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RESEARCH ARTICLE

Energy Efficient Tree-Based Routing Algorithm for Wireless Sensor Networks

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ABSTRACT To address the issue of uneven sensor node distribution and unbalanced energy consumption leading to premature node death in wireless sensor networks, an energy efficient tree-based routing algorithm is proposed. The algorithm calculates the optimal number of branches that minimize network energy consumption by constructing a tree-based energy model. Based on the optimal number of branches, with the base station as the root node, a multi-layer tree routing is formed from near to far according to the distance between the node and the base station. During the formation of routing tree, the nodes whose residual energy of the nodes is less than the energy threshold can only become end nodes, thus avoiding premature death of the nodes due to excessive energy consumption of the nodes. Nodes transmit data to the base station along the routing tree. The routing tree is updated at dynamic intervals instead of every round to reduce energy consumption. Simulation results show that the algorithm has more balanced node energy consumption, lower network energy consumption, and longer network stability period and network lifespan than the other three protocols.

INDEX TERMS Energy efficient, optimal number of branches, routing tree, wireless sensor networks.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are self-organizing networks composed of numerous sensor nodes that can collaboratively monitor, collect, and transmit information from the real world. With the continuous advancement of information technology, the application fields of WSNs are expanding, providing more intelligent and automated solutions for various industries. However, WSNs face challenges such as limited node energy and uneven network coverage, which severely restrict their performance. Particularly in large-scale deployments, uneven energy consumption among nodes often leads to the depletion of energy in some nodes, resulting in network instability or even paralysis. To address these challenges and meet the growing demands, continuous research and improvement of routing algorithms are necessary to enhance the overall performance of the network.

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Currently, research on routing algorithms for WSNs has yielded significant results. Researchers are primarily focused on optimizing the low-energy adaptive clustering hierarchy (LEACH) [1] protocol to enhance network performance by improving cluster head election mechanisms and optimizing energy balancing strategies. In the review [2], the improved LEACH algorithm is categorized into five main classes: algorithms for optimizing cluster head (CH) selection, algorithms for optimizing data transmission, algorithms for optimizing both CH selection and data transmission, algorithms executed using the fuzzy logic approach, and algorithms that use external energy sources to maximize network energy efficiency [2].

In clustering protocols, selecting efficient nodes in the network as cluster heads is a key factor in conserving resources and extending network lifespan. The selection of cluster heads typically requires a comprehensive consideration of factors such as remaining energy, centralization, mobility, location, and energy consumption. When nodes are capable of mobility, the selection of cluster heads also needs to consider aspects such as node communication range, movement speed, and so on [3]. In heterogeneous wireless sensor networks, it is common practice to prioritize the selection of high-capability nodes as cluster heads [4].

In [5], a low-power and low-latency routing protocol based on LEACH is proposed. This protocol modifies the threshold for cluster head selection by incorporating energy, density, and distance factors. Only nodes with remaining energy above the average are eligible to become cluster heads.

In recent years, machine learning algorithms have been increasingly applied in routing design. Clustering and swarm intelligence algorithms are employed to form and optimize clusters. Swarm intelligence is also utilized for path selection to minimize energy consumption and prolong network lifespan.

In [6], the K-means algorithm and the ant colony algorithm (ACO) are applied for routing. By improving the clustering method between sensor nodes, the optimal path for data transmission is determined, and the energy consumption of nodes is reduced.

In [7], an optimal combination of weighted optimization (OCW) and improved ant colony optimization (IACO) algorithms is utilized to enhance the LEACH protocol. This includes the implementation of a dynamic replacement mechanism to update cluster head nodes and reduce energy consumption. To improve the quality of selected cluster head nodes, the OCW method dynamically adjusts weights by considering three influencing factors: remaining energy of nodes, node density, and distance between nodes and the sink node in different regions. Additionally, the IACO is employed to optimize inter-cluster transmission paths.

Researchers are continually attempting to introduce various algorithms into protocols to enhance network performance. In [8] a fuzzy algorithm is used for clustering to form inhomogeneous static clusters, effectively avoiding the energy hole problem and thus prolonging the network life cycle. An optimized fuzzy clustering algorithm for cluster head selection is proposed in [9], which is combined with particle swarm optimization to form energy efficient inter-cluster paths, thus optimizing energy consumption. In [10] an improved firefly algorithm is used for clustering to make more reasonable divisions. Inter-cluster routing is established using an improved ant colony algorithm for routing between cluster heads to reduce energy consumption for data transmission. In [11], a game algorithm controls the state switching of nodes between sleep and activity, while the ant colony optimization algorithm forms node routes to reduce the energy consumption and prolonging network lifetime. In [12], the butterfly optimization algorithm is used for optimal cluster head election, and ant colony optimization algorithm establishes energy efficient inter-cluster routing which reduces energy consumption and maximizes network lifetime. In [13],a genetic algorithm is used to form clusters and elect cluster heads by combining energy, density, and distance of nodes. In [14] dragonfly algorithm is used to select the best cluster heads and optimal routes to enhance the energy efficiency of the network. In [15], clustering is performed using the K-means method based on the optimal number of clusters, and Dijkstra's algorithm is used to form intra-cluster and inter-cluster routes. In [16], Dijkstra's algorithm is applied in path planning to collect cluster head data from mobile sink node, effectively reducing the energy consumption of cluster head nodes. In [17], the minimum spanning tree (MST) and Dijkstra's algorithm are used, the former for constructing intra-cluster routing tree and the latter for determining the most efficient path for inter-cluster data transfer. In [18], tuna swarm optimization (TSO) is used to optimize cluster formation, making clusters more compact and reducing intra-cluster communication distance and energy consumption. In [19] MST is used to form routes within and between clusters, and data is sent to the rendezvous point via cluster header, which then transmits it to the mobile sink node. This approach reduces energy consumption and balances network load.

In terms of network topology, there has been a transition from single-hop clustered routing,such as LEACH, to multi-hop clustered routing and multi-tier clustered routing. Further modifications to clustered routing protocols have led to the formation of chain-type networks, such as the PEGASIS [20] protocol network, or tree-type networks that combine clusters and chains.

The energy efficient scalable routing algorithm (EESRA) [21] adopts a three-layer hierarchical structure to reduce the load on cluster heads and uses multi-hop transmission for intra-cluster communication while randomizing the cluster head selection.

In [22], the author proposed a hybrid and efficient routing algorithm. The algorithm divides the network into four regions and selects a CH from each region. The node closest to the base station is chosen as the cluster head for each region. Within the cluster, according to the distance threshold, nodes can only communicate with nodes whose distance is below the threshold, and cannot communicate beyond the threshold distance. At the same time, the energy of the node also needs to be greater than the energy threshold to communicate with other nodes. Dijkstra algorithm is used to form the shortest path among communicable nodes. Nodes transmit data to the CH through the shortest path, and the CH passes the collected data to the base station.

An enhance PEGASIS algorithm is proposed in [23]. Nodes are divided into clusters, and chains are formed within each clusters. Select the starting node and destination node within each cluster, with the destination node typically being the node closest to the base station within the cluster. Due to the random allocation of nodes, when the base station is far away from the distribution area, the energy consumption of the destination node is relatively high and it is easy to die prematurely. Another Enhanced Energy Efficient Routing protocol [24] modifies the selection of leader nodes for forwarding data to the base station by considering the remaining energy of nodes and their distance from the base station. In [25], a method is proposed for dividing the network into regions and forming chains within each region. Within each chain, a chain leader and a secondary leader node are identified. These two nodes send data to the base station separately, aiming to balance the energy consumption of the leader nodes.

The authors in [26] proposed an energy-efficient routing protocol using two-level tree-based clustering (EE-TLT). The network is divided into different sectors, each containing a balanced number of nodes, and each sector is a cluster. Additionally, based on the sensing range of the base station, the network is divided into different levels. Therefore, multiple polygonal regions are formed within each cluster, and CHs are selected within each cluster based on a cost function that is related to the remaining energy of the nodes and the distance to the base station. Select appropriate relay-CHs in the CHs. Sub-CHs are chosen within each polygonal region based on a cost function that is related to the remaining energy of the nodes, the distance to the base station, and the number of neighboring nodes. Within each polygonal region, a minimum spanning tree is formed with the sub-cluster head as the root. Between CHs, sub-CHs, relay-CHs, and base stations (BS), the minimum spanning tree is formed with the base station as the root. Thus, a two-level tree is constructed to establish data transmission paths from nodes to the BS.

In [27], the authors proposed a method for combining election and routing amongst cluster heads in heterogeneous WSNs (CER-CH). It introduces a top-down CH routing tree, which is a tree-based network that combines clusters and chains. The approach balances node energy consumption by updating cluster heads.

Researchers are committed to balancing and optimizing energy consumption to extend the network's lifespan, but it is still difficult to avoid premature death of some nodes especially cluster head nodes or leader nodes.

In this paper, we propose an energy efficient tree-based routing algorithm. The algorithm establishes an energy consumption model based on the characteristics of the network and analyzes the optimal number of branches for tree-based routing. Based on this optimal number of branches, a routing tree is formed by arranging nodes from the closest to the BS to the farthest. The routing tree is not updated in every round, instead, it is refreshed at dynamic intervals to reduce energy consumption during the routing formation process. During the updating process, an energy threshold is designed based on the remaining energy of the nodes to facilitate balanced energy consumption. This algorithm delays the emergence of dead nodes and extends the network lifespan by balancing the energy consumption across nodes. Its main contributions are as follows:

1. Based on the tree-based network characteristics, network energy modeling is carried out to calculate the optimal number of branches of the routing tree. According to the optimal number of branches, the routing tree is formed by combining the distance between nodes and base stations and the distance between nodes.

2. The routing tree update rule. According to the remaining energy of the network, the energy threshold is designed. In the process of updating route, the residual energy of relay nodes must be greater than or equal to this threshold. This threshold also works in conjunction with a dynamic interval to indicate whether the network routes are updated or not. The dynamic interval is determined by the network topology and node energy consumption.

3. The routing tree formed avoids low energy nodes from becoming relay nodes, avoids long distance data transmission, effectively balances the energy consumption of the nodes, delays the emergence of dead nodes, and prolongs the life cycle of the network.

The paper is organized as follows: Section II describes the network and energy models; Section III presents our innovative approach; Section IV outlines the simulation settings and results, analyzes the results; Section V presents the conclusion.

II. THE SYSTEM MODELS

This section primarily describes the network and energy models.

A. NETWORK MODEL

Wireless sensor networks consist of sensor nodes and a base station, as shown in Figure 1. The nodes are randomly deployed within a two-dimensional monitoring area. A tree-based routing transmission strategy is proposed to collect data from the sensors. Figure 1 illustrates a non-clustered network where the nodes form a routing tree.

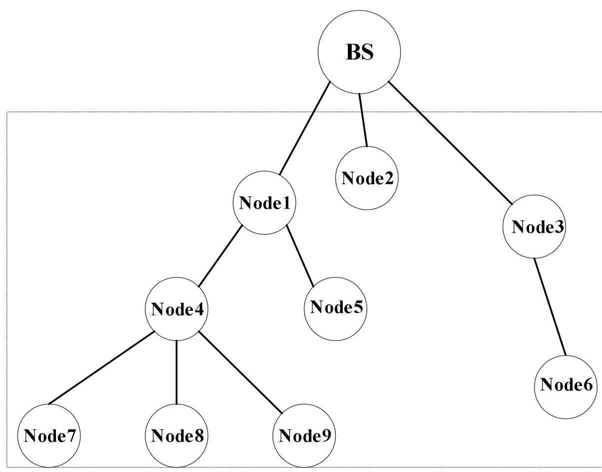

FIGURE 1. Network model.

The network model is based on the following assumptions: each node has the same initial energy, their positions are fixed and unique after deployment, and each node can sense its location and remaining energy, allowing for transmission power adjustment. Each node has a unique identifier and can communicate with one another. The base station is located outside the monitoring area. It can directly communicate with the nodes within the monitoring area. Additionally, we assume that the base station has unlimited energy and computational capabilities. Nodes transmit data to the base station via a routing tree, progressing from distant to nearby nodes.

In Figure 1, Node 4, Node 1, and Node 3 are referred to as relay nodes, which collect data from other nodes. Nodes 2, 5, 6, 7, 8, and 9 are termed endpoint nodes, which do not receive data from other nodes. Additionally, Nodes 2, 1, and 3 are classified as branch nodes, which are the nearest nodes to the base station in their respective branches. The number of branches in the routing tree corresponds to the number of branch nodes.

Nodes periodically collect information from their respective areas and transmit it along the routing tree path. End nodes in the routing tree send the collected data to their parent nodes. After aggregating data from all child nodes, the parent node transmits the fused data to its parent, continuing this process until the data reaches the BS. The completion of data transmission by all nodes constitutes one round.

B. ENERGY CONSUMPTION MODEL

This study employs a first-order wireless communication energy consumption model consistent with the LEACH protocol. The energy consumed by a node to transmit m bits of data is calculated as follows:

$$E_{TX}(m,d) = \begin{cases} mE_{elec} + m\varepsilon_{fs}d^2, & d < d_c \\ mE_{elec} + m\varepsilon_{mp}d^4, & d \geq d_c \end{cases} \tag{1}$$

Here, d presents the transmission distance, E_{elec} denotes the energy consumed per bit for transmission or reception, ε_{fs} is the circuit amplification coefficient for the free space model, and ε_{mp} is the circuit amplification coefficient for the multipath fading model. The parameter d_c is a distance constant, calculated as follows:

$$d_c = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \tag{2}$$

Thus, the energy consumed by a node to transmit data increases with distance. When the transmission distance exceeds the distance constant, the energy consumption rises significantly.

The energy consumed by a node to receive m bits of data is calculated as follows:

$$E_{RX}(m) = m \times E_{elec} \tag{3}$$

In addition to transmitting and receiving data, relay nodes in the network are also required to perform data fusion, which consumes a significant amount of energy. Assuming that the energy consumed for fusing 1 bit of data is E_{DA}, the energy consumed by a node for fusing m bits of data can be calculated as follows:

$$E_{DA}(m) = m \times E_{DA} \tag{4}$$

III. THE PROPOSED ALGORITHM

This paper presents an energy efficient routing algorithm that forms a routing tree with the base station as the root node. The algorithm consists of two main steps: calculating the optimal number of branches and constructing the routing tree. During the optimal branch calculation phase, we model the entire energy dynamics based on the tree network architecture and derive the expression for the optimal number of branches. The routing tree formation phase is divided into two aspects: initial tree routing formation and routing tree updates.

A. OPTIMAL NUMBER OF BRANCHES

Based on the routing tree and energy model, the energy consumption of nodes within the network is analyzed.

As shown in Figure 1, there are three branches in the figure. Node2 is one branch, Node1, Node4, Node5, Node7, Node8 and Node9 form another branch, and Node3 and Node6 are the third branch.

Assuming a network with N nodes distributed in an $L \times L$ area, the routing tree consists of h branches and k endpoint nodes. Clearly, k is greater than or equal to h, and the number of relay nodes is $N - k$.

According to the network energy consumption model, energy is consumed for sending, receiving, and fusing data, all of which are proportional to the data size. Assuming that each transmission involves m bits, the energy consumption for endpoint nodes is solely due to transmission.

The energy consumption of each endpoint node i (E_{endi}) can be expressed as:

$$E_{endi} = E_{TX}\left(m, d_{ij}\right) \tag{5}$$

Here, d_{ij} represents the distance between node i and node j, where node i is an endpoint node transmitting data to relay node j.

For relay nodes that receive data from other nodes, their energy consumption includes the energy for receiving data, the energy for fusing their own data with the received data, and the energy for sending data. Assume that relay node i receives data from a_i nodes. The energy consumption of relay node $i(E_{midi})$ can be expressed as:

$$E_{midi} = E_{TX}\left(m, d_{ij}\right) + \sum_{a_i} E_{RX}(m) + (a_i + 1)E_{DA}(m) \tag{6}$$

The total energy of the network (E_{net}) can be expressed as:

$$E_{net} = \sum_{k} E_{endi} + \sum_{N-k} E_{midi} \tag{7}$$

According to the network model, endpoint nodes can be categorized into two scenarios: one is to send data to relay nodes and the other is to send data directly to the BS. Similarly, relay nodes can also be classified into two cases: one is to transmit data to other relay nodes and the other is to send data to the BS. Clearly, the total number of endpoint nodes and relay nodes transmitting data to the BS is h. All nodes in the network must send data, Only the data from ordinary nodes that communicate directly with the BS are not received by other nodes. Therefore, the number of data received by ordinary nodes is $N-h$. Likewise, the number of data to be fused is $2N-h-k$. Equation (7) can be rewritten as:

$$E_{net} = \sum_{N-h} E_{TX}\left(m, d_{ij}\right) + \sum_{h} E_{TX}\left(m, d_{iBS}\right) + (N-h) \times E_{RX}(m) + (2N-h-k) \times E_{DA}(m) \tag{8}$$

If the nodes are uniformly distributed, then for a monitoring area divided into h branches, the mean square of the distance between any two ordinary nodes with coordinates (x, y) and (u, v) is:

$$E(d_{inB}^2) = E((x-u)^2 + (y-v)^2) \tag{9}$$

where d_{inB} represents the distance between the nodes within a branch.

Assume that N nodes are uniformly distributed over the $L \times L$ range. When the BS is outside the monitoring area and there are h branches. By this assumption, the range of values of h is $[1, \sqrt{N}]$. Since the nodes are uniformly distributed, it is equivalent to dividing the $L \times L$ square into h equal rectangles, and the branching structure formed within the h rectangles is the same. For computational convenience, one of the sides is chosen to have a range of $[0, L]$ and the other side is a $[0, L/h]$ rectangle for the calculation. If the value range of x in the integration is $[0, L]$ and the value range of y is $[0, L/h]$, or if the value range of y in the integration is $[0, L]$ and the value range of x is $[0, L/h]$. Therefore, taking the former as an example, the following results can be calculated:

$$E(x^2) = \iint x^2 \frac{h}{L^2} dxdy = L^2/3 \tag{10}$$

$$E(xu) = E(x)E(u) = L^2/4 \tag{11}$$

$$E(u^2) = E(x^2) \tag{12}$$

$$E((x-u)^2 = L^2/6 \tag{13}$$

Similarly, it can be concluded that:

$$E((y-v)^2 = L^2/6h^2 \tag{14}$$

$$E(d_{inB}^2) = E((x-u)^2 + (y-v)^2) = \frac{R^2}{6}(1+\frac{1}{h^2}) \tag{15}$$

Let the average distance from the nodes in the area to the base station be d_{toBS}. Then, the overall energy of the network can be expressed as:

$$E_{net} = (N-h) \times E_{TX}\left(m, d_{inB}\right) + h \times E_{TX}\left(m, d_{toBS}\right) + (N-h) \times E_{RX}(m) + (2N-h-k) \times E_{DA}(m) \tag{16}$$

d_{inB} is substituted into (16) and let $\varepsilon_a d^b = \begin{cases} \varepsilon_{fs} d^2 & d < d_c \\ \varepsilon_{mp} d^4 & d \ge d_c \end{cases}$, then E_{net} is given by the following equation:

$$E_{net} = (N-h) \times (mE_{elec} + m\varepsilon_{fs} d_{inB}^2) + h \times (mE_{elec} + m\varepsilon_a d_{toBS}^b) + (N-h) \times mE_{elec} + (2N-h-k) \times mE_{DA} \tag{17}$$

Take the derivative of h on the above equation, and when the first derivative is 0, the above equation has a minimum value.

$$\frac{\partial E_{net}}{\partial h} = 0 \tag{18}$$

Obtain the optimal number of branches (h_{opt}) by solving according to the above equation:

$$h_{opt} = \left(N\varepsilon_{fs}L^2 \Big/ 3(\varepsilon_a d_{toBS}^b - E_{elec} - E_{DA} - \frac{\varepsilon_{fs}L^2}{6}) \right)^{1/3} \tag{19}$$

B. ROUTING TREE CONSTRUCTION

To reduce the overall energy consumption of the network, it is necessary to find the shortest transmission path under the condition of h_{opt} branches. This algorithm employs a heuristic to establish the minimum energy consuming path. The routing tree process is divided into two distinct scenarios: initial routing tree formation and routing tree updates.

1) INITIAL ROUTING TREE FORMATION

During the initial routing tree formation, only location information is considered, starting with the node nearest to the BS. Nodes are then sequentially evaluated based on their distance to the base station to identify the path with the lowest energy consumption, ultimately creating a routing tree.

After reporting their geographic locations to the BS, the BS can calculate the distances between itself and the nodes, as well as among the nodes, resulting in a distance matrix D.

$$D = \begin{bmatrix} 0 & d_{12} & d_{13} & \cdots & d_{1n} \\ d_{21} & 0 & d_{23} & \cdots & d_{2n} \\ d_{31} & d_{32} & 0 & \cdots & d_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ d_{n1} & d_{n2} & d_{n3} & \cdots & 0 \end{bmatrix}$$

Here, $n = N+1$, with the BS treated as the $N+1$ node in the network, and d_{ij} representing the distance between nodes i and j,and d_{ij} equals d_{ji}. The h_{opt} nearest nodes to the base station are identified from matrix D; these nodes communicate directly with the BS, forming h_{opt} branches. The squared distance from these nodes i to the base station is represented as $d_{s-s}(i)$, with these nodes considered visited. The BS is also regarded as a visited node, where $d_{s-s}(N+1) = 0$.

Next, the nearest unvisited node q to the BS is identified. The distances between node q and all visited nodes i are calculated, aiming to minimize $d_{qi}^2 + d_{s-s}(i)$. If there exists a relay node i that satisfies this condition, node q is selected to communicate with node i. The value of $d_{s-s}(q)$ is updated as $d_{s-s}(q) = d_{qi}^2 + d_{s-s}(i)$. A routing tree is formed after traversing all the nodes according to this algorithm.

Taking Figure 2(a) as an example, assume $h_{opt} = 2$. Nodes A, B, C, D, E, and F are distributed within the area, with BS representing the base station. The distance matrix between the base station and the nodes is as follows:

$$D = \begin{bmatrix} d_{AA} & d_{AB} & d_{AC} & d_{AD} & d_{AE} & d_{AF} & d_{ABS} \\ d_{BA} & d_{BB} & & & & \cdots & d_{BBS} \\ d_{CA} & \cdots & d_{CC} & & & \cdots & d_{CBS} \\ d_{DA} & \cdots & & d_{DD} & & \cdots & d_{DBS} \\ d_{EA} & \cdots & & & d_{EE} & \cdots & d_{EBS} \\ d_{FA} & \cdots & & & & d_{FF} & d_{FBS} \\ d_{BSA} & \cdots & & & & & d_{BSBS} \end{bmatrix}$$

The specific distance values are as follows:

$$D = \begin{bmatrix} 0 & 2.06 & 2.69 & 2.97 & 3.16 & 1.12 & 1.8 \\ 2.06 & 0 & 3.6 & 0.94 & 2.69 & 1.41 & 2.24 \\ 2.69 & 3.6 & 0 & 4.09 & 2.06 & 3.61 & 4.47 \\ 2.97 & 0.94 & 4.09 & 0 & 2.69 & 2.34 & 3.08 \\ 3.16 & 2.69 & 2.06 & 2.69 & 0 & 3.5 & 4.5 \\ 1.12 & 1.41 & 3.61 & 2.34 & 3.5 & 0 & 1 \\ 1.8 & 2.24 & 4.47 & 3.08 & 4.5 & 1 & 0 \end{bmatrix}$$

According to our algorithm, the two nearest nodes to the base station are selected to form the initial routing path, as illustrated in Figure 2(b). Next, for node B, the shortest path from the BS to B is determined, constrained to branches F or A. Since $d_{BA}^2 + d_{ABS}^2 > d_{BF}^2 + d_{FBS}^2$, node B communicates with node F. Subsequently, the relay nodes for nodes C, D, and E are identified in sequence to finally form a routing tree.

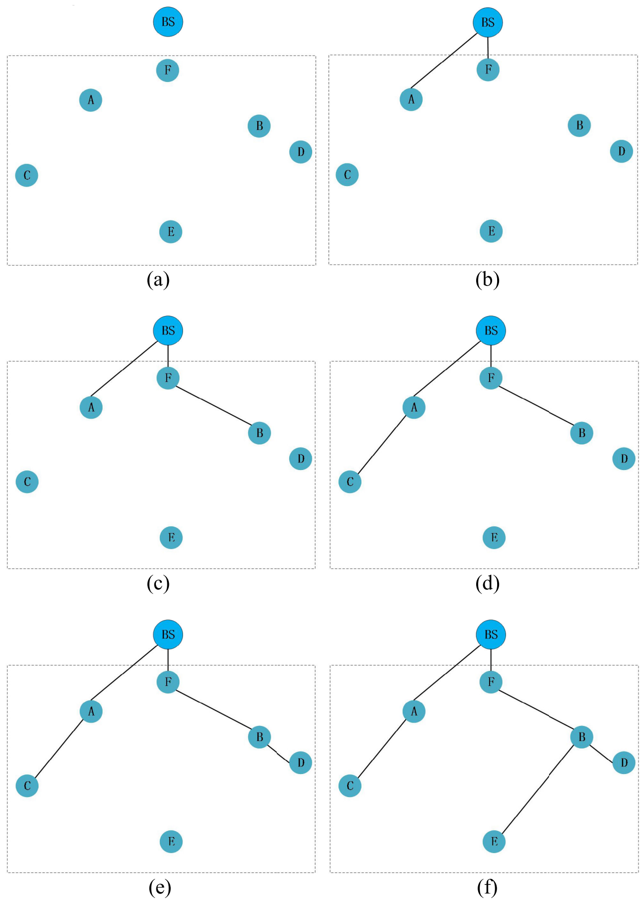

FIGURE 2. Example of routing tree generation.

2) UPDATING ROUTING TREE

During routing updates, different nodes exhibit varying energy consumption, with some nodes already experiencing significant depletion. As illustrated in Figure 2, node B needs to receive data from nodes E and D, as well as integrate its own collected data with the received data. If the routing tree is not updated, node B will incur excessive energy consumption, leading to a progressive decrease in its remaining energy. Therefore, it is necessary to update the routing tree. In this process, to balance energy consumption of relay nodes, an energy constraint will be implemented, requiring that only nodes with remaining energy above an energy threshold can serve as relay nodes, while those below the threshold will function solely as endpoint nodes.

The energy threshold expression is given by:

$$E_{th}(j) = E_{ravg}(j)^{*}\alpha(j) \tag{20}$$

$E_{ravg}(j)$ represents the mean remaining energy of the alive nodes in j^{th} round.

Let the remaining energy of node i in the j^{th} round be represented by $E_r(i,j)$, and the total remaining energy of the network in the j^{th} round be denoted as $E_r(j)$. The energy consumed by node i in the j^{th} round is referred to as $E_c(i,j) = E_r(i,j-1) - E_r(i,j)$, while the overall energy consumption of the network in the j^{th} round is represented by $E_c(j) = E_r(j-1) - E_r(j)$. Additionally, the average energy consumption of nodes in the j^{th} round is denoted by $E_{cavg}(j) = E_c(j)/n_a$,with n_a representing the number of active nodes in the network.

$E_{c\,\max}(j)$ represents the maximum energy consumption of a single node in the j^{th} round.

$$E_{c\,\max}(j) = \max_i E_c(i,j) \tag{21}$$

When no nodes die, the value of $\alpha(j)$ is as follows:

$$\alpha(j) = \left(E_{c\,\max}(j) - E_{cavg}(j)\right) \big/ E_{c\,\max}(j) \tag{22}$$

When there is node death, the value of $\alpha(j)$ is as follows:

$$\alpha(j) = 1 - \left(E_{c\,\max}(j) - E_{cavg}(j)\right) \big/ E_{c\,\max}(j) \tag{23}$$

Based on the threshold limit, the routing tree is updated. Clearly, the energy consumption of the network under the initially generated routing tree is minimized, while updating the routing tree leads to increased energy consumption (assuming the number of active nodes remains constant). Given that energy is consumed during each routing update, a dynamic interval for routing tree updates is implemented to avoid excessive energy expenditure and to ensure balanced energy consumption among nodes. As the network operates, energy consumption increases, leading to node death or an inability to support data transmission, necessitating a routing update. Therefore, the routing update strategy involves progressively shorter intervals as the network runs, with mandatory updates upon node death, otherwise adhering to the dynamic interval for routing updates.

The ratio of the energy consumption of node i in the j^{th} round to the average energy consumption of the network is given by:

$$\lambda(i, j) = E_c(i, j) \big/ E_{cavg}(j) \tag{24}$$

So, maintaining the current energy consumption, the maximum number of rounds that node i can operate is given by:

$$R_i = E_r(i, j)/E_c(i, j)) \tag{25}$$

$$R_{\min} = \min_i(R_i) \tag{26}$$

The dynamic update interval is

$$R_{dyit} = R_{\min} \big/ \lambda(\min, j) \tag{27}$$

Obviously, from the coefficient expressions of the energy threshold values in equations (22) and (23), it is known that its value is less than or equal to 1. Therefore, when the interval time of R_{dyit} reaches, it is first determined whether the remaining energy of any node is lower than the energy threshold value. If it is not lower, it will not be updated. Only when the energy of a node is lower than this value and the interval is reached, will the routing tree be updated. When the energy of all nodes is higher than this value, the routing tree will not be updated after the interval arrives, and will continue to run according to the newly calculated R_{dyit} to reduce the energy consumption of updating routing trees in the network.

In summary, the flowchart of the proposed algorithm is shown in Figure 3.

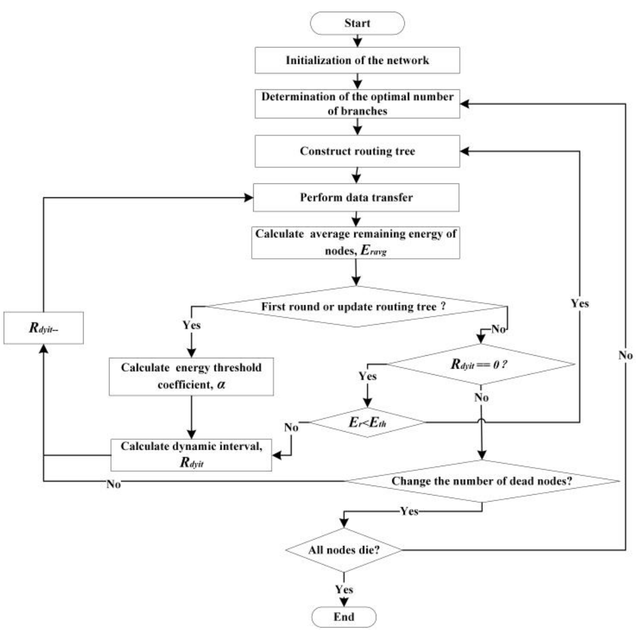

FIGURE 3. Flowchart of proposed algorithm.

IV. SIMULATION AND PERFORMANCE EVALUATION

A. SIMULATION PARAMETERS

The simulation parameters are shown in the Table 1.

TABLE 1. Simulation network parameters.

Network Parameters	Value
Network coverage area	100 m × 100 m
BS coordinates	(50,150)
Total number of nodes	100
Initial energy of node	0.5 J
Data packet size	4000 bits
Control signaling size	200 bits
E_{elec}	50 nJ/bit
E_{DA}	5 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4

B. PERFORMANCE EVALUATION

We will evaluate the performance of our proposed protocol from five aspects and compare it with protocols such as LEACH, EESRA and EE-TLT. In these protocols, all the sensor nodes are of the same type and have the same initial energy. In simulation, sensor nodes are considered dead when their residual energy is less than or equal to 0.

The first routing tree generated by this algorithm during network operation is shown in Figure 4.

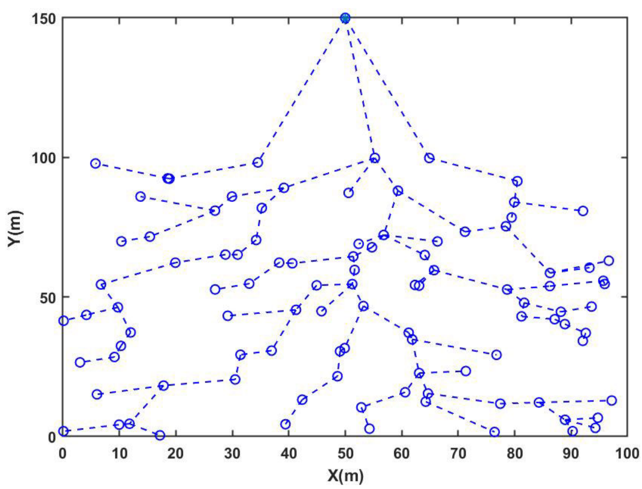

FIGURE 4. Routing tree of proposed algorithm.

1) NETWORK LIFESPAN

The duration from the network initiation to the death of all nodes. A longer network lifespan indicates better energy efficiency of the algorithm.

As can be seen in Figure 5, our proposed algorithm has a longer network lifespan compared to the other three algorithms. The network lifespan of our algorithm is 1509 rounds, while the LEACH protocol is 786 rounds, the EESRA protocol is 935 rounds, and the EE-TLT protocol is 1260 rounds. Our algorithm extends the network lifespan by 91.98%, 61.39%, and 19.76% compared to the LEACH, EESRA and

EE-TLT, protocols, respectively. It is evident that our protocol consumes less energy and balances the energy consumption among nodes, which is beneficial for prolonging the network lifespan.

2) NETWORK STABILITY PERIOD

The duration from the network's initiation to the death of the first node. A longer network stability period indicates better network reliability and more balanced energy consumption among nodes.

Figure 5 shows the number of alive nodes during the network operation. In our protocol, the first node death occurs in the 951st round, while LEACH experiences the first node death in the 219th round, EESRA in the 472nd round, and EE-TLT in the 517th round. Our algorithm outperforms LEACH, EESRA, and EE-TLT by 732, 524, and 434 rounds, respectively. Moreover, it can be observed that our protocol has a stability period that accounts for 63.02% of the network lifespan, while LEACH, EESRA, and EE-TLT protocols account for 27.86%, 50.48%, and 45.32% of their respective network lifespans. Our protocol achieves a longer stability period by using energy threshold values to restrict low-energy nodes from acting as relay nodes, thereby avoiding premature death due to excessive energy consumption.

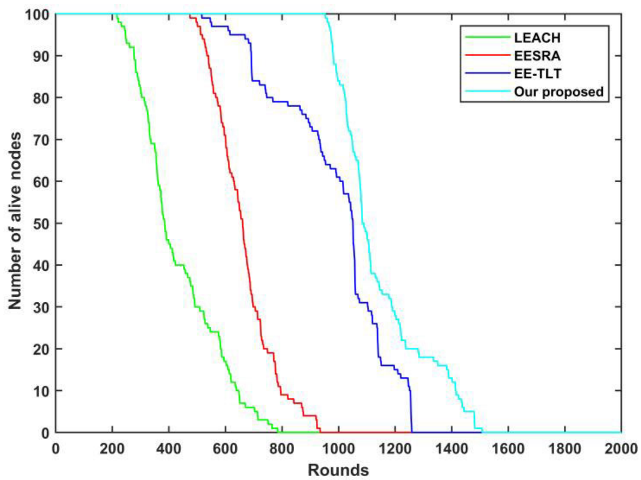

FIGURE 5. Number of alive nodes per round.

3) NETWORK REMAINING ENERGY

The overall remaining energy of the network during operation. Higher remaining energy indicates lower overall energy consumption of the network.

Figure 6 illustrates the overall remaining energy of the network during its operation. The steepness of the remaining energy curve reflects the energy consumption of the network, with steeper curves indicating higher energy consumption. Our protocol exhibits the highest remaining energy in the network.

Figure 7 displays the average remaining energy curve of nodes for each round for each protocol. Significant fluctuations in the average remaining energy curve indicate rounds with a high number of node deaths, resulting in an increase in the average remaining energy of the surviving nodes. According to Figure 5 and Figure 7, it is found that our protocol consistently maintains a higher average residual energy while having more alive nodes as compared to LEACH, EERSA and EE-TLT protocols.

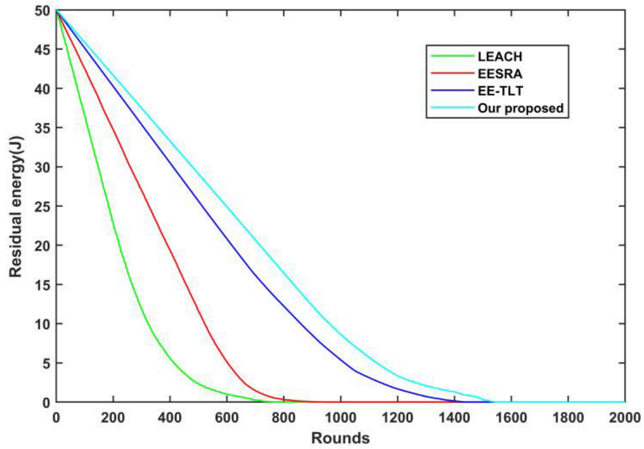

FIGURE 6. Residual energy per round.

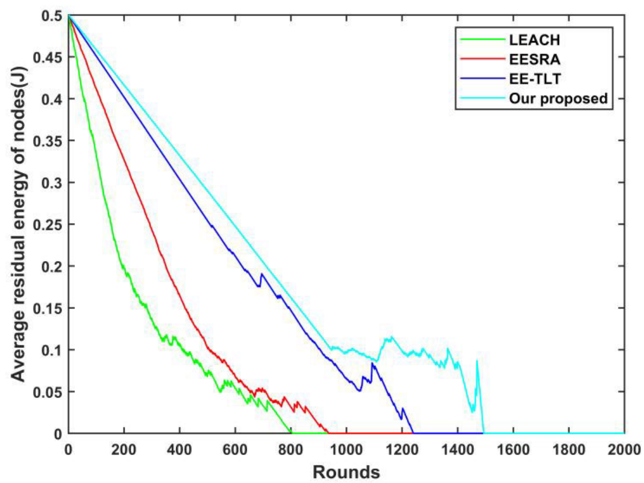

FIGURE 7. Average residual energy of nodes per round.

4) NODE DEATH NUMBER

The number of nodes that die during operation. Key observations include the scenarios of 5% node death, 25%,50%,75% node death, and 100% node death. Greater fluctuations in the node death count indicate more uneven energy consumption among the nodes.

The changes in the number of dead nodes can be observed from Figure 5. Figure 8 provides a more intuitive comparison of the number of dead nodes for each protocol. In our protocol, the number of dead nodes occurs later than in the LEACH, EESRA, and EE-TLT protocols across different proportions. Additionally, it can be noticed that the fluctuations

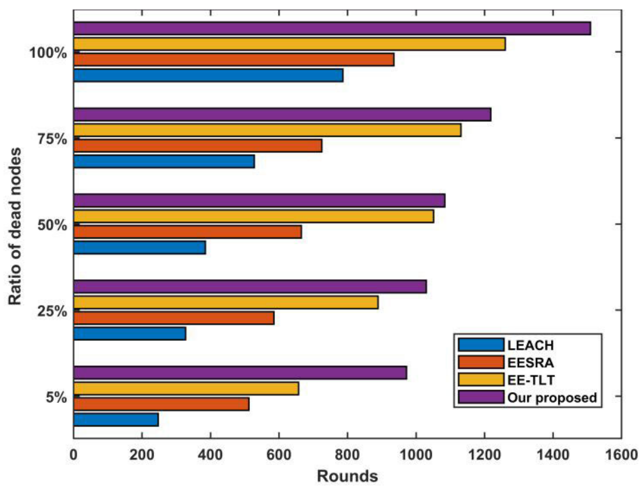

FIGURE 8. The ratio of dead nodes.

in the number of dead nodes in our protocol are smaller than those in the EE-TLT protocol, and is basically consistent with the LEACH and EESRA protocols. Our protocol strives to achieve energy balance among nodes while minimizing energy consumption.

Figure 9 shows that when 52 nodes die, a new routing tree is formed. The red color in the figure indicates the dead nodes. After the death of some nodes, the surviving nodes transmit data over a longer distance and the energy consumption increases relatively.

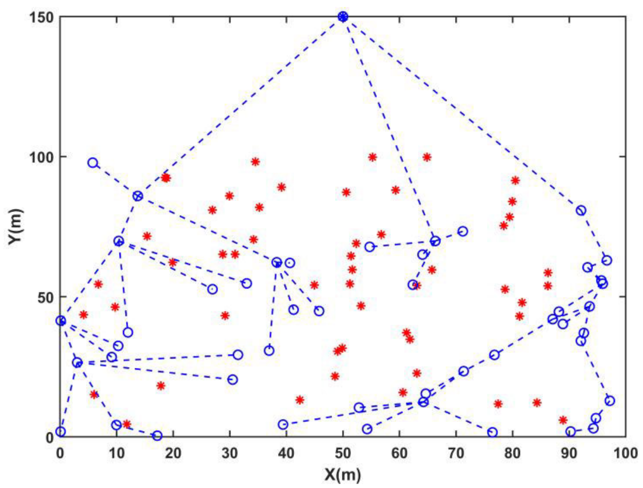

FIGURE 9. Routing tree after node death.

5) NETWORK THROUGHPUT

The total amount of data packets successfully transmitted from network nodes to the BS.

The network throughput provides an overall indication of the network's performance. When the node distribution remains unchanged in the monitoring area, the farther the base station is from the monitoring area, the more energy is consumed to transmit data to the base station, and the fewer data packets are transmitted over longer distances. Figure 10 presents a comparison of the number of transmitted data packets for four protocols, considering different base station positions at coordinates (50, 150), (50, 175), (50, 200), (50, 250), (50, 300), (0, 150), (25, 150), (75, 150), (110, 150), while maintaining the same node distribution. Our protocol achieves a higher network throughput compared to other protocols. This is because our protocol selects closer distances for data transmission, resulting in lower energy consumption. Additionally, the energy threshold restriction ensures a more balanced energy consumption among nodes communicating with the base station.

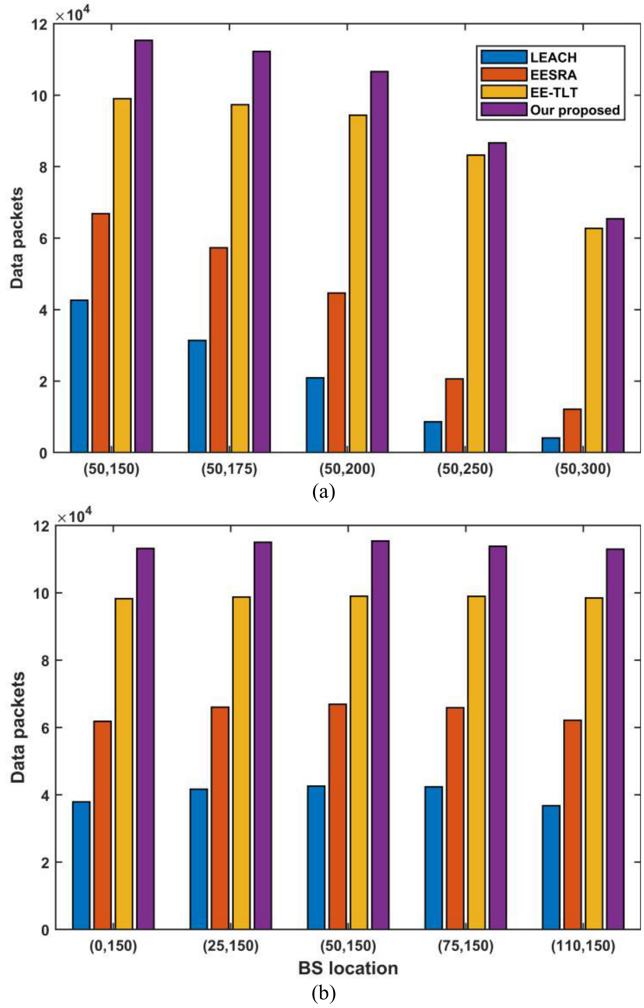

FIGURE 10. Transmission of data packets at different BS locations.

However, from the observed trend in Figure 10(a), as the base station moves farther away, the network throughput of our protocol approaches that of the EE-TLT protocol. This is because as the distance between the base station and nodes increases, our protocol has fewer branches, resulting in smaller differences in the routing trees between our protocol and EE-TLT. Consequently, the energy consumption difference between the two protocols becomes smaller, leading to a diminishing difference in network throughput.

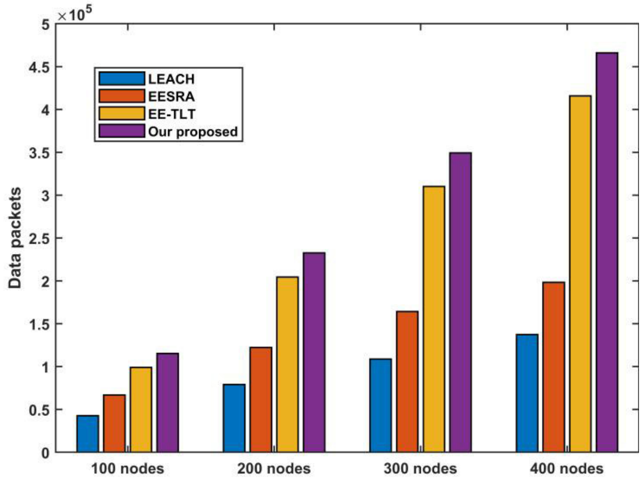

FIGURE 11. Transmission of data packets at different number of nodes.

TABLE 2. Comparison of ten sets of simulation results.

Case	Protocol	FDN	NL	Data Packets
1	LEACH	167	798	42536
	EESRA	510	941	66551
	EE-TLT	497	1270	99370
	Our proposed	923	1899	114587
2	LEACH	212	837	43690
	EESRA	494	940	67252
	EE-TLT	517	1240	99361
	Our proposed	949	1891	115491
3	LEACH	160	803	42583
	EESRA	479	918	66459
	EE-TLT	420	1273	98845
	Our proposed	955	1488	114280
4	LEACH	204	800	42667
	EESRA	493	884	66788
	EE-TLT	577	1239	99457
	Our proposed	934	1486	114943
5	LEACH	180	856	42992
	EESRA	475	924	66920
	EE-TLT	538	1335	98878
	Our proposed	960	1844	114951
6	LEACH	125	824	41726
	EESRA	494	907	65954
	EE-TLT	444	1271	98590
	Our proposed	944	1504	114690
7	LEACH	199	899	44325
	EESRA	517	930	68230
	EE-TLT	405	1249	99146
	Our proposed	952	1507	115044
8	LEACH	135	806	43249
	EESRA	510	985	66997
	EE-TLT	415	1234	98866
	Our proposed	931	1677	114864
9	LEACH	117	831	45174
	EESRA	527	1004	68821
	EE-TLT	415	1269	99405
	Our proposed	975	1601	115397
10	LEACH	218	753	46699
	EESRA	487	1004	68749
	EE-TLT	446	1254	99548
	Our proposed	983	1531	115052

Figure 11 illustrates the changes in network throughput for the four protocols as the number of nodes in the monitoring area varies, with the base station located at (50,150). The total number of nodes considered are 100, 200, 300, and 400, respectively.

The foregoing has presented a performance comparison among four protocols with respect to the distribution of 100 nodes illustrated in Figure 4. For a more comprehensive comparison, Table 2 presents the data associated with the occurrence of the first death node(FDN), network lifespan(NL), and the total number of data packets for the four protocols under ten distinct node random distribution circumstances with a base station located at coordinates (50, 150).

It is evident from the tabulated data set, our algorithm consistently performs better than the other three protocols regardless of the distribution scenarios. As can be seen from Table 2, in our algorithm, the average number of rounds when the first node dies is 950.6, the average network lifespan extends to 1642.8 rounds, and the average total number of transmitted data packets reaches 114,929.9.

V. CONCLUSION

Our proposed protocol balances node energy consumption network's stable period and further prolongs its overall lifespan. By dynamically updating the routing tree using varying intervals, the energy consumption associated with its formation is reduced. The simulation analysis conducted under the node scenario shown in Figure 4 shows that our protocol extends the network's stable period to 4.34 times, 2.01 times, and 1.84 times compared to LEACH, EESRA, and EE-TLT protocols, respectively. Furthermore, our protocol extends the network lifespan by 91.98%, 61.93%, and 19.76% respectively. Based on the average values obtained from multiple simulations, our algorithm extends the network stable period to 5.56 times, 1.91 times, and 2.03 times respectively. Meanwhile, in terms of network lifespan, it achieves significant extensions of 100.17%, 74.08%, and 30.03% respectively, effectively enhancing the overall performance of the network.

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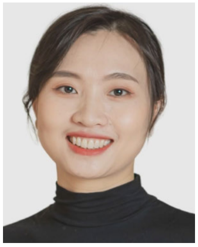

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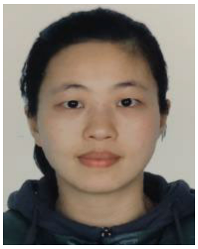

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