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Enhancing the effectiveness of wireless sensor networks through consensus estimation and universal coverage

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Wireless sensor networks (WSNs) consist of numerous sensor nodes equipped with sensing, computing, and communication capabilities, where battery power is a critical limitation. Efficient energy management is vital to ensure sustained WSN performance. This study introduces a novel approach to enhance coverage and minimize energy consumption in WSNs. The method divides the network environment into distinct regions, activating only one node per region based on its residual energy and centrality, while other nodes enter a low-energy sleep mode to conserve power. Active nodes are periodically reselected through a duty cycle to distribute energy load and prevent premature node shutdowns. To address uncovered regions, a consensus estimation algorithm uses data from neighboring active nodes, weighted by their proximity, to estimate environmental data, ensuring continuous coverage. Additionally, multi-hop routing optimizes data transmission to the base station by reducing transmission distances, further enhancing energy efficiency. Simulation results across multiple scenarios demonstrate that this approach significantly reduces energy consumption and extends network lifetime compared to existing protocols, such as LEACH, LEACH-C, and ECRM, achieving approximately 60% and 20% improvements over LEACH and ECRM, respectively. This method effectively balances coverage and energy efficiency, making it a robust solution for WSN applications.

Keywords Coverage, Zoning, Duty cycle, Consensus Estimation, Wireless sensor networks

Numerous sensor nodes dispersed extensively around an environment that gather data from the surroundings make up a sensor network[1]. The sensor nodes' locations aren't always obvious and preset[2]. It is feasible to leave them in hazardous or unreachable locations thanks to this capability[3]. However, this also implies that sensor network protocols and algorithms need to be capable of self-organization[4,5]. The capacity for cooperation and coordination amongst sensor nodes is another distinctive characteristic of sensor networks[6]. Since each sensor node has a processor built into its circuit, it first runs a number of elementary operations on the data it has collected before sending the semi-processed data to the center or other nodes in charge of processing and analyzing the data While a single sensor may not be very powerful, the aggregation of hundreds of tiny sensors opens up new possibilities[7–9]. The true power of WSNs lies in their capacity to employ a large number of self-organizing small nodes for a variety of purposes[10], including simultaneous routing, environmental condition monitoring, Fuzzy weight-based coordination in multi-agent systems that supports consensus estimation method to maintain coverage of empty regions[11]., and Fault-tolerant control strategies that combine the consensus estimation method with robust data estimation guarantees in the presence of sensor errors that monitor the health of equipment or system structure. Each network node usually has one or more sensors[12], Event-driven consensus control that cycles tasks and estimates consensus for energy-efficient WSN performance[13], event-based control schemes under delay conditions in wireless sensor networks (WSNs)[14], and game theory-based fault tolerance methods help balance node energy consumption and resilience[15].

A radio transceiver (or any other wireless communication device), a tiny CPU, a power source (often a battery), and one or more sensors are usually present in every network node. In WSNs, energy consumption reduction and complete coverage are seen as important issues; if these are ignored, the network's efficiency will be severely compromised[16]. After a brief while, the sensor nodes will shut off if the network's energy usage is not controlled[17]. The node's power supply ran out, which is why it shut down[18,19]. Since a node's power source is

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limited, non-replaceable, and not rechargeable, it becomes practically useless when it runs out. e WSN's efficiency is directly impacted by node shutdowns[20]. As a result, it is crucial to take energy consumption into account while using WSN solutions. overage is a topic of discussion in WSNs Symbiotic blockchain consensus for improving the efficiency of wireless networks, which enhances the consensus estimation approach to maintain coverage of empty areas[21].

Nodes in a network are primarily responsible for reading environmental data, and they must communicate with one another in a way that allows them to feel the information in their surroundings as a whole. Coexistence communication is used for energy optimization in 6G networks, which is consistent with the current approach to reduce energy consumption in WSNs Deep reinforcement learning is used to optimize energy consumption in data collection, which enhances the active node selection approach to reduce energy consumption[21,22]. The effectiveness of the WSN will decline in an uncovered area. Deep learning-based intrusion detection system for WSNs that enhances network stability[23]. Opportunistic communication for data collection in wireless networks that enhances the research multi-stage routing approach to reduce energy consumption and uses data-driven optimization to reduce energy consumption in heterogeneous networks[24,25]. The amount in the area without coverage was only partially calculated thanks to the employment of the consensus estimation method, which is carried out by the nodes next to the area without coverage.

The framework of this study addresses the significant challenge of energy efficiency and effective coverage in WSNs (WSNs). The authors propose an innovative methodology that integrates environment zoning, duty cycles, and consensus estimation to enhance network performance. By dividing the network environment into distinct areas and designating a single active node in each region, the method minimizes energy consumption while maintaining global coverage. The active nodes are selected based on their energy and centrality to ensure longevity and balance in load distribution. The methodology also employs multi-hop routing and a consensus estimation technique to manage uncovered areas effectively, ensuring that the network remains functional even when some nodes are inactive or non-operational.

The motivation for this research stems from the inherent limitations of WSNs, particularly their reliance on finite energy sources and the critical need for uninterrupted coverage. Inefficient energy use can result in premature node shutdowns, leading to network inefficiencies and gaps in environmental monitoring. Existing solutions often fail to address the combined issues of energy optimization, load balancing, and global coverage comprehensively. This study aims to overcome these limitations by leveraging innovative techniques such as environment zoning and consensus estimation, ensuring a longer network lifespan and reliable performance under varying scenarios and conditions.

The main innovation of this research is in presenting a hybrid approach based on consensus estimation, task cycling, and environment partitioning in WSNs. This method optimizes energy consumption and increases network stability by dividing the network environment into separate regions and selecting active nodes based on criteria such as residual energy and centrality. Also, using the consensus estimation algorithm, data from uncovered regions are estimated using information from neighboring nodes, which prevents gaps in network coverage. This combination of innovative approaches, along with the use of multi-stage routing to optimize data transmission, has led the proposed method to significantly improve network efficiency compared to other methods and increase network lifetime. The main contributions of the research are as follows.

- The proposed method significantly reduces energy consumption through the implementation of a duty cycle and the strategic selection of active nodes based on energy and centrality.
- The study introduces a consensus estimation algorithm that uses data from neighboring nodes to estimate values for regions without active nodes. This innovation ensures continuous network coverage and maintains functionality even in areas where nodes are inactive or depleted.
- The proposed approach employs multi-hop routing to optimize data transmission to the base station. By balancing the load across various layers and minimizing transmission distances, the method reduces energy strain on specific nodes, enhancing overall network stability and efficiency.

The rest of the paper is organized as follows. Section 2 reports on related works. Section 3 discusses the proposed key management method. Evaluation and simulation of the proposed model are discussed in detail in Sect. 4, and finally, Sect. 5 reports on conclusions and future work.

Related work

WSNs (WSNs) are extensively employed for remote monitoring and tracking applications, including battlefield surveillance, target detection and tracking, traffic condition assessment, power system oversight, and health monitoring, owing to their notable advantages in flexibility, reliability, and cost-effectiveness[26,27]. Nevertheless, several pivotal WSN applications, including intelligent transportation and smart grid monitoring, impose stringent requirements regarding resource allocation and security. A summary of recent advancements in these two primary research topics concerning WSN-based monitoring systems is presented. In[28], a performance analysis of device-to-device communications in macro-micro wireless networks is presented. The primary findings in this area of research are classified as protocol-based scheduling, static event scheduling, dynamic event-driven scheduling, and event-triggered scheduling. The second section reviews the most recent findings on secure distributed state estimation, specifically addressing data integrity threats, available data assaults, and distributed attack detection. Ultimately, various complex challenges in the domain of distributed state estimation are examined for prospective future research.

In[29], a weight matrix is introduced that streamlines the average consensus method in mobile WSNs, thereby prolonging network longevity and ensuring optimal algorithm performance. The primary contribution arises from a theorem that delineates the alteration of the Laplacian spectrum of a simple undirected finite graph upon the addition of an arbitrary edge to the graph. The mixing parameter of the optimal fixed weights in a full finite graph of any order ensures convergence in time-varying topologies without necessitating reconfiguration of edge weights.

The research[30] focuses on fault detection via a completely distributed WSN. Initially, they introduced a convex hull approach to determine a collection of extreme points alongside adjacent nodes, ensuring that the message time remains constrained as the node count escalates. Secondly, they presented a Naive Bayes classifier and a convolutional neural network (CNN) to enhance convergence performance and detect node problems. Ultimately, they examined the convex hull, Naive Bayes, and CNN algorithms utilizing real-world datasets to detect and categorize defects.

In intelligent transportation and railway signalling systems, the utilization of WSNs for estimating train speed and location has garnered research interest due to measurement errors and inaccuracies, necessitating the development of an effective methodology. The primary aim of the work[31] is to present a sensor calibration technique for achieving precise speed and position measurements. A wireless automated system for a library using RFID devices is presented in[31]. In light of the goal position and speed requirements, WSNs with a redundancy of 2 * (2oo2) (utilizing 1 Hz and 7 Hz GPS speed sensors) and balises were evaluated.

[32] introduces an innovative Kalman filter technique for WSNs via a random consensus approach. In contrast to centralized algorithms, distributed filtering strategies necessitate reduced computational effort for each sensor and yield more resilient estimations, as they just utilize data from adjacent nodes inside the network. Nonetheless, inadequate local sensor estimation resulting from restricted observability and alterations in network architecture, which disrupt global agreement, presents significant challenges. Inspired by these discoveries, they propose a rumor-based stochastic distributed Kalman filter algorithm. The suggested algorithm facilitates information interchange and computation inside any connected sensor network[33]. Additionally, the computational burden can be allocated to a sensor that interacts with a randomly chosen neighbour at each time interval according to the gossip algorithm protocols.

[34] presents a new optimal clustering approach based on hybrid grey goose optimization (HGGOC). This algorithm combines the precision of the golden sine strategy with the efficiency of grey goose optimization. In 6G-enabled IoMT networks, the algorithm to optimize cluster head selection is guided by the Lévy flight mechanism. Data security and transparency are further improved by the incorporation of blockchain technology. An approach to data monitoring and control employing IoT-enabled WSNs with mobile sinks in IoT-enabled HWSNs (OptiGeA) based on evolutionary algorithms is presented in[35]. In order to choose cluster heads (CHs), the OptiGeA protocol incorporates energy, density, distance, and heterogeneous node capacity into its fitness function. To provide an objective comparative assessment, OptiGeA is examined using a single sink, several static sinks, and numerous mobile sinks.

As listed in Table 1, there are still a number of research gaps in the WSN literature despite these developments. These shortcomings support the necessity of our suggested approach, which combines environment zoning, duty cycling, consensus estimate, and multi-hop routing to fully solve load balancing, energy efficiency, and coverage continuity.

Proposed method

This section will analyze the suggested plan and provide a detailed explanation of it. As previously indicated, worldwide coverage is one of the fundamental difficulties in WSNs. Since the environment's data that the network controls needs to be accessible at all times. Put differently, it may be argued that a portion of the network without coverage poses a significant risk to the overall effectiveness.

Network model

There are numerous network model designs; two of the current versions will be looked at in the research that follows.

Arrangement of nodes

It is assumed in this design that n sensor nodes are dispersed randomly in an $X_m \times y_m$ two-dimensional environment. Because of the homogeneity of the network, sensor nodes share comparable hardware and are not

Ref.	Key Approach	Strengths	Research Gaps	How Proposed Method Addresses
29	Weight matrix for consensus	Enhances longevity, optimizes convergence	No coverage strategy for null regions	Uses consensus estimation to cover null regions (Sect."Unanimity estimation")
30	Convex hull, Naive Bayes, CNN	Effective fault detection	Lacks energy optimization, coverage restoration	Employs duty cycling and zoning for energy efficiency and coverage (Sect. 3.1.3–3.1.4)
31	Sensor calibration for transportation	High accuracy in specific applications	Limited to specific use cases, no general coverage solution	Provides scalable zoning for diverse environments (Sect. 3.1.3)
32	Rumor-based Kalman filter	Reduces computational load	Inaccurate in sparse regions, no global coverage	Ensures coverage via consensus estimation and active node selection (Sect. 3.1.4–3.1.6)
34	Hybrid grey goose clustering	Secure, efficient clustering	No coverage restoration, limited load balancing	Balances load via multi-hop routing and covers null areas (Sect. 3.1.5–3.1.6)
35	OptiGeA with evolutionary algorithms	Effective for heterogeneous networks	No mechanism for uncovered areas	Uses consensus estimation and zoning for comprehensive coverage (Sect. 3.1.3–3.1.6)

Table 1. Research gaps in existing WSN Studies.

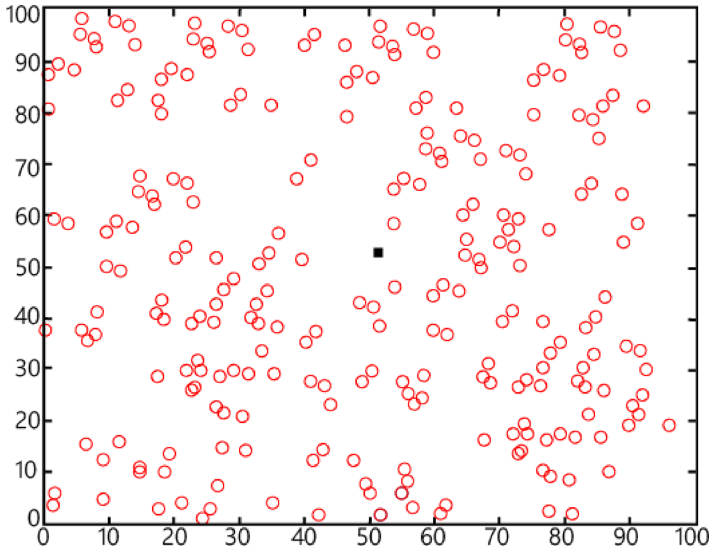

Fig. 1. Layout of a Wireless Sensor Network.

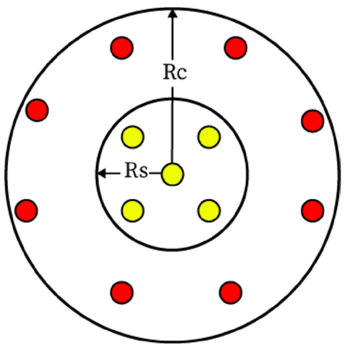

Fig. 2. Sensing range (RS) and communication range (RC) for representing a sensor node to support multi-hop routing and proposed coverage strategy to reduce energy consumption.

inherently superior to one another. Figure 1 illustrates this design in action. The base station (black dot) is at the middle of this picture, which shows the random placement of 200 sensor nodes (red hollow circles) throughout a 100 × 100 pixel area. It illustrates the network's spatial arrangement, which is essential for the suggested zoning and active node selection approach to maximize energy efficiency and coverage.

Sensation - communication model
It is assumed that the sensor nodes in the model shown in Fig. 2 have an Communication Range (RC) and an Sensing Range (RS) It should be mentioned that in order to connect with other nodes in the WSN, sensor nodes utilize telecommunication devices with a restricted range. These nodes' limited range is caused by a number of issues, one of which being their physical design, which prevents heavy equipment from being installed on small node kits due to their apparent volume limitations. The range of telecommunication equipment of nodes might also be limited by environmental conditions, however, as discussed above. If the range is unrestricted, interference, noise, and other problems will arise in the network due to the enormous number of sensor nodes up to thousands at times in the WSN. Reducing these interferences by coordinating and synchronizing such a large number of nodes is realistically very difficult, if not impossible[36]. The power supply issue is the main element limiting the communication equipment's range in sensor nodes since it requires more energy for the node to transmit data over longer distances.

Throughout this study, the symbol R_C stands for the RC that is, the region in which the node's communication apparatus can broadcast data. The boundaries of the node's ability to detect environmental elements are known as the RS. Adaptive backstepping control is used for nonlinear systems with output modeling error and external disturbances for management in wireless sensor networks[37,38]. The primary changes in the environmental factors falling under their domain are often picked up by the sensors in the sensor nodes. We can list the parameters of pressure, heat, vibration, light, humidity, and so on among them.

The nodes depicted in Fig. 2 as hollow circles are actually in the node's sense region, whereas the filled and hollow circles are in the node's communication zone. Another way to put it is that the circles that are displayed

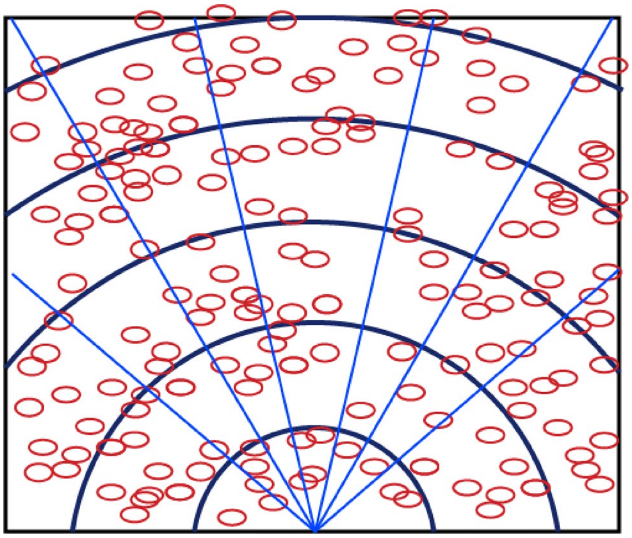

Fig. 3. The process of dividing the WSN environment into distinct areas using the guidance signal of the base station.

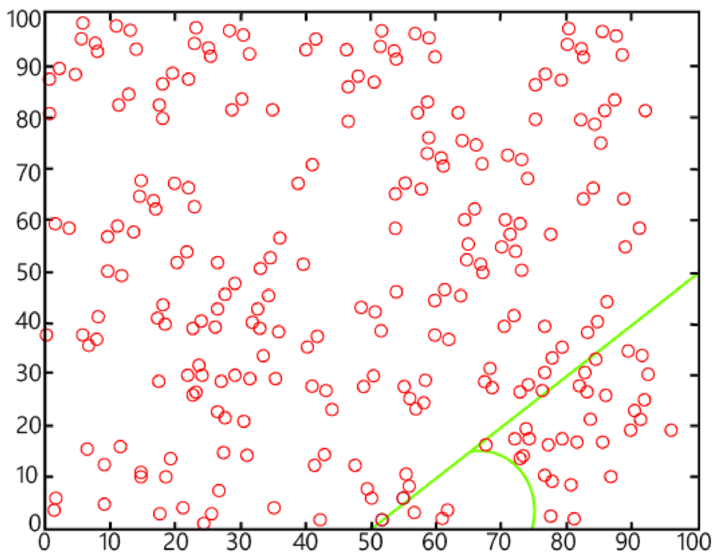

Fig. 4. Initial network segmentation stage for a base station broadcasting a pilot signal at an angle of 10 degrees.

as solids are in the central node's communication domain rather than its sensing area. Some existing solutions define the RC twice as the RS in order to ensure direct contact between neighboring nodes, owing in part to their ease of implementation. By combining reinforcement learning and hierarchical sliding mode control, an H∞ method for nonlinear systems with a dynamic event-driven mechanism improves the system's resilience to uncertainties[39]. A node's communication area is represented by a circle with its center and radius equal to R_C; in other words, the areas where the distance between the node and that location is R_C less than $(d < R_C($.The definition of the sensing region and the communication area $d < R_C$ are likewise comparable.

Network division

It's time to examine the network's coverage procedure now. As seen in Fig. 3, segmenting the network into distinct regions is the first strategy taken into consideration for establishing coverage in the WSN. Figures 4, 5 and 6 depict the region division procedures. In the initial phase, the base station broadcasts the guiding signal at an angle of α. It is positioned in the middle of the figure's bottom horizontal line. In order to calculate the relative distance to the base station, sensors that receive this guidance signal within the first *i* time interval measure the signal strength. In this case, *T* is a predetermined distance threshold of 35 m, proportional to the received signal's strength, as determined by the base station's guidance signal.

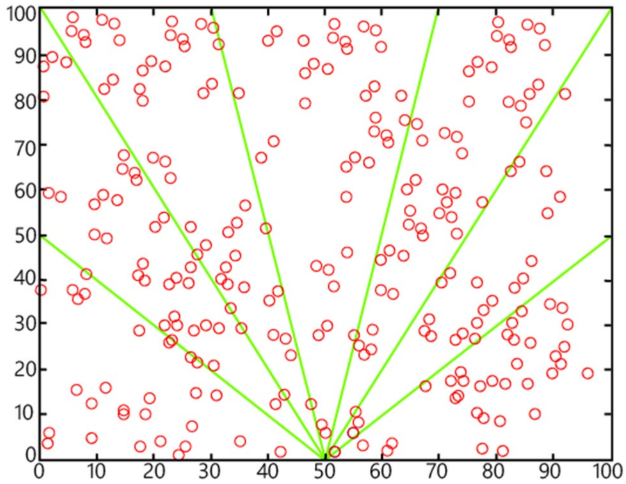

Fig. 5. Base station signal transmission at specific angles to divide the network into different areas.

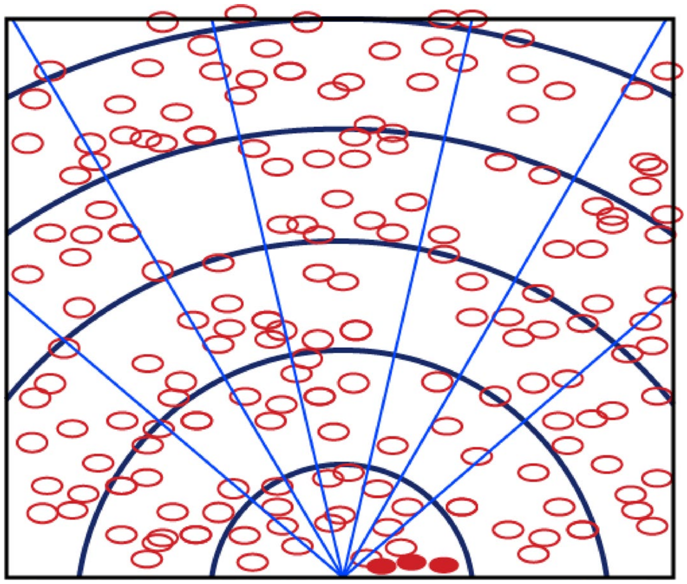

Fig. 6. Nodes in the first area (Nodes within the first area with a distance of < 35 m and an angle of 10 degrees, determined based on signal strength).

The article[14] states that T is 35 m and angle is 10 degrees. This leads to the placement of the nodes in the area (1 and 1) with an angle of 10 degrees and a distance from the base station of less than 35 m. The nodes in Area 1 are displayed in Fig. 6.

The first step of the network segmentation procedure in the suggested WSN technique is depicted in Fig. 4, where the base station broadcasts a guide signal at a 10-degree angle to separate the surroundings into discrete zones. Accurate zoning is made possible by the sensor nodes measuring the signal strength to ascertain their relative distance from the base station. In order to optimize energy usage and provide thorough coverage, this stage is essential for dividing the network into manageable zones, each of which has an active node.

The network segmentation process is continued in Fig. 5, which illustrates how the base station guiding signal, which is sent at particular angles, divides the WSN into layered zones. As stated in Sect. 3.1.3, a signal angle and a 35-meter distance threshold define each zone. In order to reduce energy consumption while preserving coverage, this zoning technique makes sure that nodes are arranged in a systematic manner, permitting only one active node per zone.

The nodes in the first zone, which is delineated by an angle of 10 degrees and is less than 35 m from the base station, are depicted in Fig. 6. The first layer of the zonal network is made up of these nodes, which are distinguished by the strength of their signals. This figure demonstrates how well the zonal process divides the zones for active node selection, guaranteeing that just one node is operational to provide coverage and conserve energy.

Division of duties
It is sufficient for one active node to provide coverage for every area of the WSN. Consequently, other nodes' activity will be ineffective and waste energy[36,40]. The suggested approach, like many others of a similar nature, is carried out in phases. During the setting phase, the active node in the region is chosen on the basis of its maximum energy remaining; during the stability phase, the active node detects its surroundings and relays this information to the base station. The reset phase is then carried out at a specific time, and the active node could shift[41]. The phases of stability and adjustment are referred to as one round and are repeated at predetermined intervals. Algorithm 1 displays the active node selection mechanism for each region in each round, whereas Fig. 7 depicts the network's rounds and phases. Nodes with low energy are typically put in sleep mode to preserve coverage in WSNs, whereas nodes with high energy are placed in active mode to sense and transmit environmental data to the base station.

A node in each part of the network environment is in charge of sensing and transmitting the data it detects to the base station, also referred to as the active node. Until the end of the current round, all other nodes in the vicinity are in sleep mode. The active node needs a lot of energy for its various functions, including detecting and transmitting information. In contrast, the sleep mode of the node uses the least amount of energy because just its activator circuit and timer are operational[42]. Therefore, nodes with greater energy should be chosen as active nodes in order to establish coverage and avoid nodes from shutting down quickly.

Otherwise, the low-energy active node that is chosen during the process of sensing and transmitting information may, under certain conditions, shut down and interfere with network functionality. The active node should ideally be positioned in the middle of the region, not only because it can cover the entire space but also because it has the shortest distance to other areas, in addition to taking into account the maximum energy when choosing the active node. Even if the residual energy is more significant than the centrality, the shortest path to other areas will be very helpful when discussing the estimation of the node's null regions. The node that has the highest value is thus chosen to be the active node[43,44] The following equation yields the value of each node:

$$Centrality_i = max\_distance - distance\_between\,(middle\ of\ area\ and\ node_i\,)\ Value_i = \left(4 * \left(\frac{node_i\_remainnig}{intial\_energy}\right)\right) + \left(\frac{centrality_i}{max\_centrality}\right) \quad (1)$$

.

Accordingly in this regard, $max\_centrality$ is the maximum distance between a node of the area and the center of the same area, $distance\_between$ shows the distance between node *i* and the center, initial_energy, *i*, the remaining energy of the node, node *i*_remainng, the area of initial energy, and the centrality of the node *i*. Since the unit of energy and centrality are different from each other, the unit of energy is Joule and the unit of centrality is meter, and to combine them, the units must be removed. For this purpose, we will divide the centrality by the maximum available centrality ($max\_centrality$) and the energy by the maximum energy of the node (*energy_initial*). In this case, energy and centrality will be converted into numbers between zero and one. Since the remaining energy of the node in being selected as a node Active has a greater effect, so we will increase its value by a factor of 4.

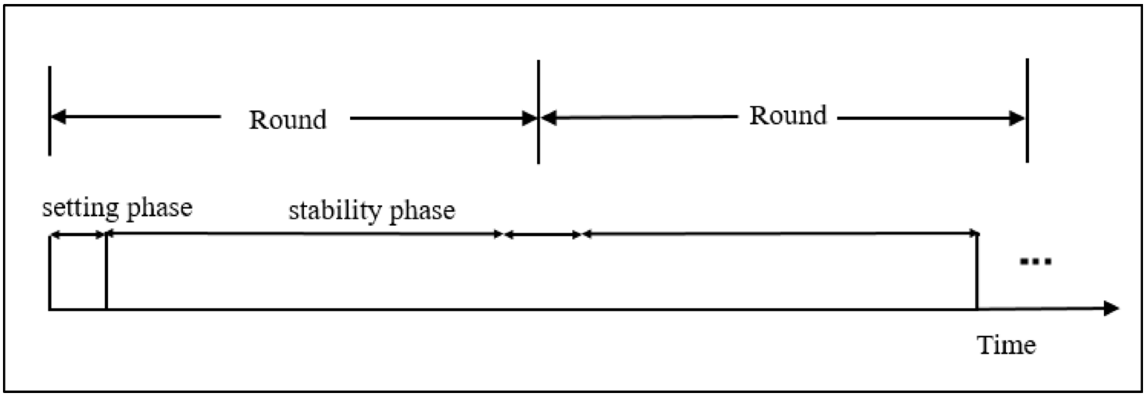

Fig. 7. Network cycles and phases for the adjustment steps including duty cycle stability and reset in the proposed method.

```
Select Active Node
Input: S (sensor nodes array), Area (region array)
Output: Updated S, Area with active node assignments
Global: SR(sensing range)
  for area = 1:1:length(Area)
      if Area (area).empty == −1 then     // Check if region is not marked as empty
        max_value = 0     //Initialize maximum value for node selection
        active node = −1     // Initialize active node index
 for i = 1:1:length(Area(area).member(I)).value  > do     // Iterate through nodes in region
      if S(Area(area).member(I)).value  >  max_value then     // Compare node value
        max_value = S(Area(area).member(i)).Value     // Update max value
        active_node = Area(area).member(i)      // Update active node
      end
  end
      if active_nod = −== −1 then // No active node found
        Area(area).empty = 1 // Mark region as empty
      else
        S(active_node).type =' active' // Set selected node as active
      end
    end
  end
```

Algorithm 1. Selecting the active node in each area

The active node selection procedure is provided in the method shown in algorithm 1. The node in each region that has the highest value that is, the most energy and centrality is identified by this technique. The nodes with the highest value among the members of each region are chosen as active nodes after each area is examined first. When all of the member nodes in the area have been checked, if the active node is not present, the region is considered to be empty of nodes.

Data transfer to the central station

The sensor nodes in each area are used to choose the active nodes. These nodes are in charge of gathering and transmitting environmental data to the base station. Nodes with the most energy are chosen as active nodes in each area since active nodes are expensive[45]. A WSN's primary function is to gather data about the surrounding environment and transmit it to a central location known as a base station or well. Because of the network's zoned architecture, sending data from active nodes at higher layers to the base station uses more energy.

The following is the use of multi-step routing to lessen these broadcasts. Load balancing is facilitated by multi-hop routing and is crucial for WSNs. Following the receipt of information, the local active node is prepared to transmit data to the base station[46]. Without doing anything extra, the information is delivered from the active node to the base station if it is close to the active node area. The first layer's nodes, indicated in Fig. 8 by their red tint, are found close to the base station. Other nodes must move them to the lower layers so that they can transmit their data to the base station.

Nodes in the lower layers that are in the same area as the present node, or one number less or greater, have precedence over other nodes. As a result, the packet needs to travel less to get to the base station. As with many other sensor network operations, routing involves energy expenditure. The primary function of routing is the sending and receiving of data. The quantity of bits communicated and their distance traveled are the factors

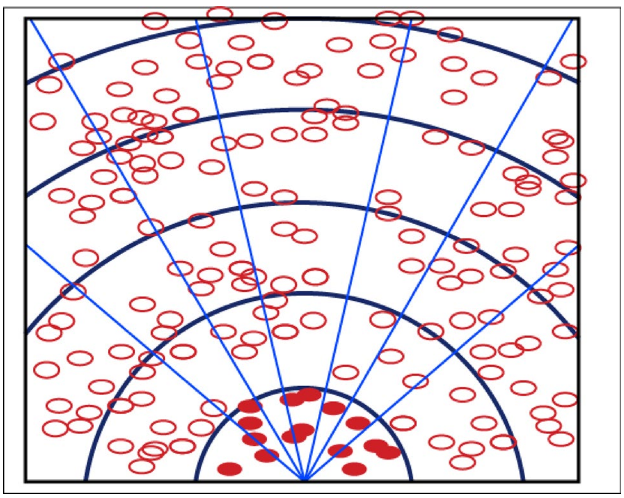

Fig. 8. Nodes of the first layer (Layer 1 nodes marked in red indicate those closest to the base station).

affecting whether data transmission energy usage rises or falls[47,48]. The data packet's journey length should be maintained constant to minimize the data packet's distance traveled. In this instance, sophisticated routing strategies are not necessary because of the various regions and layers present as well as the modest number of active nodes[49]. In order for a packet to be routed to the base station, higher layer nodes must choose a node in their lower layer. For instance, nodes in layer 5 must choose an active node in layer 4 to send the packet to that node. Layer 4 nodes that are in the vicinity of the present node, or one number greater or lower, have precedence over other nodes. Direct transmitting is used in these regions if there are no nodes[50]. The selection of different areas results in a longer packet transmission distance to the base station, which is the reason this issue is being considered.

An example of transmitting a packet is shown in Fig. 9, and algorithm 2 illustrates the algorithm used by the active nodes in the top layers to locate the next node in the lower layers. Figure 9 displays the connections between active nodes in each of the two sections on each line. In order to reach the base station, the active node in the higher area sends its sensed data to the active node in the lower area indicated by the black line.

```
Find next step for royting
Input: S (sensor nodes array), Area (region array)
 Output: Updated S with next step for routing
   Global: sink (base station coordinates)
     for i = 1 to length(S) − 1 do // Iterate through all nodes except sink
 if strcmp S(I).type,'active' then  // Check if node is active
     mindist = 1000 //Initialize minimum distance to sink
           next_step = length(S) // Default to sink if no closer node found
           for j = 1:1:length(S) − 1 do  // Iterate through potential next nodes
            if S(j).type == 'active' and S(i).layer == S(j).layer + 1 and abs(S(i).area -
               S(j).area) <= 1 then  // Check layer and area proximity
               dist = distance(S(j), sink)  // Calculate distance to sink
             if dist < mindist then // Update if closer node found
                next_step = j
        mindist = dist
             end
            end
          end
             S(I).next_step = next_step  // Assign next node for routing
          end
        end
```

Algorithm 2. Determining the next lower layer node

The procedure for locating the next node is depicted in algorithm 2. Every node that is active has this algorithm running on it. The base station package is first delivered directly to the next node in line if there isn't

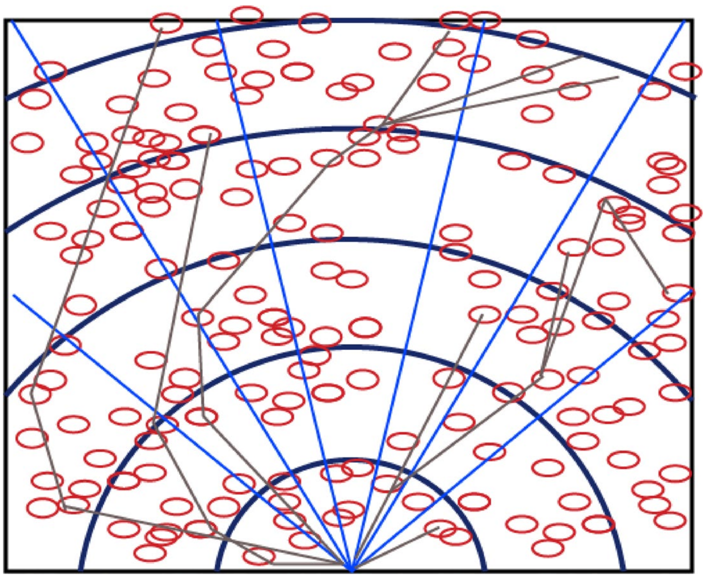

Fig. 9. Active nodes and base station communication for data transmission from active nodes in higher layers to the base station via lower layer nodes.

a node in the targeted locations. The condition that considers only active nodes in the layer below the present node and in areas with the same or different numbers is investigated in the following. The node in these regions that is closest to the base station is chosen to be the next node to receive packets. As per the statements made, the decision was made with the intention of shortening the data packet's network journey.

Unanimity Estimation
We will eventually arrive at a point in the network operation where one area's nodes are totally off and the other area is unreachable. In this case, a strategy to keep the coverage should be considered. We shall apply a method known as the polling approach, which has been proposed for this purpose, in this study. The foundation of this concept is the observation that the read data from the nodes in the surrounding areas is more akin to that of the covered area. Fault-tolerant control strategies that enhance the consensus estimation method by ensuring robust data estimation in the presence of sensor errors[12]. Therefore, by averaging the data from the nearby places, the value in the null area can be found. The distance is also taken into account in this assessment because the closer the sensors are to one another, the more similar the information they sensed will be[51]. Another parameter employed in the estimation is the separation between the center of the unoccupied space from each active node in the covered areas. The null area information of the node is estimated at the base station and is found in Eqs[52,53]..

$$Estimated - Data = \frac{\sum_{area=1}^{k} Sensed\_Data_{area} \times \ Dist_{\text{area\_node center o f empty area}}}{\sum_{area=1}^{k} Dist_{\text{area\_node center o f empty area}}} \tag{2}$$

.

1. Input: S (sensor nodes array), Area (region array), i (null region index)
2. Output: Updated S, Area with coverage status
3. Coverage=0 // Initialize count of neighboring regions with active nodes
4. for $k = 1:1: lengh\ Area(I).nab$ do// Iterate through neighboring regions
5. if $Area\ (Area(I).nab(k)).empty == 1$ then// Check if neighbor has active node
6. $Coverage = Coverage + 1$ // Increment coverage count
7. end
8. end
9. if $Coverage > 2$ then// Check if sufficient neighbors for estimation
10. $Area(I).empty = -1$ // Mark region as coverable via consensus estimation
11. else
12. $Area(I).empty = 1$ // Mark region as uncovered
13. end
14. end

Algorithm 3. Consensus Estimation algorithm

In this formula, the distance between the active node of the adjacent area to the center of the empty area node area with the symbol $Dist_{\text{area\_node center o f empty area}}$, the data sensed by the areas with the symbol $Sensed_Data_{area}$and the number of areas with The active node is indicated by the symbol k. algorithm 3 shows the consensus estimation algorithm. In this algorithm, the null region of node *i* is considered as input. Then all the neighboring areas of this area will be investigated. If there is a non-zero area in the neighborhood of the null area *i*, the number of areas that can cover the null area *i* is added.

1. ***Input:*** *Area (region array), S (sensor nodes array)*
2. ***Output:*** *Updated Area with neighbor assignments*
3. ***for*** $area = 1:1: lengh(Area)$ ***do*** *// Iterate through all regions*
4. *K=0 // Initialize neighbor count*
5. ***for*** $area\ 2:1:1: lengh(Area)$ ***do*** *// Compare with other regions*
6. ***if*** $Area.active_{node} >= 0$ *and* $Area2.active_{node} >= 0$ *and* $area\ != area2$ ***then*** *// Check for active nodes in both regions*
7. ***if*** $distance(S(Area(area).active_{node}), S(Area(area2).active_{node})) < Rc$ ***then*** *// Check if within communication range*
8. *k=k+1 // Increment neighbor count*
9. *Area(area).nab(k)=area2 // Add region2 to neighbors list*
10. ***end***
11. ***end***
12. ***end***
13. ***end***

Algorithm 4. Neighbor Detection Algorithm

After the completion of the loop, if the coverage areas are not more than two areas, the area *i* cannot be covered by its neighbors, otherwise it can be covered.

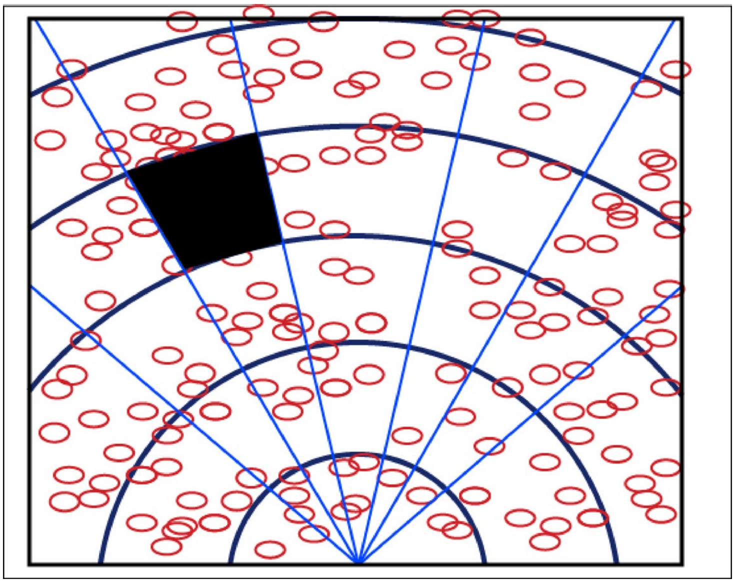

Fig. 10. Node empty area to indicate a void area without active nodes.

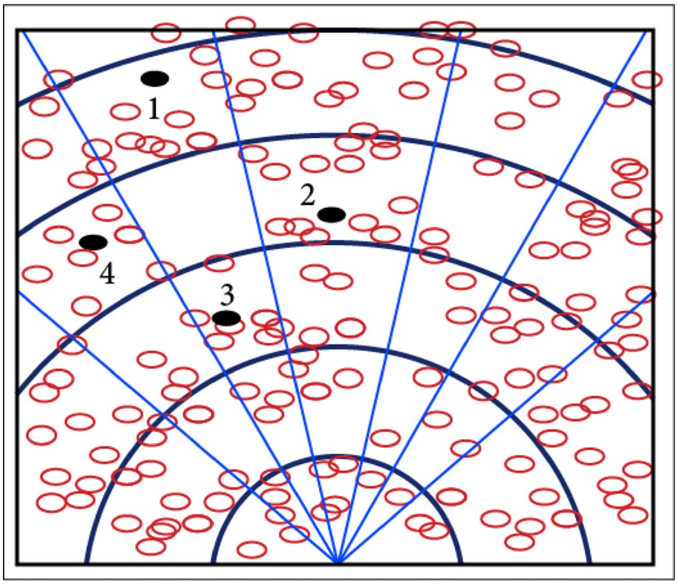

Fig. 11. Active Nodes and Neighboring Areas to indicate active nodes in neighboring areas around an empty area.

The goal of algorithm 4 pseudocode is to pinpoint nearby locations. In this way, all areas of area 2 are checked for each area. If the active node in area 2 is closer to the active node in area than the communication radius R_C, those two adjacent regions are also taken into account. In this instance, area 2 is stored in the area neighbors array, and one unit is added to the number of surrounding areas of area.

A major problem in sustaining network coverage is illustrated by Fig. 10, which depicts a dead zone in a WSN where no nodes are operational. When every node in a zone is unloaded or turned off, a dead zone is produced, as explained in Sect. 3.1.6. The suggested consensus estimation procedure, which fills this gap by predicting environmental data using inputs from nearby active nodes, is highlighted in this picture.

The active nodes in the nearby zones of a dead zone are depicted in Fig. 11, along with an explanation of their function in the consensus estimation procedure. The algorithm uses Eq. (2) to average the sensed data from these active nodes, which are shown by solid circles, and weights the data according to how close they are to the dead zone center.

Parameter	The value
Number of nodes (first scenario)	200
The perimeter length	100
The width of the perimeter	100
The coordinates of the well	(50, 50)
Initial energy (scenario 1)	0.01 joules
The length of the data packet	4000 bits
The length of the control packet	32 bits

Table 2. Basic simulation parameters.

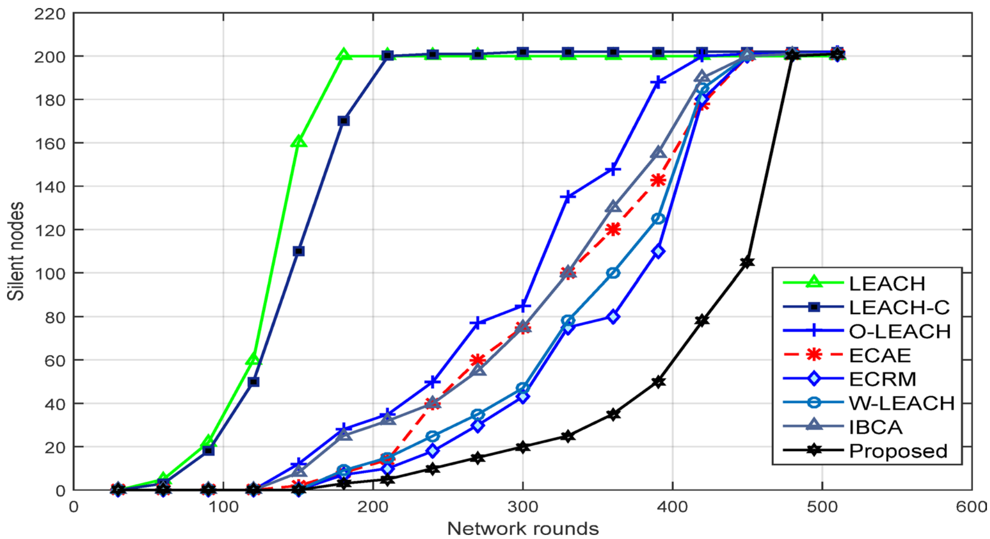

Fig. 12. Number of Dead Nodes in Scenario 1.

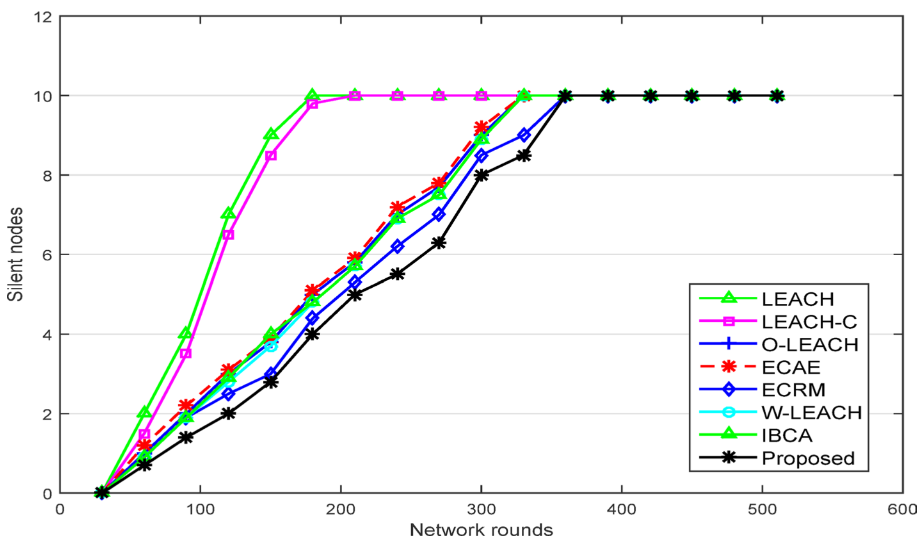

Fig. 13. Energy Consumption in Scenario 1.

Experimental results

This section will compare and assess the proposed plan using the following methods: Low-Energy Adaptive Clustering Hierarchy (LEACH)[54], LEACH-Centralized (LEACH-C)[55], Optimized LEACH (O-LEACH)[17], Energy-Conserving Adaptive Election (ECAE)[56], Weighted LEACH (W-LEACH)[19], Improved Biogeography-based Clustering Algorithm (IBCA)[20] and Energy-Efficient Clustering and Routing Mechanism (ECRM)[57].

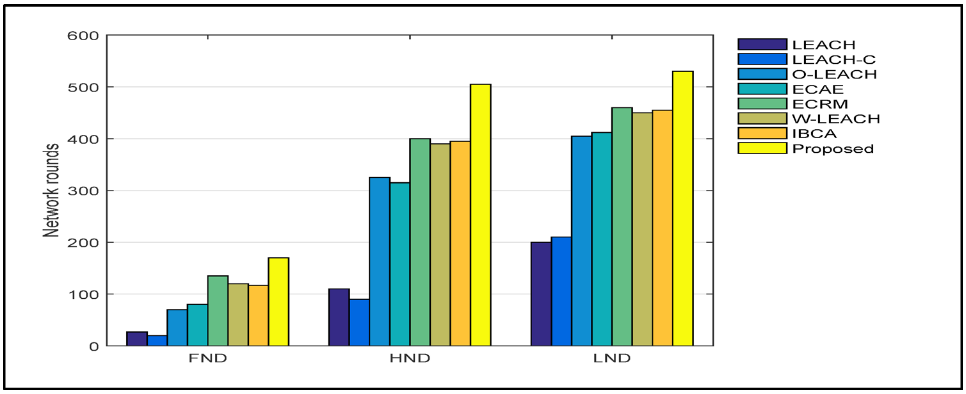

Fig. 14. FND, HND, and LND Metrics in Scenario 1.

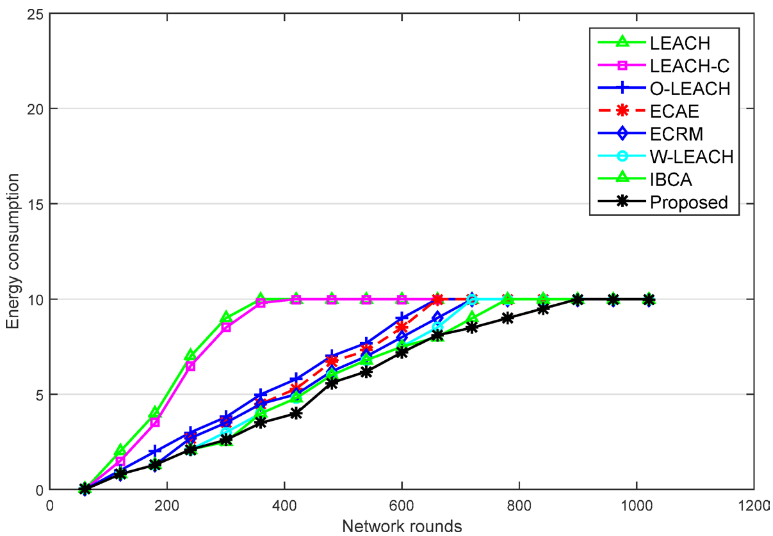

Fig. 15. Energy Consumption in Scenario 2.

Several scenarios will be looked at in order to assess the proposed plan. The network's initial parameters must be set before the simulation can begin. The number of nodes, the distribution of nodes, the node's initial energy, the size of the node distribution environment, the well's coordinates, etc. are among the main parameters. Table 2 displays the network's initial configuration parameters for the first scenario.

Simulation results

The first scenario

The results of the first scenario are displayed in Figs. 12, 13 and 14. In this scenario 20 sensor nodes with an initial energy of 0.05 J are dispersed throughout a square area that is [100 × 100] in size. According to the acquired results, the suggested algorithm performs better than other approaches in terms of energy consumption in all network rounds and has less dead nodes overall than other methods in different rounds.

The blackout times of the First Node Dead (FND), half of the Half Nodes Dead (HND), and the Last Node Dead (LND) are additional factors that are compared when comparing various techniques in the WSN. The FND, HND, and LND that arise from executing the first scenario are displayed in Fig. 14. The fact that the first node in the suggested way shuts down later than the others clearly demonstrates the suggested method's superior performance. The fact that HND and LND in the suggested method come much later than in the other ways further supports its superiority.

The second scenario

This scenario is created with some changes in the first scenario to observe the effect of the initial energy of the node on the network execution process and its results. The output from the execution of the second scenario is shown in three Figs. 15, 16 and 17. Similar to the first scenario, this one also has 200 sensor nodes overall, each having an initial energy of 0.1 J. The sensor nodes are dispersed around a square area that is 100 × 100 in size. The results indicate that the suggested approach performs better than the other approaches in terms of energy consumption throughout all network rounds. Additionally, the suggested algorithm has less dead nodes than the

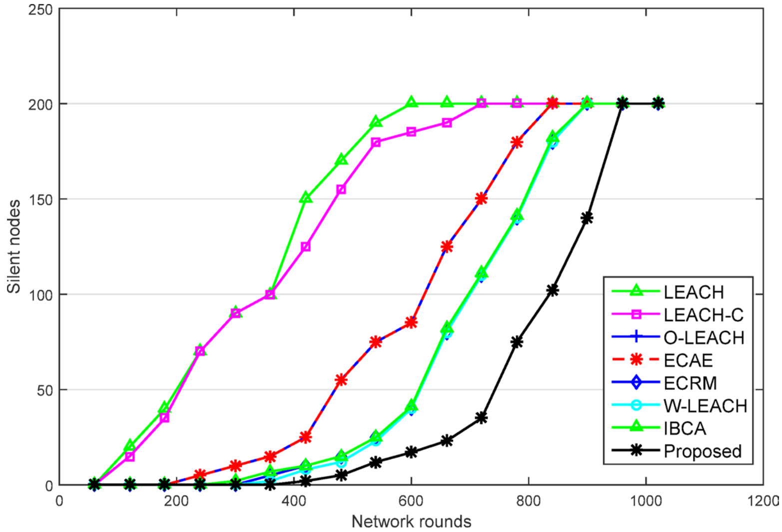

Fig. 16. Number of Dead Nodes in Scenario 2.

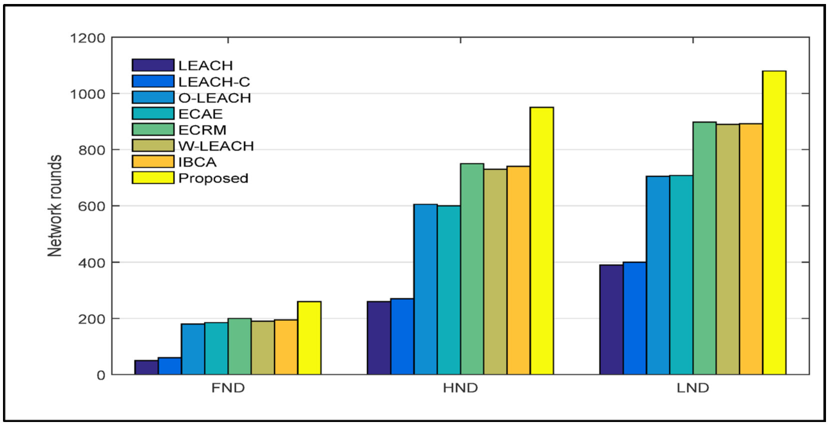

Fig. 17. FND, HND, and LND Metrics in Scenario 2.

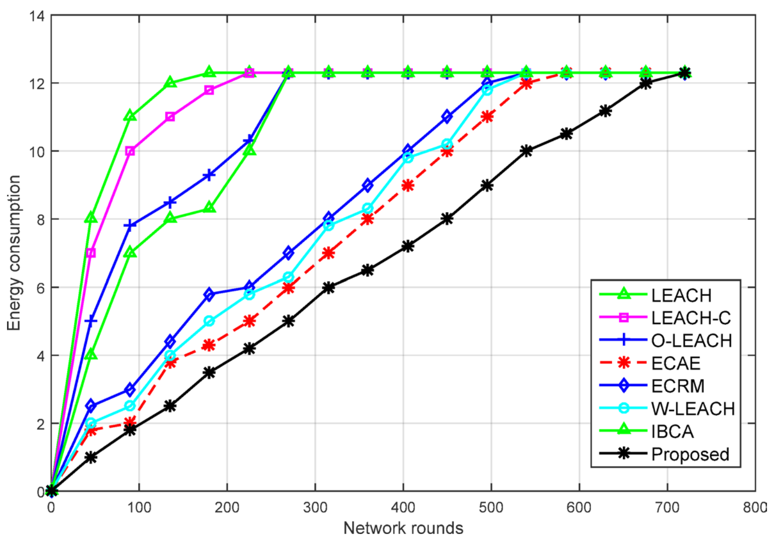

Fig. 18. Energy Consumption in Scenario 3.

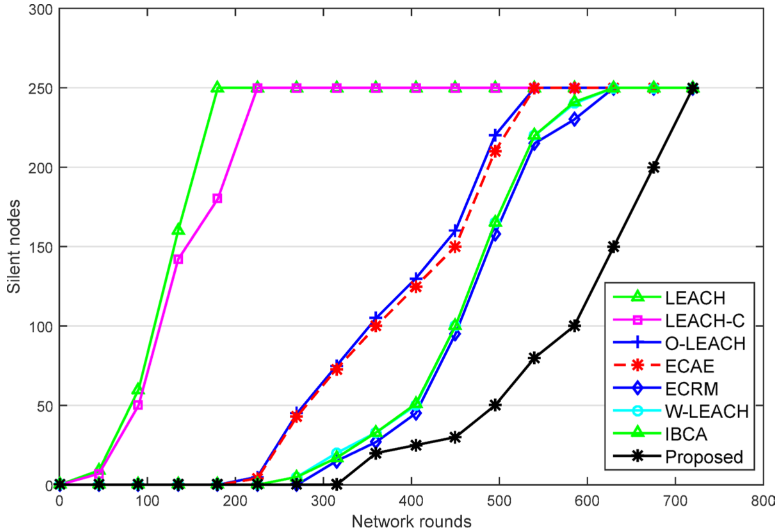

Fig. 19. Number of Dead Nodes in Scenario 3.

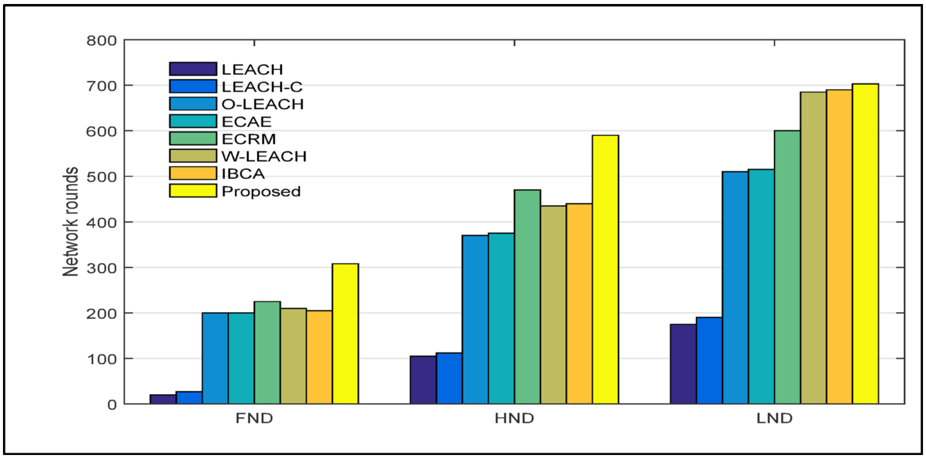

Fig. 20. FND, HND, and LND Metrics in Scenario 3.

other ways in various rounds. Figure 17 shows a comparison between the initial shutdown node and the three approaches discussed above for shutting down half of the nodes in this scenario.

The results show that the suggested method takes significantly longer to shut down than alternative methods for the first node, half nodes, and all nodes. Consequently, when compared to alternative approaches, the suggested solution in this circumstance likewise performs better.

The third scenario

The results of the third scenario are displayed in Figs. 18 and 19, and 20. Here, the number of sensor nodes is changed to 250, and their initial energy is 0.05 joules. The sensor nodes are dispersed over a square environment that has dimensions of [100 × 100]. Based on the collected data, the suggested algorithm performs better than other approaches in terms of energy consumption in all network rounds, and it has less dead nodes overall than other methods in different rounds. Figure 20 compares the three strategies stated above for the first off node, off half of the nodes, and off the last node in this case. The findings show that other approaches have substantially faster shutdown times for the initial node, all nodes, and half nodes than the suggested method. Consequently, when compared to alternative approaches, the suggested solution in this circumstance likewise performs better.

We will draw the conclusion that the suggested method always uses less energy than alternative methods and gives the network a longer lifespan based on the results of the simulation under various conditions and changing the fundamental network parameters, such as the initial energy and the number of nodes. The power of the proposed method is demonstrated by showing its superiority over the ECRM, ECAE, IBCA, and W-LEACH methods all of which are very effective in the field of WSN coverage. The utilization of work cycles, multi-step routing, normal uniform distribution in the environment, etc., is primarily responsible for the suggested method's efficacy.

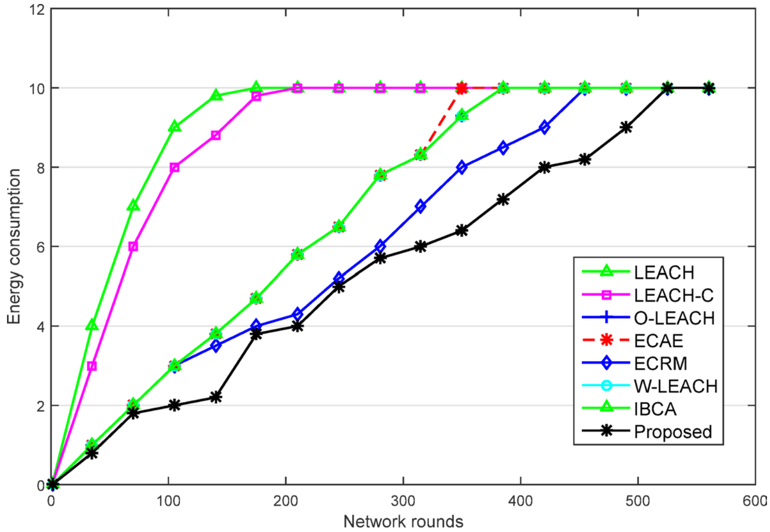

Fig. 21. Energy Consumption in Scenario 4.

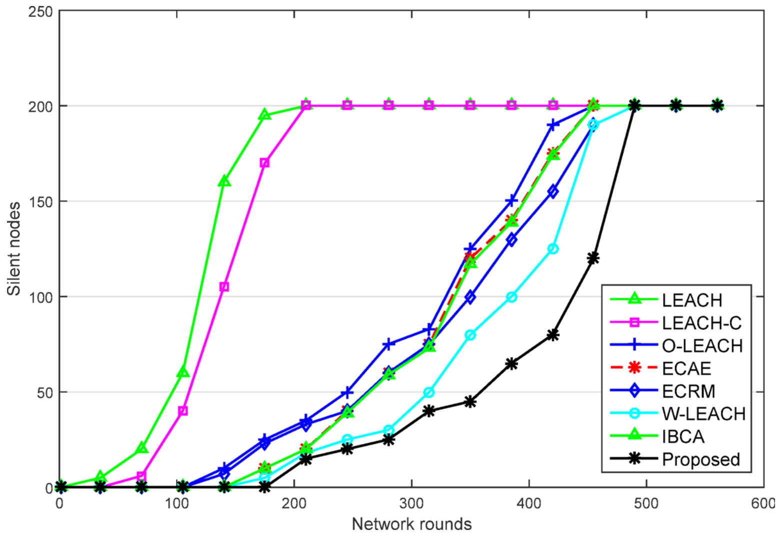

Fig. 22. Number of Dead Nodes in Scenario 4.

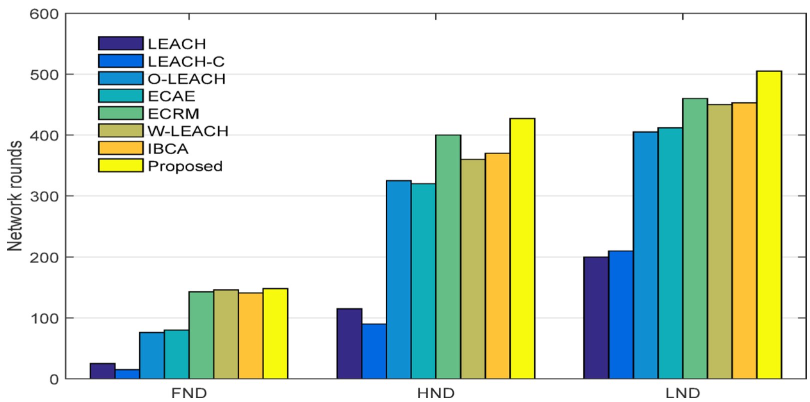

Fig. 23. FND, HND, and LND Metrics in Scenario 4.

Round	LEACH	LEACH-C	O-LEACH	ECAE	ECRM	W-LEACH	IBCA	Proposed
	The number of dead nodes							
1	0	0	0	0	0	0	0	0
69	5	3	0	0	0	0	0	0
137	25	18	3	2	0	0	0	0
205	32	26	7	5	0	0	0	0
273	75	68	16	7	2	3	6	0
341	167	121	19	13	4	6	10	2
409	200	175	29	19	7	11	19	5
477	200	200	55	35	14	19	25	7
545	200	200	78	59	25	29	31	10
613	200	200	89	77	31	39	41	16
681	200	200	124	115	70	79	86	21
749	200	200	149	138	100	109	110	35
817	200	200	189	175	136	142	145	50
885	200	200	200	200	175	178	179	76
953	200	200	200	200	200	200	200	100
1021	200	200	200	200	200	200	200	138
1089	200	200	200	200	200	200	200	200

Table 3. Numerical results of scenario 2 in the number of dead nodes section.

Proposed (1)	IBCA (2)	W-LEACH (3)	ECRM (4)	ECAE (5)	O-LEACH (6)	LEACH-C (7)	LEACH (8)

Table 4. Methods arranged according to average efficiency.

8	7	6	5	4	3	2	1	
0	−1	−1	−1	0	0	−1	0	1
−1	−1	−1	−1	−1	−1	0	1	2
0	−1	−1	−1	0	0	1	1	3
−1	−1	−1	−1	0	0	1	1	4
0	−1	−1	0	1	1	1	1	5
0	−1	0	0	1	0	1	1	6
−1	0	1	1	0	1	1	1	7
1	1	1	1	1	0	1	1	8

Table 5. Different approaches according to the importance of average efficiency.

The fourth scenario

In Figs. 21, 22 and 23 show the results of the implementation of the fourth scenario. In the proposed method, there is a solution that some nodes will go to shutdown mode in some rounds of the network in order to optimize energy consumption. One of the features of this solution is that it removes the gap that existed in the past routings, and avoids sending duplicate information in one round. Although most of the methods that have been used to compare the results (such as W-LEACH and IBCA) have also used this solution, but in order to make sure that the results do not depend too much on this solution, the present experiment in the first scenario was performed by removing the shutdown solution. We have done some nodes for all the methods and put them in the fourth scenario. This test is according to the first scenario with 200 nodes, 0.05 energy and dimensions (100×100).

Figure 21 illustrates how, when the node rest solution was eliminated from the suggested technique, the energy consumption graph once again outperformed the other ways under comparison for the proposed method. The graph of the number of dead nodes in this scenario also shows that, in comparison to other methods, the suggested method was still able to reduce the total number of dead nodes in the network's lifetime by eliminating some nodes' resting solutions, which is one of the innovations and benefits of the above method. Possess The numerical outcomes of scenario 2 for the number of dead nodes over the network's lifetime are shown in Table 3. The methods are summarized in Table 4 according to their average efficiency. The suggested approach has a rank of 1. The question now is whether this configuration is the best one. Table 5 is the result of applying the t-test to this data. Table 5 presents a comparison of all eight approaches throughout thirty executions.

Algorithm	Variance amount
Proposed	**783**
IBCA	**861**
W- LEACH	**884**
ECRM	**924**
ECAE	**929**
O-LEACH	**780**
LEACH-C	**868**
LEACH	**804**

Table 6. Variance analysis of several techniques.

Area	(1,1)	(1,2)	(1,3)	(1,4)	(1,5)	(1,6)
Variance	1/41	4/03	1/33	14/2	0	0
Area	(2,1)	(2,2)	(2,3)	(2,4)	(2,5)	(2,6)
Variance	6/01	1/65	1/55	4/79	1/09	0
Area	(3,1)	(3,2)	(3,3)	(3,4)	(3,5)	(3,6)
Variance	0	0	6/69	8/97	12/3	1/39
Area	(4,1)	(4,2)	(4,3)	(4,4)	(4,5)	(4,6)
Variance	18/7	3/92	5/89	5/80	5/61	0
Area	(5,1)	(5,2)	(5,3)	(5,4)	(5,5)	(5,6)
Variance	3/79	19/5	13/8	15/6	6/42	0
Area	(6,1)	(6,2)	(6,3)	(6,4)	(6,5)	(6,6)
Variance	0	17/1	11/2	4/13	2/07	0
Area	(7,1)	(7,2)	(7,3)	(7,4)	(7,5)	(7,6)
Variance	3/17	2/5	9/24	0	0	0

Table 7. Proposed method's area variance Analysis.

If the ratio of i to j in Table 5 is 1, then indicates that technique i is superior to method j in terms of the t test, which measures the difference in efficiency between the two approaches. If the ratio of i to j in the preceding table is −1, method j is superior to method i and there is a substantial difference in the effectiveness of these two techniques according to the t test. In terms of the t test, the efficiency of these two approaches does not differ significantly, and none of the methods i nor j is superior to the other, if the ratio of i to j in the preceding table is 0. Table 5's results show that the suggested strategy is better than the other approaches. The analysis of variance for the suggested approach and other methods is displayed in Table 6. The parameters specified in the first scenario are the same ones taken into consideration for this section.

Table 6 shows the degree of variation between various approaches for 200 nodes inside the [100 × 100] meter plot of land. These figures show the square of the total variation between the nodes' locations and the average of all the nodes spread across the earth's dimensions. The optimal energy usage is directly and significantly impacted by the nodes' reduced variance, and the lower this value is, the less energy will be utilized to transmit information between these nodes. We now split the land into areas that will have less variance by using the suggested strategy to divide it into separate areas. Table 7 provides each area's areas and variance.

The fifth scenario

These sensor nodes, which are dispersed around a square area with dimensions of [100 × 100], are assumed to number 150 in this scenario. Their initial energy is 0.05 J. We wish to demonstrate which of these 100 nodes will fail within the initial few rounds in this scenario. In reality, we would like to display the proximity of these dead nodes to the central station. The network's energy usage will decrease with the distance between the destroyed nodes and the central station. The 30 nodes that are destroyed in the first few rounds are seen in Fig. 24.

Figure 24 shows that the nodes near the central station in the suggested strategy are still active, while the first area only has one lost node.

The sixth scenario

One of the main objectives of clustering techniques is to lower the energy consumption of networks. The purpose of this test is to demonstrate how energy was saved by the clustering method when sending, receiving, and transferring network packets to the central station. The suggested network has an energy of more than 600 joules after 1000 simulation seconds, as shown in the graphic in Fig. 25.

This strategy is expected to work for another 2000 s if the trend continues. Comparable and concurrent approaches, however, have lost almost half of their network's original energy. Here, the suggested approach is

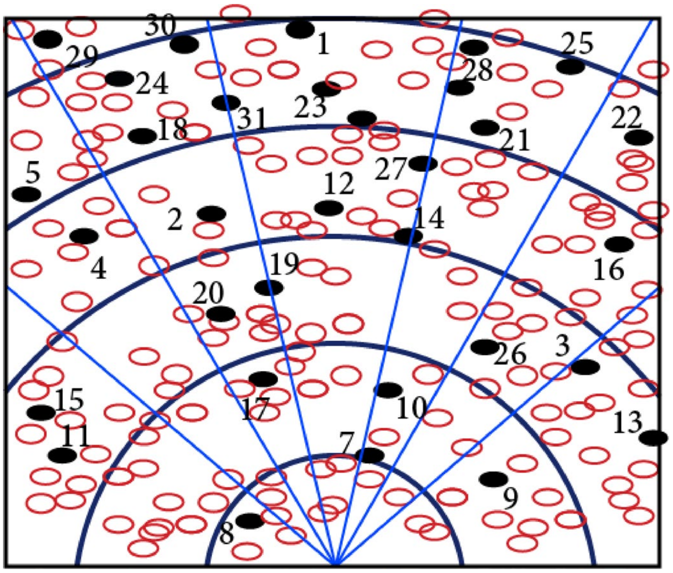

Fig. 24. Locations of First 30 Dead Nodes in Scenario 5.

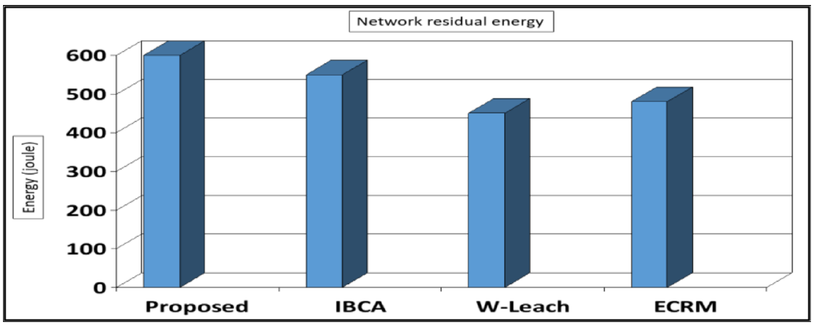

Fig. 25. Residual Network Energy After 1000 s in Scenario 6.

contrasted with the top three approaches from the past. The number of sensor nodes in this scenario is 200, and their initial energy is 0.05 J. They are dispersed throughout a square area that is [100 × 100] in size.

It is important to remember that the cluster size and cluster head selection procedure should be designed to balance the load on the clusters. Certain clusters will vanish sooner if the sizes of the clusters are out of proportion. The clusters in the suggested strategy are balanced. Thus, as Fig. 25 illustrates, the clustering balance has helped to increase the suggested method's efficiency. One may wonder if the suggested approach would lead to clusters that are too small, which would lead to an increase in the number of clusters and an increase in the network's energy usage. In answer to this query, it can be stated that extra-cluster communication overhead will result from having more clusters than the ideal number; on the other hand, early cluster head replacement and emptying will occur from having fewer clusters than the ideal number. As a result, the set in which the suggested strategy results in comparatively small cluster sizes but an optimal number of clusters is found there.

The parameter of normal routing load is another one that we looked at while evaluating the simulation results. The routing will load more quickly the smaller the value of this option. This parameter, which can be computed using Eq. (3), is another significant and influencing component in network routing.

$$NRL = \frac{sent\ Data + Forward\ Packet}{Recieved\ Data} * 100 \tag{3}$$

.

Stated differently, the normal routing load parameter is the percentage difference between the total amount of data that is transmitted and forwarded and the total amount of data that is received within the network. Undoubtedly, a smaller proportion indicates a higher level of network efficiency.

The usual routing load test for the suggested approach is displayed in Fig. 26 alongside other approaches. Comparing the suggested strategy to alternative approaches, the findings of this figure demonstrate its superior efficiency.

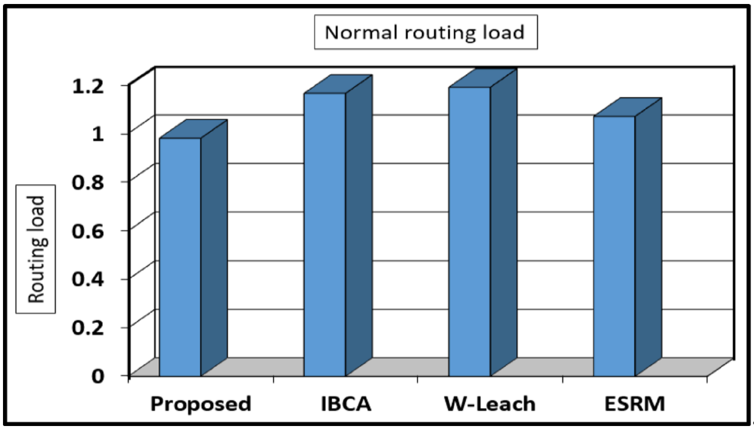

Fig. 26. Normal Routing Load Comparison in Scenario 6.

Conclusion

A WSN consists of hundreds or thousands of small devices called sensor nodes that interact with each other to perform certain tasks. A node reads environmental information by its sensors and sends it to a center called a base station for further processing and final decision through its telecommunication components (antenna). The limitation of the resources of a node, including the power supply, creates new challenges for the WSN. When the energy of a node runs out, that node will be removed from the network and will remain unused. In this situation, the information of a part of the environment may not be readable, so the so-called coverage in that area is lost. It can be said that the efficiency of the WSN is jeopardized by the shutdown of the sensor nodes. Therefore, a technique should be considered that, in addition to the global coverage in the WSN, the blackout of the nodes occurs later. Our goal was to improve the coverage in a WSN using the task cycle process in a way that increases the network efficiency. In the proposed plan, the network environment is divided into different areas and one node is selected as the active node in each area.

If there is no active node in an area, a node is sent to the desired area from the adjacent nodes. According to the simulation results, the proposed method has been able to increase the efficiency of the network to an acceptable level. In the evaluation section, the proposed plan has been compared with the basic LEACH protocol and 6 similar methods in different conditions and scenarios. These two designs have been selected due to their publication date, proximity to the proposed design, and their validity. Based on the obtained results, the proposed method using environment zoning has improved the consensus estimation and the cycle of national coverage tasks in the wireless network to an acceptable extent. This improvement, which was measured using MATLAB software, is about 60% compared to the LEACH method and 20% compared to ECRM, which has the best results among other methods. In the proposed scheme, multi-step routing causes the occurrence of a phenomenon called a hole or hot spot, so that the nodes of the first layer bear a lot of load. There are several solutions to solve this problem, one of which is to move the well in the environment. The possibility of moving the well in the environment, determining the direction of movement, etc. is one of the problems of this plan. You can use direct sending to avoid hot spots. So that each node sends its information directly to the well. In this case, the hot spot will not be created around the well, but the nodes of the last layer will turn off quickly due to consuming a lot of energy to send information to the well. Another solution is to move the nodes in the environment in order to balance the load. How the node moves in the environment, ability to move, energy consumption for movement, etc. are also challenges of such plans. In general, presenting a plan to deal with this issue needs more investigation and study, which is left to those interested for future work.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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