining the average energy of the network as following:

$$E_{avg}(r) = \frac{\sum_{i=1}^{N} E_{res}(r)}{N} \qquad (2)$$

Nodes with energy greater than or equal to the average energy ($E_{res}(r) \geq E_{avg}(r)$) are more likely to be selected as CHs. This energy model ensures that nodes with higher energy (advanced and super nodes) are more likely to become cluster heads, promoting effective energy consumption throughout the network.

ii. Energy dissipation model

The energy dissipation model optimizes the network's energy consumption by taking into account both transmission energy and reception energy [18], as these are two basic operations in WSN. Traditionally, the data transmission process consumes more energy than the data reception [33].

a. Transmission Energy

- For short distances

$$E_{Tx}(k,d) = k \times (E_{elec} + E_{fs} \times d^2) \qquad (3)$$

- For long distance

$$E_{Tx}(k,d) = k \times (E_{elec} + E_{mp} \times d^4) \qquad (4)$$

Where k is the number of bits, d is the distance, E_{elec} is the electronics energy, $E_{fs}$is the free space energy, and E_{mp} is the multipath energy.

b. Reception Energy

$$E_{RX}(k) = k \times E_{elec} \qquad (5)$$

c. Data Aggregation Energy

$$E_{DA}(k) = k \times E_{DA} \qquad (6)$$

where E_{DA} is the energy required for data aggregation

b. Network Model

Our hybrid strategy distributes nodes in a way that maximizes energy efficiency and prolongs network lifetime. The base station is located in the middle of the 200x200-meter network. Normal nodes are dispersed closest to the base station and have the lowest energy level assigned to them. Therefore, they communicate directly with BS, which reduces energy consumption. Advanced nodes are positioned carefully in two zones, one to the right and one to the left of the typical node zone. They have more energy than normal nodes. These nodes group together to form clusters, and among them, a CH is chosen. With taking into account distance and residual energy. By using cluster-based communication to transmit data to the BS, advanced nodes, minimize the energy consumption of distant nodes. Super nodes are located at the top and bottom of the network, where they have the maximum energy. Their CHs gather data from other super nodes and send it to the BS as part of their participation in cluster-based communication. These nodes are able to handle more complex network communication duties because of their larger energy reserves. This node distribution scheme is shown in Figure 1.

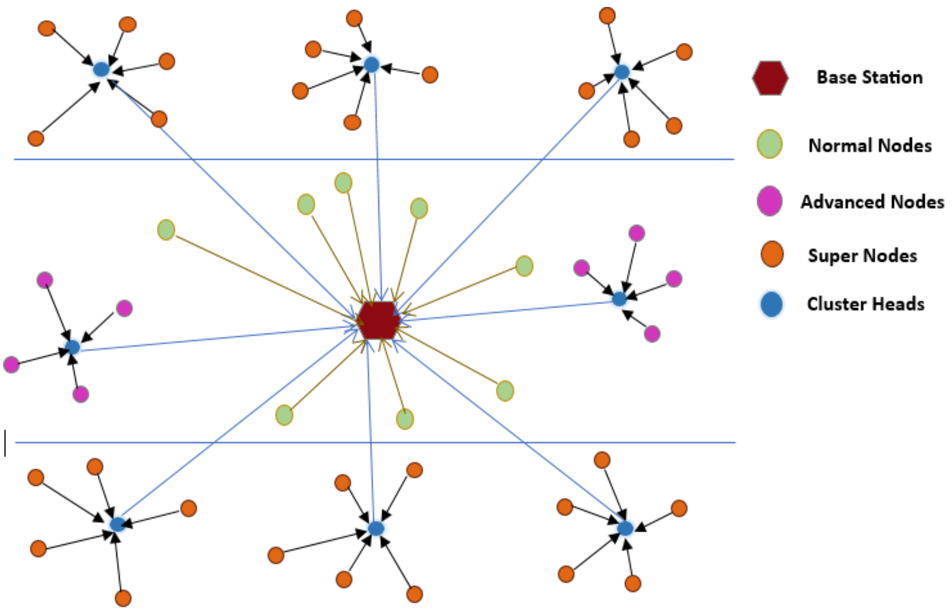

Figure 1. Communication of nodes with BS

4. The proposed protocol

The proposed HDEZ-SEP protocol combines the zone-based approach of Z-SEP with DE-SEP. The network will be separated into zones. Cluster heads selected within each zone depending on node residual energy. According to this hybrid, both geographical and energy issues are considered in the cluster head selection process. Resulting in a more balanced and efficient network.

a. Nodes' Weighted Probabilities

The CH selection mechanism in the proposed HDEZ-SEP is based on a probability calculation. It is based on two factors: distance to the base station and residual energy. By improving the selection process based on the node's location, the protocol conserves energy, especially in areas with high communication demands. The probabilities of the three types of nodes can be calculated using Eqs. (7-9):

i. Normal Nodes

$$P_{nrm} = \frac{p.(\frac{E_{res}}{E_0})}{(1+m\alpha+v\gamma).(\frac{d_{to\ BS}}{d_{avg}}+1)} \tag{7}$$

ii. Advanced Nodes

$$P_{adv} = \frac{p.(1+\alpha).(\frac{E_{res}}{E_0})}{(1+m\alpha+v\gamma).(\frac{d_{to\ BS}}{d_{avg}}+1)} \tag{8}$$

iii. Super Nodes

$$P_{sup} = \frac{p.(1+\gamma).(\frac{E_{res}}{E_0})}{(1+m\alpha+v\gamma).(\frac{d_{to\ BS}}{d_{avg}}+1)} \tag{9}$$

Where, p is the desired percentage of CHs, E_{res} is the residual energy of the node, $d_{to\ BS}$ is the distance from the node to the BS, and d_{avg} is the average distance of all nodes to the BS.

b. *The proposed CH* selection *mechanism*

The suggested hybrid protocol combines the advantages of Z-SEP and DE-SEP in its CH selection mechanism. During CH selection, the proposed routing protocol takes into account each node's position relative to BS, as well as its initial energy and the network's average energy. As a result, a node with higher energy and close to BS has increased chances of being picked as CH. Here, energy consumption is decreased during data transmission since the adjacent CH uses less energy than the distant CH. The proposed routing protocol algorithm is described in algorithm 1.

To maximize energy efficiency and network performance, it takes into account residual energy, zone factor, and communication cost. The selection process integrates three key factors; these factors are calculated using Eqs. (10-12):

i. Residual 0Energy Factor:

$$E_{res} = \frac{S(i).E}{E_0} \qquad (10)$$

This factor lowers the probability that nodes with low energy will become CHs by giving priority to nodes with higher residual energy.

ii. Zone Factor:

$$zoneFactor = \{1 \quad if\ d(i, sink) \leq \frac{distance_{max}}{2}\ 0.5 \quad if\ d(i, sink) > \frac{distance_{max}}{2} \qquad (11)$$

This component reflects the zoning method of Z-SEP by giving nodes closer to the sink a higher weight.

iii. Communication Cost Factor:

The communication cost factor is calculated using the distance to (BS):

$$commCostFactor = \frac{d_{toBS}}{network\ size\ factor} \qquad (12)$$

Distance to the BS is the distance of a node from the BS.

$$d_{toBS} = \sqrt{(S(i).xd - sink.x)^2 + (S(i).yd - sink.y)^2} \qquad (13)$$

Here, $(S(i).xd, S(i).yd)$ and ($sink.x$, $sink.y$) are the coordinates of the sensor node and BS respectively.

Network size factor is the diagonal length of the deployment area:

$$network\ size\ factor = \sqrt{xm^2 + ym^2} \qquad (14)$$

iv. Hybrid Selection Probability:

$$P_{hybrid}\,(i) = \frac{energy\ factor}{commCostFactor \times zoneFactor} + 0.1 \times rand \times\ energy\ factor \qquad (15)$$

We now use $d_{to\ BS}$ to indicate the distance between a member node and BS that can be calculated using Eq. (13). $d_{to\ CH}$ indicate the distance between a member node and its closest CH described in Eq. (15). In order to conserve energy when sending data, we calculate the minimum possible distance d_{min} between $d_{to\ BS}$and $d_{to\ CH}$ in Eq.(17). Member nodes send data to the base station directly if d_{toBS} is less than $d_{to\ CH}$; otherwise, data is sent to BS via CH.

$$d_{toCH} = \sqrt{(S(i).xd - X_{CH})^2 + (S(i).yd - Y_{CH})^2} \tag{16}$$

Here, $(X_{CH}\ , Y_{CH})$, are the coordinates of CH.

$$d_{min} = min(\ d_{toBS}\ \ , d_{toCH}) \tag{17}$$

Algorithm 1: HDEZ-SEP Based Routing

CH_set: Set of Cluster Heads (CHs).

CH_count: CH counter.

CH_max: Maximum allowed CH count (percentage of alive nodes).

Non_CH: Set of non-CH or member nodes.

N_rand: Random number.

Hybrid_Factor: Combination of Communication Cost Factor, Zone Factor, and Residual Energy.

Normal, Advanced, Super: Different types of nodes with varying energy levels

```
Begin
Build the sensor network.
for r = 1 to r_max do
  $CH_{set}$=0;
  $CH_{count}$=0;
  calculate $P_{nrm}, P_{adv}\ , P_{sup}$ and $E_{avg}$ by using Eq. (3), (8)-(10);
    for $i = 1\ to\ n$ do
        if $CH_{count} < CH_{max}$ then
            if node i belongs to the Near zone or Mid zone or Far zone then
                calculate $P_{hybrid}\ , T_n, T_a, T_s$ using Eq. (15),(18)-(20);
                if ($N_{rand} \leq T_n(i)$ & $E_{res}(r) \geq E_{avg}(r)$
                    if node i belongs to the Near zone then
                        Normal node is selected as CH;
                    else if node i belongs to the Mid zone then
                        Advanced node is selected as CH;
                    else if node i belongs to the Far zone then
                        Super node is selected as CH;
                    end if
                    $CH_{set}$= $CH_{set} \cup \{i\}$ ;
                    $CH_{count}$ = $CH_{count}$+ 1;
                    calculate $E_{TX}(k,d)\ , E_{Rx}(k,d)$ by using Eq. (3)-(5);
                    update $E_{res}(r)$;
            end if
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        end if
    end for
    for $i = 1\ to\ n$ do
        if ({i} ∈ $n$on_CH & $E_i\ (r) > 0$)then
            calculate $d_{to\ BS}, d_{to\ CH}, d_{min}$ by using Eq. (13) & (16) &(17) & then assign
                nodes to the nearest CH based on calculated distances
            calculate $E_{Tx}(k, d)$ by using Eq. (3) or (4)
        end if
    end for
    for each zone (Near, Mid, Far) do
        if ({i} ∈ Far Zone) then
            Communicate with the Mid Zone CHs for data transmission to the BS
        Else if ({i} ∈ Mid Zone) then
            Communicate directly with Near Zone CHs or the BS.
        Else if ({i} ∈ Near Zone) then
            Communicate directly with the BS.
        end if
    end for
end for
end
```

c. Thresholds Criteria for CH Selection

T_n, T_a, and T_s represent the thresholds for Normal, Advanced, and Super nodes in the fourth round, respectively. Each node creates a random number between 0 and 1. If the generated number is fewer than the threshold, the node will be considered as a potential CH.

i. Normal Nodes

$$T_n(i) = \begin{cases} \dfrac{p_n \times P_{hybrid}\,(i)}{1 - p_n \times p_{hybrid}(i) \times \left(mod\left(r, \frac{1}{p_n}\right)\right)} & if\ i\ \in G \\ 0 & otherwise \end{cases} \qquad (18)$$

where p_n is the baseline probability of normal nodes becoming CHs, r is the current round, and G is the set of nodes that have not been CHs in the last $\frac{1}{p_n}$ rounds.

ii. Advanced Nodes

$$T_a(i) = \begin{cases} \dfrac{p_a \times P_{hybrid}\,(i)}{1 - p_a \times p_{hybrid}(i) \times \left(mod\left(r, \frac{1}{p_a}\right)\right)} & if\ i\ \in G \\ 0 & otherwise \end{cases} \qquad (19)$$

where $p_a = p_n \times (1 + \alpha)$ adjusts the probability for advanced nodes.

iii. Super Nodes

$$T_s(i) = \begin{cases} \frac{p_s \times P_{hybrid}(i)}{1 - p_s \times p_{hybrid}(i) \times \left(mod\left(r, \frac{1}{p_s}\right)\right)} & if\ i \in G \\ 0 & otherwise \end{cases} \quad (20)$$

where $p_s = p_n \times (1 + \gamma)$ adjusts the probability for advanced nodes.

A small quantity of energy is used in this method. A CH that is close to BS gathers all the information from the other CH and sends it to BS. Because it has the maximum communication time, this lengthens the network's stability period.

5. Simulation results and discussion

Terms used in simulations include objects, parameters, and the domain in which the network gathers input and sends it to a sink for additional processing. In this section, we simulate the heterogeneity of nodes in both our protocol and the parent protocol. We also examine the performance behavior of our proposed protocol using various evaluation situations. Our proposed approach uses two modes of communication. In the typical nodes zone, where sensor nodes are close to the base station, direct transmission is more energy-efficient than clustering. Data is communicated between advanced nodes and super node zones via the cluster heads who are elected. The simulation parameters used to analyze the performance of the proposed HDEZ-SEP are shown in Table 1. Every round, every parameter value is measured.

Table 1: Network parameters

Parameters	Values
Network size	200 m×200 m
Sensor nodes	200
Position of BS	(100,100)
Initial energy for normal nodes	0.5J
Transmitter/ receiver electronics energy	50 nJ/bit
Energy dissipation for multipath	0.0013 pJ/bit/m^4
Energy dissipation for free space	10 pJ/bit/m^2
Optimal probability	0.1

The figures (2-5) evaluate the number of dead nodes, alive nodes, the total residual energy, and throughput respectively, in comparison with two state of arts WSN routing protocols.

a. Analysis of network parameters

i. Analysis of network stability

The analysis of Figure 2 shows a compelling hierarchy of performance among the three protocols, with HDEZSEP showing significantly better stability characteristics than both DESEP and ZSEP. The green line (HDEZSEP) remarkably maintains zero dead nodes until approximately 2000 rounds before exhibiting the same sharp increase to 200 dead nodes by 2200 rounds, while the red line (ZSEP) performs somewhat better with dead nodes first appearing around 1500 rounds and reaching the 200-node threshold by 1700 rounds. Therefore, the proposed HDEZ-SEP appears to have a comparatively higher network trustworthiness.

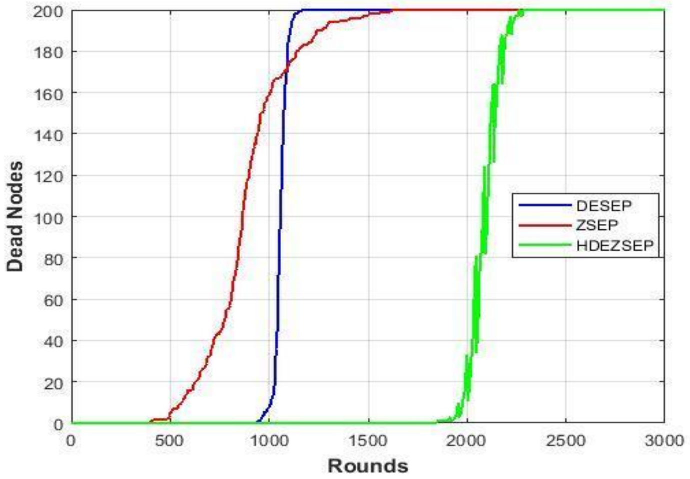


Figure 2. Dead nodes

ii. Analysis of network lifetime

The network lifetime parameter is explored in Figure 3. Additionally, the analysis takes place in rounds, contrasting the DE-SEP, Z-SEP, and the proposed HDEZ-SEP protocol's alive node number, and all deployed sensor nodes in HDEZ-SEP survived longer. The lifetime length in the proposed HDEZ-SEP appears significantly better. The last node in the proposed HDEZ-SEP dies after about 2200 rounds. The proposed strategy can keep more alive nodes among the typical nodes by eliminating long-distance communication, which uses a lot of energy. Cluster heads use energy-efficient communication channels with the base station. Implementing the new routing protocol results in higher average energy conservation each round. In a heterogeneous network, the proposed HDEZ-SEP is preferable over DE-SEP and Z-SEP due to its extended network lifetime.

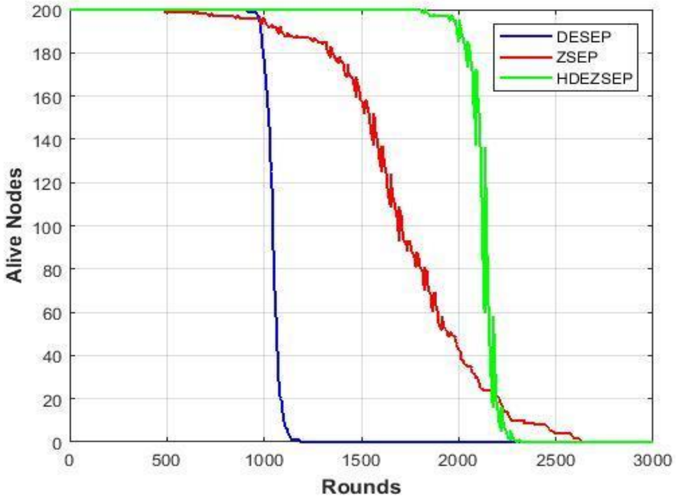


Figure 3. Network Lifetime

iii. Analysis of Residual energy

Figure 4 displays the network's adjusted residual energy for each round, as it is important to detect the anomalies on the network node, demonstrating how the suggested protocol performs better than the current methods. The results validate that the proposed HDEZ-SEP uses less energy when compared to alternative methods. This increased energy consumption performance is mostly the result of giving nearby nodes more weight than far-off nodes when choosing a CH. As a result, the procedure makes sure that the available energy is used efficiently during data transmission while keeping the sensor network's homogeneity.

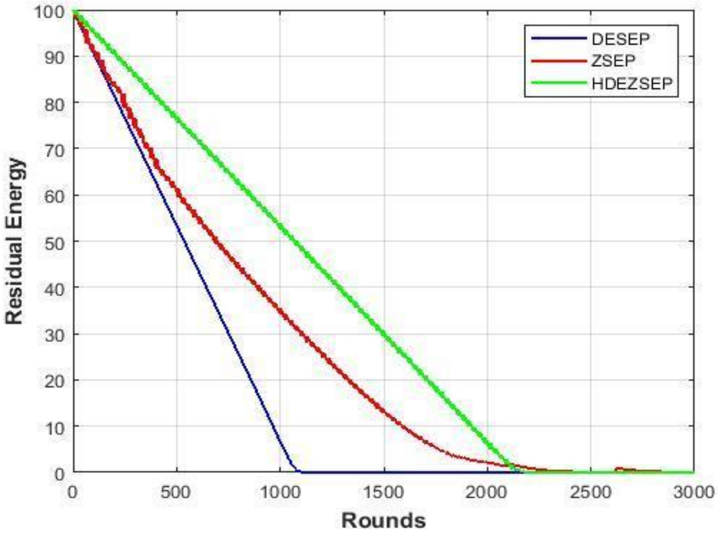


Figure 4. Residual Energy

To highlight the results further, the residual energy levels for each technique at the point of reaching zero energy are shown numerically in table 2. For DE-SEP, this happened at round 1500. For Z-SEP, the residual energy at this point was 5.2370, and for the proposed HDEZ-SEP, it was 30.4019.

Table 2: The residual energy by DE-SEP, Z-SEP and HDEZ-SEP

Round	DE-SEP	Z-SEP	HDEZ-SEP
0	100	100	100
500	53.4985	56.1179	76.3488
1000	6.7894	26.4886	52.7193
1500	0	5.2370	30.4019
2000	0	0.2472	6.5576
2500	0	0	0

iv. Analysis of Throughput

In Figure 5, the results of the simulation are used to analyze the network throughput. What is taken into account is the total amount of packets that are sent to the base station. In the initial rounds from 0 to 500 rounds, all three protocols show a similar initial rise in throughput. In the mid-range rounds from 500 to 1500 rounds, DE-SEP reaches its maximum throughput at approximately 1000 rounds and does not expand further, but HDEZ-SEP, the proposed protocol, keeps growing and catches up by 1500 rounds, indicating that it may be better than Z-SEP for longer operation. In the final range, both the hybrid protocol and DE-SEP stabilize at similar maximum throughput, with Z-SEP slightly behind. However, the proposed HDEZ-SEP does not significantly outperform DE-SEP, as both reach comparable final values.

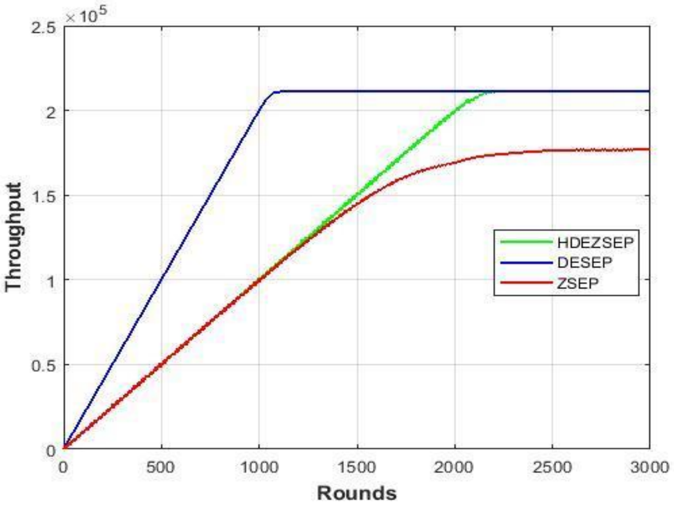
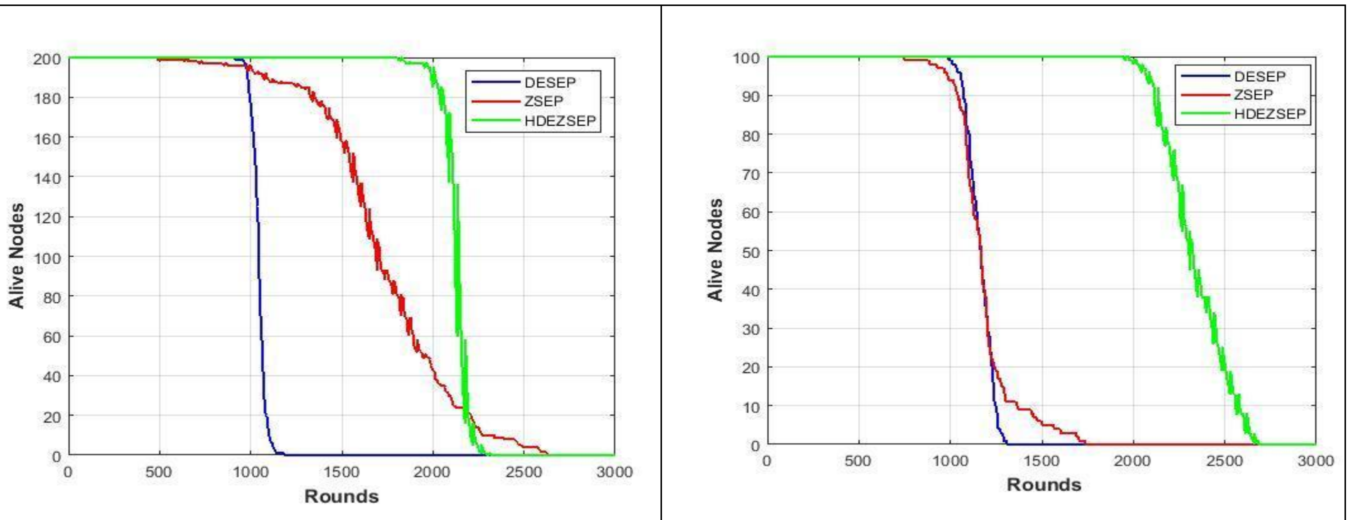


Figure 5. Throughput

b. Network Configuration

i. Alive nodes

In Figure 6, in both configurations, the proposed protocol HDEZ-SEP clearly outperforms both DE-SEP and Z-SEP in terms of node longevity. This is particularly noticeable in larger networks (200x200 meters), where the hybrid protocol sustains alive nodes for a much longer period, indicating superior energy efficiency. The protocol performs consistently across different deployment areas, making it suitable for applications requiring long-term monitoring and network stability.



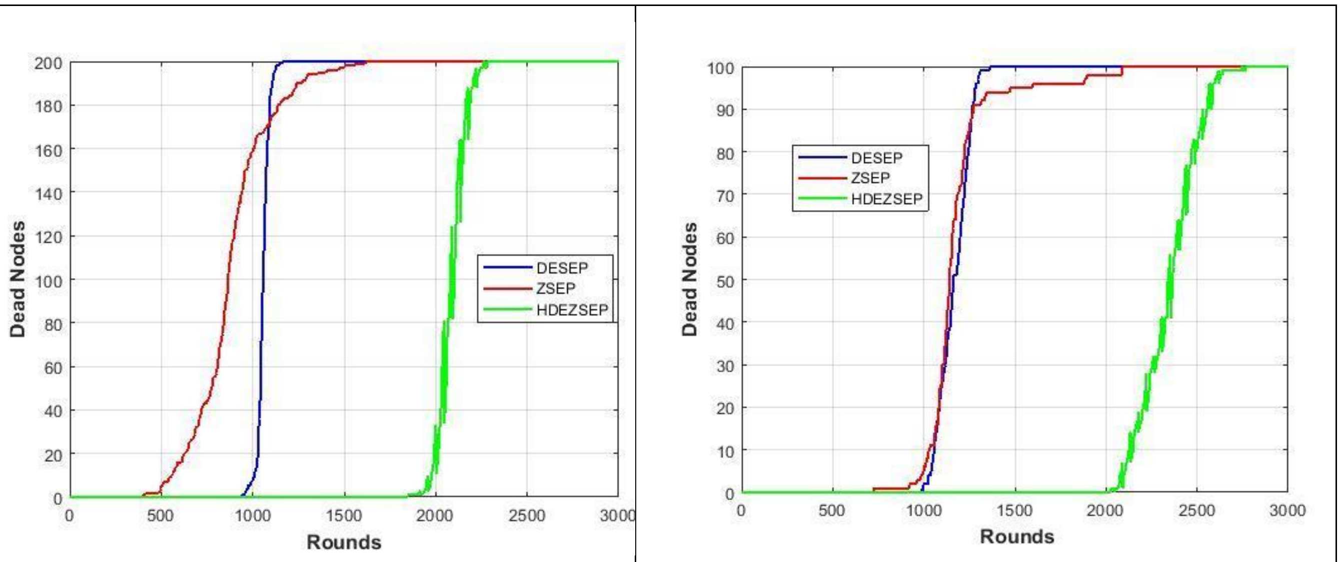
(a)

(b)

Figure 6. Comparing Alive nodes for (a) $M=200^2$, n=200 nodes and (b) $M=100^2$, n=100 nodes

ii. Dead Nodes

The results in Figure 7 indicate that the proposed protocol HDEZ-SEP is particularly effective in both larger and smaller network configurations, though its advantages are more pronounced in the larger network (200x200, 200 nodes) as shown in Figure 7 (a). The increased node count and larger area allow for better energy distribution and more efficient cluster head selection, maximizing the benefits of the proposed approach. In both cases, HDEZ-SEP demonstrates clear superiority in sustaining node lifetimes, but its efficiency is slightly more impactful in larger deployments. This suggests that the proposed protocol is well suited for scenarios with dense node deployment over larger areas, where energy efficiency is crucial for maintaining network longevity.



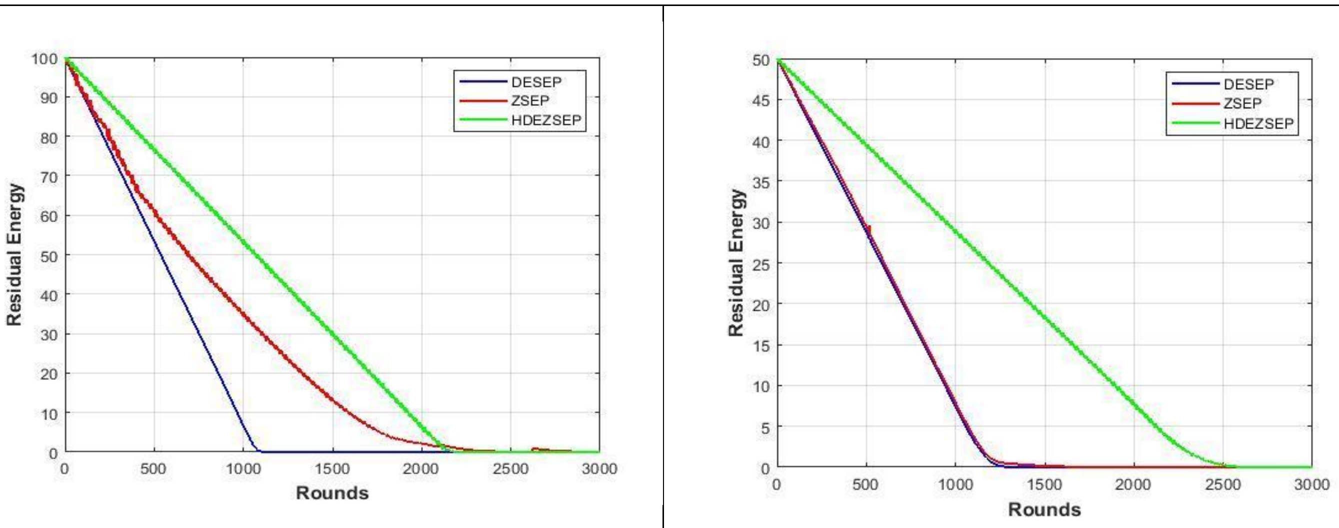
(a)

(b)

Figure 7. Comparing Dead nodes for (a) M=200^2, n=200 nodes and (b) M=100^2, n=100 nodes

iii. Residual Energy

As shown in Figure 8 for both the larger (200x200) and smaller (100x100) networks, the proposed HDEZ-SEP outperforms DE-SEP and Z-SEP by maintaining higher residual energy over a greater number of rounds. However, this improvement is more pronounced in the larger network (200x200), where node count and area size increase the demand for energy efficiency. The hybrid protocol's ability to slow down energy consumption in larger networks demonstrates its suitability for dense, wide-area deployments, where prolonging network lifetime is critical. Meanwhile, in smaller networks, the energy conservation benefits of the proposed HDEZ-SEP are still evident, but the gap between it and Z-SEP is narrower due to the reduced energy consumption needs of a smaller deployment area.



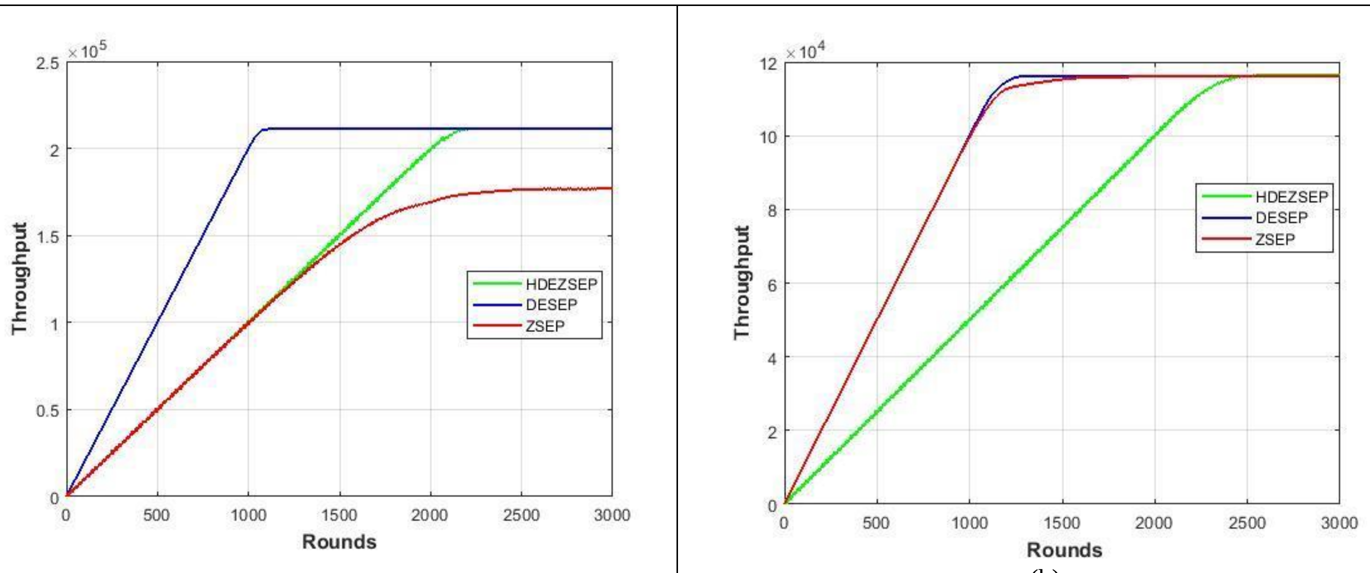
(a)

(b)

Figure 8. Comparing residual energy for (a) M=200^2, n=200 nodes and (b) M=100^2, n=100 nodes

iv. Throughput

The throughput comparison in Figure 9 shows that the proposed HDEZ-SEP outperforms DE-SEP and Z-SEP in both network configurations. In the larger network (200x200, 200 nodes), HDEZ-SEP achieves the highest throughput, sustaining it over more rounds, demonstrating its efficiency in handling higher node density and larger areas. In the smaller network (100x100, 100 nodes), all protocols perform similarly in the early rounds, but HDEZ-SEP maintains a slight advantage in throughput, showing better energy conservation. While the performance gap is narrower in smaller networks, HDEZ-SEP consistently proves superior, especially in larger deployments where energy efficiency and data aggregation are more crucial.



(a)

(b)

Figure 9. Comparing throughput for (a) M=200^2, n=200 nodes and (b) M=100^2, n=100 nodes

From our comparative analysis in figures (2-5), we can obtain a comparison between the proposed HDEZ-SEP, DE-SEP and Z-SEP in table 3. It demonstrates this comparison across CH selection mechanism used and all evaluated metrics: network lifetime, energy efficiency and throughput.

Table 3: The comparison between DE-SEP, Z-SEP and HDEZ-SEP.

Feature	**DE-SEP**	**Z-SEP**	**HDEZ-SEP**
Cluster Head (CH) Selection Mechanism	CH selection is based on residual energy and distance from the BS. it lacks intra-cluster communication optimization, leading to inefficiencies in large-scale networks.	CH selection incorporates a zone-based approach. However, it does not consider distance to the BS during CH selection.	Combines node heterogeneity, residual energy, and proximity to the BS with a dynamic zone-based strategy for optimal CH selection.
Energy Efficiency	Limited energy efficiency due to location of CH far from BS.	Improves on DE-SEP by using zones, but still has no balance energy usage between zones.	Balances energy consumption within clusters (via zones) and between clusters (via distance-based CH selection), resulting in more uniform energy depletion and longer-lasting nodes Significantly energy usage and reduce consumption by 10 %

Network lifetime	Extends lifetime to 1,000 rounds	Extends lifetime to 1,500 rounds (50% improvement over DE-SEP).	Extends lifetime to ~2,000 rounds (~100% improvement over DE-SEP) Nodes deplete energy more evenly, resulting in fewer dead nodes and prolonged overall functionality of the network.
Throughput	Achieves reasonable throughput by considering residual energy during CH selection.	Higher throughput due to reduced energy spent on communication within zones.	Throughput remains comparable due to balanced CH selection and efficient energy use but does not substantially exceed DE-SEP's throughput.

6. Discussion

Through the outcome of this study, it has been observed that the proposed Hybrid Distance, Energy, and Zone-Based Stable Election Protocol (HDEZ-SEP) exhibits significant performance gains over the current DE-SEP and Z-SEP protocols, particularly in terms of energy efficiency, network lifetime, and scalability. HDEZ-SEP successfully trades energy use among heterogeneous sensor nodes by combining the zone-based model of Z-SEP with the energy- and distance-sensitive cluster head (CH) selection of DE-SEP. This equal energy loss is especially noticeable in the simulation results, where the number of dead nodes remained at zero until approximately 2000 rounds, compared to 1500 in Z-SEP and 1000 in DE-SEP. This means that network stability and reliability have greatly improved, making the protocol quite valuable for long-term operations, such as environmental monitoring, precision agriculture, and disaster management, where continuity of data capture over extended periods is vital. The gain in unused energy also demonstrates that HDEZ-SEP is highly effective in minimizing energy wastage. As can be seen in the residual energy curves, HDEZ-SEP utilizes less energy per round by selecting CHs in accordance with residual energy and distance to the base station (BS), thereby reducing the energy expenditure associated with data transmission. The zoning scheme of the protocol allocates nodes based on their initial energy levels so that normal nodes can directly communicate with the BS, and advanced and super nodes can use the clustering mechanism. This architecture can significantly reduce the loading of low-energy nodes and is much more energy-efficient (by a factor of about 10) than DE-SEP. The hybrid CH selection mechanism also ensures that energy-intensive roles are allocated to nodes with higher energy reserves, making energy depletion uniform and delaying node death in large-scale network applications (200 × 200 meters, 200 nodes). Although throughput among all protocols converged to similar levels in the later rounds, HDEZ-SEP continued to deliver packets at higher rates over a specific period, especially in large-scale network deployments (200 × 200 meters, 200 nodes). This indicates its scalability and ability to handle a higher node density without compromising network reliability. The limitations of energy balancing and multi-hop communication optimization in Z-SEP and DE-SEP prevented them from meeting the demands of large-scale deployments, resulting in earlier node failures and lower data delivery rates as the deployment size increased. The ability of HDEZ-SEP to be used in both small (100 × 100 meters) and large-scale networks is also linked to the superiority of the protocol, which is based on a multi-hop communication strategy that helps extend the network's lifetime, as less weight is loaded on the long-range node. HDEZ-SEP reduces the path loss characteristic of long-distance communication and is widely recognized as a significant source of energy inefficiency in WSNs, enabling nodes in outer zones to transmit their data through intermediate CHs. The protocol is more resilient to uneven node distribution and the dynamism of the network environment, a common weakness of many clustering protocols, including LEACH, SEP, and Z-SEP, which heavily depend on single-hop communication. However, throughput performance indicates that HDEZ-SEP benefits are more pronounced in energy optimization than in improving network capacity. The throughput figures indicate that maintaining higher data delivery over a longer duration is possible, but the total peak throughput is not significantly higher than that of the DE-SEP. In general, HDEZ-SEP is a promising solution to some of the most urgent issues in WSN routing, especially energy heterogeneity, uneven energy depletion, and scalability. Through a combination of zone-based deployment schemes, hybrid CH selection, and multi-hop communication, it can effectively overcome the so-called hotspot phenomenon around the BS and extend the network operations. These results align with recent studies that have proposed hybrid and adaptive WSN routing solutions [1-4], which focus on combining multiple optimization parameters to enhance overall network robustness.

7. Conclusions and future work

In this paper, HDEZ-SEP is a new hybrid clustering routing protocol explicitly developed to improve energy efficiency, network lifetime and robustness in heterogeneous WSNs, namely, Wireless Sensor Networks. The proposed protocol also addresses the fundamental limitations inherent in traditional clustering protocols, including

DE-SEP and Z-SEP, through a clever combination of distance-awareness, energy heterogeneity, and zone-based architecture. The simulation results obtained using HDEZ-SEP enable the achievement of more adaptive and balanced routing, where multi-parameter cluster head (CH) selection strategies are performed simultaneously, considering the residual energy, distance between the node and the base station (BS), and the cost of communication and network zones. Interestingly, the stability of the network is significantly improved, and the first node is killed on the 2000th round, much better than DE-SEP (1000 rounds) and Z-SEP (1500 rounds). Moreover, the management of energy conservation becomes more effective as HDEZ-SEP utilizes its hybrid selection scheme to transfer energy-consuming tasks to high-capacity nodes, and allows low-energy nodes to communicate with the BS directly when separated by short distances. The fact that energy usage is distributed more evenly during data transmission proves that the proposed protocol helps prevent the untimely death of nodes and further increases the overall network lifespan. The zoning mechanism of the protocol, which spatially allocates regular, advanced, and super nodes according to their energy capacity, also contributes to the efficient allocation of roles and minimal overhead on communications.

Although the throughput performance (measured as the number of packets delivered to the BS) is similar to the current protocols, in the later rounds of the simulation, HDEZ-SEP performs better in the initial and central phases of the network provision. This means that HDEZ-SEP not only is energy-efficient but also can support reliable data flow over long distances, which makes it highly applicable to long-term, mission-critical applications of the WSN, such as environmental monitoring, smart agriculture, and disaster response systems, including the issue of the hot spot effect that is commonly experienced in the immediate vicinity of the BS in single-hop communication systems. This attribute enhances the network's resilience in a larger-scale deployment and supports the protocol's scalability potential. It also exhibits scalability across various network specifications, as illustrated by the findings from large-scale and small-scale implementation cases. Despite the spectacular gains, throughput results indicate that the primary benefit of HDEZ-SEP is energy optimization, rather than bandwidth maximization, which provides a promising future research direction. It should include security functionality such as lightweight encryption and trust models to manage problems related to data integrity and node authentication, particularly in hostile or sensitive environments. The protocol can also be scaled to suit mobile sensor nodes, or sink mobility can be enabled to support dynamic and real-time monitoring requirements. Another potential energy source that can be considered to extend network life and enable further green computing activities, as well as apply machine learning algorithms such as reinforcement learning or deep neural networks, is the capture of solar or ambient RF energy. With such an integration, sel, self-adaptive and intelligent routing could be utilized, particularly in large and volatile network environments. Physical implementation on hardware systems, such as MicaZ or TelosB motes, will also be essential for testing simulation performance and determining protocol feasibility in terms of latency, computational efficiency, and fault tolerance.

In summary, HDEZ-SEP represents a significant step towards creating energy-saving routing in the WSN setup. The inclusion of Quality of Service (quality of service) parameters, such as latency, jitter, and reliability, would assist in tailoring HDEZ-SEP to the needs of individual applications, particularly time-sensitive or multimedia WSN applications. Its capacity to balance power usage, settle network latency, and preserve operational effectiveness substantiates its great potential as a base protocol for next-generation Internet of Things (IoT)-based sensing environments.

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