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Energy Saving Routing Algorithm for Wireless Sensor Networks Based on Minimum Spanning Hyper Tree

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Abstract

With the rapid development of wireless sensor networks (WSNs), designing energy-efficient routing protocols has become essential to prolong network lifetime. This paper proposes a minimum spanning tree-based energy-saving routing algorithm for WSNs. First, sensor nodes are clustered using the LEACH protocol and minimum spanning trees are constructed within clusters and between cluster heads. The spanning tree edge weights are optimized considering transmission energy, residual energy, and energy consumption rate. This avoids channel competition and improves transmission efficiency. An energy-saving routing model is then built whereby deep reinforcement learning (DRL) agents calculate paths optimizing the energy utilization rate. The DRL reward function integrates network performance metrics like energy consumption, delay, and packet loss. Experiments show the proposed approach leads to 10-15W lower average switch energy consumption compared to existing methods. The throughput is high since overloaded shortest paths are avoided. The average path length is close to shortest path algorithms while maintaining energy efficiency. In summary, the proposed minimum spanning tree-based routing algorithm successfully achieves energy-saving goals for WSNs while guaranteeing network performance. It provides an efficient and adaptive routing solution for resource-constrained WSNs.

Keywords: minimum spanning tree algorithm, undirected graph, DRL agent, clustering, multi hop transmission energy consumption

1 Introduction

Large scale wireless sensor network (WSN) is a kind of wireless network with dense nodes, various types and heterogeneous networks. Its constituent units are sensor nodes, which are characterized by low cost, large number and small size. In order to master the environmental situation in an all-round way, nodes are widely distributed and intensively deployed [1]. Through a variety of large number of sensor devices, real-time collection and perception of changes in corresponding physical quantities are carried out, and then converted into information that can be transmitted through the network, and the collected information is gathered together [2]. At present, the equipment, network and data management technologies of WSN are expanding to more rich scenarios, including intelligent factories, smart cities and other fields [3–7]. Sensor nodes are deployed to collect data of products and machines for the operation of smart factories [8]. By deploying sensor networks, cities will be transformed into smart cities, providing efficient platforms for the public and staff, and effectively managing urban resources [9]. The biggest limitation of the current large-scale WSN comes from the energy limitation and the lack of its own resources. The energy limitation is reflected in the inability of sensor nodes to make secondary energy supplement, and the lack of resources is reflected in the limitations of node processing capacity and storage resources [10]. Therefore, in the WSN scenario, improving the efficiency of network energy consumption and extending the network life is the top priority.

Research shows that communication energy consumption is the most important part of sensor energy consumption. Nodes sense information through sensors and send information in the form of signals through the communication module in the node. In wireless sensor networks, especially in large-scale deployment networks, many sensor nodes are distributed in a wide area, and have to use multi hop transmission to send the collected data to sink nodes outside the node communication range. Routing is the focus of multi hop transmission [11]. Therefore, when designing routing protocols, in addition to considering the problems existing in traditional networks, priority must be given to energy consumption and the limitations of nodes themselves. It has become a common means to balance network energy consumption and extend network lifetime through energy-saving routing in WSN. The mainstream research of energy-efficient routing often starts from minimizing the total energy consumption on the routing path. The overall energy consumption depends on the distance between nodes and the number of intermediate nodes [12]. Therefore, in addition to the minimum hop path or the shortest distance path, WSN routing also considers the residual energy level or power consumption rate of each node.

Reference [13] proposed a K-Means based routing energy saving algorithm for wireless sensor networks, which randomly divides all nodes in the network into k clusters. For each cluster, select its center node as the representative node of the cluster, and calculate the distance from all nodes in the cluster to the representative node. For each non representative node, compare its distance with the representative node of the cluster. If the distance between the node and the representative node is less than the distance between the node and other representative nodes, add the node to the cluster of the representative node until all nodes are divided into a cluster. For each cluster, select the node with the highest energy in the cluster as the master node of the cluster, and transmit the data of other nodes through the master node. For each cluster, set the transmission power of the non master node in the cluster to the minimum value to reduce energy consumption. When the energy of a node in the network is lower than the threshold value, the node is removed from the network, and the cluster division and master node selection are performed again. Through the above steps, the K-Means based routing energy saving algorithm for wireless sensor networks can be realized, which can effectively reduce the energy consumption of nodes in the network and extend the life of the network. Reference [14] proposes a clustering routing energy saving algorithm based on Dijkstra algorithm in wireless sensor networks. First, all nodes in the network are randomly divided into k clusters. For each cluster, select its center node as the representative node of the cluster. Use Dijkstra algorithm to calculate the shortest path with other representative nodes, and add the nodes on the path to the cluster. Select the node with the highest energy in the cluster as the master node of the cluster, and transmit the data of other nodes through the master node. Set the transmission power of the non master node in the cluster to the minimum value to reduce energy consumption. When the energy of a node in the network is lower than the threshold value, the node is removed from the network, and the cluster division and master node selection are performed again. Realize clustering routing energy saving algorithm based on Dijkstra algorithm, effectively reduce the energy consumption of nodes in the network, and extend the life of the network. The advantage of this algorithm is that it can choose the route according to the distance between nodes, avoiding some unnecessary energy consumption, and improving the energy efficiency of the network. Reference [15] proposed a routing energy saving algorithm for wireless sensor networks based on grey prediction, collected energy consumption data of all nodes in the network, and used grey prediction model to predict. For each node, the distance from its neighbor node to the node is calculated, and the distance and energy consumption of the neighbor node are taken as input variables to predict the energy consumption of the node in the future. According to the prediction results of node energy consumption, a path with the least consumption is selected as the routing path of the node, and the nodes on the path are divided into the same cluster. Set the transmission power of the non master node in the cluster to the minimum value to reduce energy consumption. The energy saving algorithm of wireless sensor network routing based on gray prediction is implemented, which effectively reduces the energy consumption of nodes in the network and extends the life of the network. The advantage of this algorithm is that it can predict the energy consumption of nodes based on historical data, avoiding some unnecessary energy consumption, it improves the energy efficiency of the network.

In view of the problems such as excessive energy consumption, poor energy efficiency performance, and low network concurrent throughput, this paper introduces the Minimum spanning tree to design a wireless sensor network routing energy saving algorithm. By considering the difference between the amount of data collected by nodes and the rate of data collected by nodes, the weight of the Spanning tree is optimized, and the Minimum spanning tree algorithm is referenced to build an energy saving routing model to determine the optimization goal of energy utilization, which effectively solves the above problems.

2 Design of minimum spanning tree algorithm

2.1 Large scale wireless sensor network

At the same time, a large number of sensor nodes make the defects of WSN more obvious. Compared with traditional wireless networks, in addition to the characteristics of wireless networks, wireless sensor networks have more stringent restrictions on nodes under large-scale WSNs. For example, nodes in wireless sensor networks can also carry out battery replacement to ensure the normal operation of the network. Once nodes are too dense, on the one hand, battery replacement is more difficult, on the other hand, the frequency of node battery replacement will greatly increase [16]. Therefore, in large-scale WSN, the node chooses not to replace the battery whether or not to replace the battery. Therefore, in order to deal with energy constraints, it is usually reflected in the routing. Energy saving routing is used to save energy. In the routing mode, data is the center, and the "many to one" "collective broadcast" data communication flow mode is adopted [17]. As shown in Figure 1, it is the topology diagram of WSN.

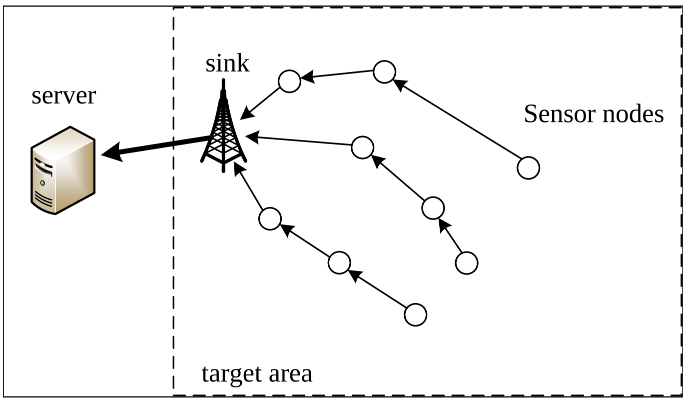

Figure 1: WSN topology diagram

Topological schematic analysis is one of the important tools for systematic research and optimization design of wireless sensor networks. According to Figure 1, large-scale WSNs are generally composed of sensor nodes, sink nodes (Sinks), and servers. Among them, sensor nodes and Sinks are often deployed in the target area, while servers are deployed far away from the target area. The working mode of large-scale WSN is: sensor nodes are densely laid in the target area, sensing area information, forwarding the sensing information through the routing of each sensor node, and finally sending it to the sink node, which forwards it to the server. Through topology diagrams, different partitions or clusters in the network can be identified and the connection relationships between each cluster can be understood. This helps to design appropriate routing protocols and manage network resources [18]. The schematic diagram shows the direct connection relationship between nodes. These connections can be wireless links or multi hop transmissions established through relay nodes. By analyzing the connection relationship, the connectivity, signal strength, and data transmission reliability of the network can be evaluated. By analyzing the above topology diagram, the best path selection method can be found to optimize the efficiency of data transmission and network energy consumption. This can provide a better understanding of the structure and performance of the network, and provide a reference basis for network deployment, management, and maintenance.

2.2 Component composition of sensor node

WSN is composed of a large number of sensor nodes. Each sensor node is composed of four important components, including the data collection component used to collect object information data. Its structure is shown in Figure 2.

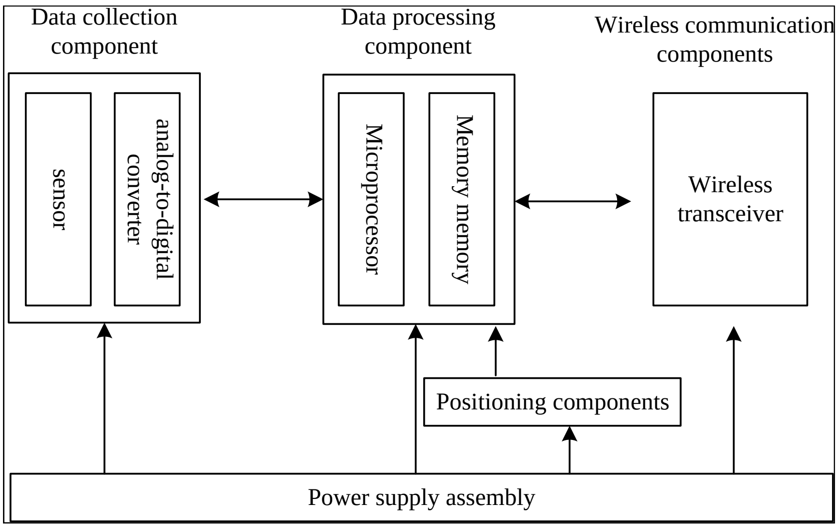

Figure 2: Schematic diagram of sensor node assembly

Analyzing Figure 2, it can be seen that the sensor node component is connected to the micro processor and memory memory in the data processing module for data interaction processing. The power supply component provides power to the sensor, micro processor, analog-to-digital converter, memory memory, and wireless transceiver.The power component in the sensor node is like the heart of the human body, providing energy for other components of the node [19]. In order to make the node small in size and low in cost, the power component of the sensor node is generally composed of small batteries such as button batteries, with limited energy. Once the battery energy is exhausted, all components in the node will no longer work. The nodes are packed with various types of sensors, which are the basic elements for sensor nodes to sense the external environment such as temperature, humidity, light, sound and other signals. In different application scenarios, different or even multiple sensors can be equipped to meet the needs. Using these sensors, nodes can collect analog signals about changes in physical environment parameters [20]. The sensor node is also equipped with a microprocessor and a micro memory to process the digital signal data collected by the sensor node data acquisition component and the information data of other nodes received by the wireless communication component. The data processing module is limited by its size and energy in the power supply module, so the processor and memory here can only store and simply process a small amount of data. In order to enable the nodes to communicate with each other and form a network, the nodes are also equipped with wireless transceiver circuits, which use data transmission antennas and power amplifiers to send their own data and receive signals from other nodes in the network. In order to know where the data is sent, it is necessary to equip the sensor nodes with positioning components. Now the more mature and common positioning method is GPS positioning, which can be used to achieve node positioning more accurately.

2.3 Research on minimum spanning tree algorithm under LEACH protocol

2.3.1 Cluster establishment phase

Calculate your own threshold $T(n)$; Then judge the size relationship between the two values. If the random number is relatively small, the node will win the cluster head election in this round and announce this message to other nodes. The cluster head selection threshold formula is:

$$T(i)=\begin{cases}\frac{P}{1-P*\left(r \bmod \frac{1}{P}\right)} & i \in G \\ 0 \text{ Other}\end{cases} \tag{1}$$

After the node successfully elects for the cluster head node, it will announce this message to other nodes. The message packet contains the location information of the cluster head node. At this point, the cluster creation phase is complete.

2.3.2 Routing within cluster

(1) Analysis of single hop transmission and multi hop transmission

In the LEACH protocol, member nodes establish a direct communication relationship with cluster head nodes, and cluster head nodes establish a direct communication relationship with sink nodes. Direct communication means that there is no other intermediate node between the two nodes, and the data will arrive at the destination node in a single hop from the source node. The single hop transmission mode is relatively simple, but the disadvantages are obvious. The corresponding running time of the node becomes shorter, leading to premature death. In addition, nodes are vulnerable to environmental interference through single hop communication, so the accuracy of information transmission is poor.

When the distance between two nodes is too large or not within the communication radius of each other, an appropriate intermediate node can be selected between the two nodes, and the intermediate node will forward the received information and its own information to other nodes. Therefore, the energy consumption of the intermediate node includes the energy consumption of receiving information and sending information. The energy consumption of single hop transmission mode and multi hop transmission mode is analyzed below. As shown in Figure 3. There are $n+1$ nodes:

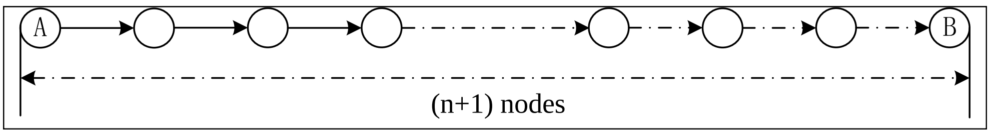

Figure 3: Schematic diagram of node transmission data

Assume that the distance between any two nodes is a, if the initial node A directly transferred k Bit data to the node B, then the energy consumption of this process:

$$E_{s-hop}=E_{T_x}(k,na)=E_{\text{elec}}\times\varepsilon_{mp}\times k(na)^2=k\times\left(E_{\text{elec}}+\varepsilon_{mp}\times kn^2a^2\right) \tag{2}$$

among them, E_{elec} represents the transmission energy consumption of the initial node, and ε_{mp} represents the energy consumption loss coefficient between nodes. If the initial node A transmitted K bit data through the intermediate node to the distance of nanode for B, the whole transmission process includes n packet transmission, $n-1$ reception of data packets. Therefore, the multi hop transmission energy consumption of this node is:

$$\begin{aligned} E_{s-hop} &= n \times E_{T_x}(k,a) + (n-1) \times E_{R_x}(k) \\ &= n \times \left(E_{\text{elec}} \times k + \varepsilon_{mp} \times k \times a^2\right) + (n-1) \times E_{\text{elec}} \times k \\ &= k \times \left((2n-1)E_{\text{elec}} + \varepsilon_{mp} \times n \times a^2\right) \end{aligned} \tag{3}$$

If the auxiliary transmission mode of intermediate nodes is better than the direct information transmission mode between nodes, the energy consumption formula needs to meet the following inequality:

$$E_{m-hop} < E_{s-hop} \tag{4}$$

$$(2\text{n}-1)E_{\text{elec}} + \varepsilon_{mp} n a^2 < E_{\text{elec}} + \varepsilon_{mp} n^2 a^2 \tag{5}$$

$$\frac{(2\text{n}-1)}{na^2} < \frac{n\varepsilon_{mp} - \varepsilon_{mp}}{E_{\text{elec}}} \tag{6}$$

$$a > \sqrt{\frac{2 \times E_{\text{elec}}}{n \times \varepsilon_{mp}}} \tag{7}$$

From Formula (7), when $n = 100, E_{\text{elec}} = 50$ nJ/bit, $\varepsilon_{mp} = 0.0013$pJ/bit/m^2. When, $a > 28$, At this time, the node can save more energy by auxiliary transmission of data packets through intermediate nodes. It can be seen that when the transmission distance between two nodes is far and the node density distribution in the environment is large, multi hop transmission by nodes will save more energy.

(2) Improvement of intra cluster routing In the coverage environment of WSNs, if all nodes in the network establish a direct communication relationship with the sink node, because the sink node is far away from the network coverage environment, it will cause a large energy loss of ordinary nodes, thus reducing the running time of the network. And all nodes communicating with the sink node at the same time will cause network bandwidth congestion, which will affect the data transmission efficiency. In particular, in the case of a large area and a large number of nodes, if ordinary nodes directly transmit data to cluster head nodes, nodes will consume more energy because they are too far away. In this case, the channel competition will inevitably be intensified, which will affect the transmission efficiency of messages. In order to better solve the above problems, this paper introduces the minimum spanning tree algorithm. The minimum spanning tree is formed within the cluster and between cluster head nodes respectively.

2.3.3 Minimum spanning tree algorithm

The minimum spanning tree makes all the nodes in the original graph connected with each other and does not form a loop. In addition, the weight sum of the nodes connecting lines to form an edge is the smallest. In this paper, prim algorithm is used to form a spanning tree between nodes in the cluster, and the cluster head node is selected as the root node. After the formation of the spanning tree, the cluster member nodes pass the information to the parent node according to a specific path, and finally to the cluster head node. For the cluster head node to form the minimum spanning tree, take the sink node as the root node, and the cluster head node organizes the network routing according to the minimum spanning tree algorithm. After the path is established, the cluster head node transmits the data to the sink node according to the specific path.

In the network composed of the minimum spanning tree algorithm, the cluster head node as an intermediate node needs to undertake more forwarding tasks, and the energy consumption of the node is fast. Considering the difference in the amount of data collected by the node and the rate of data collection, which leads to the difference in the residual energy of the node, the weight of the spanning tree is optimized. The optimized weight should not only take into account the energy consumption

Table 1: Steps to form a minimum spanning tree by organizing nodes in the cluster

The nodes in the cluster organize to form the minimum spanning tree
1. Input: $G = (V, E)$ Output: Minimum Spanning Tree T_{opt}.
2. The edge set is $V, V_{\text{new}} = \{x\}$, where, x is any point of collection V, the initial energy of the node is E_0.
3. The set of node edges is E. The weight of each edge is $W_{i,j}$.
4. Select the cluster head node as the root node.
5. Select a set edge E with the lowest weight $\langle i, j \rangle$, where node i is in collection V_{new} , j not in the collection V_{new} , but $v \in V$
6. Add j to V_{new} , adding edges $\langle i, j \rangle$ to E_{new}
7. Repeat 5-6 until $V_{\text{new}} = V$.
8. $T_{opt} \leftarrow T.T$ is the minimum spanning tree.
9. End

of information transmission between two nodes, but also take into account the sum of the remaining energy of two nodes. The weight calculation formula is as follows:

$$W_{i,j} = \frac{E_{T_X}(l, d) + E_{R_X}(l, d)}{2E_0 - E_{\text{cost}}\,(i) - E_{\text{cost}}\,(j)} \tag{8}$$

where: $W_{i,j}$ is the weight of the line edge of node i and node $j, E_{T_x}(l, d)$ is the transmission energy consumption between nodeiand node $j, E_{R_x}(l, d)$ is the receiving energy consumption of node i and node j, E_0 is node i and node j and the molecules in the formula represent the current energy state of the two nodes, $E_{\text{cost}}\,(i)$ and $E_{\text{cost}}\,(j)$ is the energy consumption from the initial time to the current round number of nodes i and nodes j. As can be seen from Formula (7), $W_{i,j}$ is decided by $E_{T_x}(l, d), E_{R_x}(l, d), E_{\text{cost}}\,(i)$ and $E_{\text{cost}}\,(j)$. The less the receiving energy consumption and the transmitting energy consumption between the two nodes, and the greater the current total residual energy of the node, that is, when the denominator value of the formula is smaller and the numerator value is larger, the smaller the value of $W_{i,j}$ is, the easier it is to select the communication path composed of two node connections.

2.3.4 Minimum spanning tree algorithm steps

(1) For the nodes in the cluster to form a spanning tree, the topology between all nodes in the cluster can use a weighted undirected connected graph as $G = (V, E)$, where V represents collection of all nodes in a table cluster, E represents the collection of connecting lines between all nodes in the graph. Set T as the final minimum spanning tree, the process of Prim algorithm forming the minimum spanning tree within cluster members is as Table 1.

All cluster member nodes follow the minimum spanning tree generated by the above steps, and carry out information transmission according to the formed path, finally reaching the cluster head node.

(2) For the cluster head node to form a spanning tree, the topological structure between all nodes in the cluster can use a weighted undirected connected graph $G = (V, E)$, where V represents a collection of all cluster head nodes and sink nodes, E represents the collection of connecting lines between all cluster head nodes in the figure. Set T as the final minimum spanning tree, the process of Prim algorithm forming the minimum spanning tree between cluster head nodes is as Table 2 .

In order to reduce the energy loss of nodes in the cluster and nodes between clusters, this algorithm takes into account the energy consumption of establishing direct communication between two nodes and the energy state of two nodes when the current number of rounds is used, and calculates the weight value of each side through formula (7). Since the node in the middle needs to receive and forward data at the same time, it consumes more energy, so on the premise of keeping the communication energy consumption between the two nodes small, try to choose the node with more residual energy as the intermediate node.

After the intra cluster and inter cluster routes are established, the nodes in the cluster pass the information to the parent node according to the specific path, and finally reach the cluster head node.

Table 2: Steps for organizing cluster head nodes to form a minimum spanning tree

Cluster head nodes organize to form a minimum spanning tree
1. Input: $G = (V, E)$ Output: Minimum Spanning Tree T_{opt} .
2. The edge set is $V, V_{\text{new}} = \{x\}$, where x is any point of collection V, the initial energy of the node is E_0.
3. The set of node edges is E. The weight of each edge is $W_{i,j}$
4. Select the sink node as the root node.
5. Select a set edge E with the lowest weight $\langle i, j \rangle$, where node i is in collection V_{new} , j not in the collection V_{new} , but $v \in V$
6. Add j to V_{new} , adding edges $\langle i, j \rangle$ to E_{new}
7. Repeat 5-6 until $V_{\text{new}} = V$
8. $T_{\text{opt}} \leftarrow T.T$ is the minimum spanning tree.
9. End

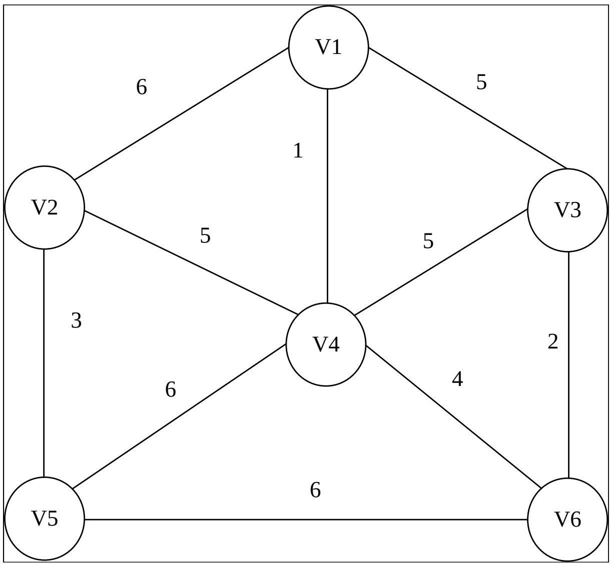

Figure 4: Undirected graph composed of 6 nodes

After receiving all the sensing information of the members in the cluster, the cluster head node fuses the data, and transmits the information to the parent node and finally to the sink node according to the specific path between clusters.

As shown in Figure 4, it is an undirected graph composed of six nodes. Figure 5 is the corresponding minimum spanning tree, and the sum of the weights of the edges is the smallest.

It can be seen from the analysis of Figure 4 that the minimum weight of the edge between V1 and V4 is 1, and the maximum weight of the edge between V1 and V2 is 6. In order to minimize the sum of the weights of the edges, the minimum weight V6 of the edge is obtained from v4. Similarly, V6 is connected to V3, V4 is connected to the second smallest weight node V2, and V2 is connected to V5. The corresponding minimum spanning tree is shown in Figure 5, realizing the minimum sum of the weights of the edges.

3 Energy saving routing algorithm based on minimum spanning tree for wireless sensor networks

The energy-saving routing module is responsible for determining the path of the source destination request. To solve the problem of energy saving and difficult to balance network performance, this paper uses the double threshold method of link utilization to ensure that not only energy saving but also load balancing are considered when scheduling streams. In the design of this paper, first, a newly arrived flow is routed according to the link utilization threshold value on the current working topology G'. If the path that meets the constraint conditions can be found on the current working topology G′, then it is forwarded according to this path; If the path satisfying the constraint conditions cannot be found

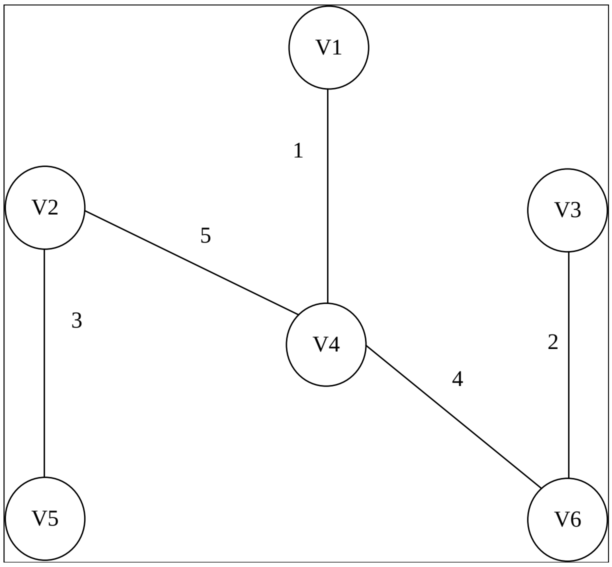

Figure 5: Corresponding minimum spanning tree

on the current working topology G′, then the PDDQR algorithm proposed in this paper is used to reroute the flow on the network on the global topology G to achieve both energy saving and network performance. PDDQR algorithm makes full use of the advantages of deep reinforcement learning that is good at solving decision-making problems, uses the competitive depth Q network based on priority experience playback, treats the routing task as a discrete control problem, and designs a reward function with weighted network performance parameters. The design of reward function integrates important performance parameters such as energy saving, load balancing and delay, which improves the energy saving effect and fully guarantees the network performance.

3.1 Energy saving routing modeling

In energy-saving routing optimization, the network topology is defined as a directed graph $G = (V, E)$. Among them, V represents a collection of network nodes, E represents a collection of edges in a network.

(1) Node model

Each node has two states to enable or hibernate. This article uses S_i represents a network node i. The value of 0 or 1 indicates that the node is dormant or active, namely:

$$S_i = \begin{cases} 1, \text{ if switch } v_i \text{ is active} \\ 0, \text{ otherwise} \end{cases} \tag{9}$$

(2) Data flow model

For data flow objects, this paper uses the following tuple structure to describe $f\left(s, d, \lambda_f, F_{ij}\right), s$ and d represent the source address and destination address of the data stream respectively, λ_f indicates the rate of the data stream, values of F_{ij} takes 0 or 1 indicate the flow respectively f is a link that does not pass or passes e_{ij}, i.e.:

$$F_{ij} = \begin{cases} 1, \text{ if flow } f \text{ passes thrpugh edge } e_{ij} \\ 0, \text{ otherwise} \end{cases} \tag{10}$$

Time of t traffic matrix TM^t containing the rate of the data stream all current source destinations. The index value of the source destination corresponds to the rate size of the stream.

(3) Link model

Each link also has two states, open or sleep, according to the state of the ports at both ends. This paper models the link as follows: tuple structure $(e_{ij}, W_{ij}, L_i, U_{ij}, X_{ij})$. Among them, e_{ij} used to identify a link and meet $e_{ij} \in E, W_{ij}$ indicates the bandwidth capacity of the link, L_i indicates the status of the link. Takes values of 0 or 1 indicate that the link is dormant or active, respectively.

U_{ij} indicates the utilization of the link. The maximum threshold value of the link utilization $U_{\max}$ is: If the link utilization is greater than $U_{\max}$, the link utilization rate is too high, which may affect the quality of service of the link transmission traffic; Minimum threshold of link utilization $U_{\min}$ is: If the link utilization is lower than $U_{\min}$ the link utilization rate is too low, and the link is not fully used,Values of X_{ij} takes 0 or 1 indicate whether the utilization of the link is between the maximum threshold $U_{\max}$ and the lowest threshold value $U_{\min}$, i.e.:

$$L_i = \begin{cases} 1, \text{ if link is } e_{ij} \text{ active} \\ 0, \text{ otherwise} \end{cases} \tag{11}$$

$$U_{ij} = \frac{\sum_{\forall f} F_{ij} * \lambda_f}{W_{ij}} \tag{12}$$

$$X_{ij} = \begin{cases} 1, U_{\min} \leq U_{ij} U_{\max} \\ 0, \text{ otherwise} \end{cases} \tag{13}$$

(4) Network topology model

For nodes and links in the network topology, there are two statuses: sleep and enable: working topology G' and global topologyG, working topology G' topology is composed of all nodes and links in the network that are in the open state; Global topology G is the topology composed of all nodes and links in the network.

(5) Common optimization objectives

Power Usage Effectiveness (PUE) is the most commonly used optimization goal, which refers to the ratio of the total energy entering the data center to the energy consumed by network equipment, as shown in Formula (6):

$$\text{PUE } = \frac{P_T}{P_{IT}} \tag{14}$$

Among them, P_T is the total annual power consumption, P_{IT} is annual power consumption of equipment of IT.

In the actual network scenario, if we one-sided pursue energy conservation and sleep as many links as possible with low link utilization, it is likely to lead to unbalanced network load and even congestion. The goal of traditional energy-saving routing optimization is mainly to minimize the number of network devices or the ratio of open network devices to total devices, while the network load balancing scheme is mainly focused on keeping all the work of the devices ignoring the energy consumption of some low utilization devices. The trade-off between energy conservation and performance has always been a challenging task. These two opposite goals clearly indicate that an overall solution is needed to maintain the balance between energy conservation and network performance.

3.2 Energy saving routing optimization method design

In this paper, the routing problem is described as a discrete control problem, and a minimum spanning tree based energy-saving routing method is proposed to enable the DRL agent to calculate a path for each source destination while optimizing the energy-saving goal, while not limiting the DRL agent tom select from the shortest paths, and gradually select the link to construct the path, taking into account the current state of the network and the energy saving goal. In order to better apply DRL to SDN energy-saving routing optimization, the state space, action space and reward function of DRL method need to be designed according to the current network environment, so as to better adapt to the SDN network environment and the task requirements of energy-saving routing optimization, and improve the optimization capability of DRL.

(1) State space

The way of designing the state space in this paper is to include the state information concerned in the energy-saving routing task environment, including link utilization, link delay and link packet loss rate. For link delay and link packet loss rate, the size is $|V|\times|V|$ and carry out normalization operation, and use $|V|, l_{ij}$ the specific implementation adopts the minimum maximum normalization method, as shown in Formula (15):

$$d_{ij} = \frac{d_{ij}^{raw} - d_{\min}^{raw}}{d_{\max}^{raw} - d_{\min}^{raw}} \tag{15}$$

The matrix of network delay is shown in Formula (16). If the next node j is the destination noded, the value is 2 ; If the next node j is the source nodes, the value is - 2; If ij is the same, the value is 0 ; If is E links present in e_{ij}, the value is $-d_{ij}$. The processing method of link packet loss rate matrix is the same as that of network delay matrix.

$$\boldsymbol{D} = [\boldsymbol{D}(\boldsymbol{G})]_{ij} = \begin{cases} -d_{ij}, (i,j) \in E \\ 2, j = d \\ -2, j = s \\ 0, i = j \\ -1, \text{ otherwise} \end{cases} \tag{16}$$

Since this paper focuses on network energy saving and load balancing, this paper uses $U_{\max}$ and $U_{\min}$ these two thresholds process the link utilization matrix as follows: when U_{ij} between $U_{\max}$ and $U_{\min}$, it is corrected to 1 ; When U_{ij} is greater than $U_{\max}$, amend it to $U_{\max} - U_{ij}$; When U_{ij} is less than $U_{\min}$, amend it to $U_{\max} - U_{ij}$. This way ensures that the agent gives priority to link utilization when routing U_{ij} be situated between $U_{\max}$ and $U_{\min}$ to ensure network energy saving and load balancing. The specific expression is shown in (3):

$$\begin{cases} \boldsymbol{U} = [\boldsymbol{U}(\boldsymbol{G})]_{ij} = \begin{cases} -p_{ij}, (i,j) \in E \\ 2, j = d \\ -2, j = s \\ -1, i = j \\ -1, \text{ otherwise} \end{cases} \\ p_{ij} = \begin{cases} U_{\max} - U_{ij}, U_{ij} > U_{\max} \\ U_{\min} \le U_{ij} \le U_{\max} \\ U_{ij} - U_{\min}, U_{ij} < U_{\min} \end{cases} \end{cases} \tag{17}$$

(2) Action space

The action space consists of all links in the network, that is $A = \left[a_1, a_2, \ldots a_{|E|}\right]$, where each action corresponds to a link in the network link set E.

(3) Reward function

When DRL is used for SDN energy-saving routing optimization, the reward function represents the reward that the system feedback to the agent after the system executes the action given by the agent, and the agent optimizes the goal of cumulative reward. The reward function directly affects the learning effect of the DRL algorithm. Because agents can choose any action in the action space at any time step, and may choose invalid actions to lead to network loops, in this paper, the reward function includes the optimization of handling invalid actions, network loops, and multiple network performance indicators.

In the time steps at the T_1, DRL agent must find the path of source node s to target node d. At any intermediate nodex, agent at time t select the corresponding action a_t, and through the reward function $f((i,j))$ calculate rewards r_t, the expression is as shown in (18) :

$$\begin{cases} r_t = f((i,j)) \\ f((i,j)) = \begin{cases} g((i,j)) & (i,j) \in E_{\text{valid}}^{x} \\ -\frac{|V|}{2} & \text{otherwise} \end{cases} \end{cases} \tag{18}$$

Among them, E_{valid}^{x} represents the set of valid actions of node x, that is, only slave departure link of nodes x. If the selected action is invalid, the agent gets penalties $-|V|/2$. If the selected action is valid, calculate the reward value of $g((i,j))$, and its expression is as shown in (19):

$$g((i,j)) = \begin{cases} -\frac{|V|}{3} \quad (i,j) \in E_{\text{visited}} \\ |V| \quad j = d \\ -|V|T_1 = d \\ (p_{ij} * \zeta_1) + (-d_{ij} * \zeta_2) + (-l_{ij} * \zeta_3) \text{ otherwise} \end{cases} \tag{19}$$

Among them, E_{visted} indicates the collection initialized to be empty at the beginning of each iteration, and the links that pass through are added step by step. If it passes again E_{visted} that the agent obtains a value of $-|\text{V}|/3$, to avoid network loops as much as possible. If the selected link includes a target node d, this is the completion status, and the agent obtains the value of the maximum reward of $|V|$, that is, the agent has found the path of this source destination request.

This article limits each iteration to T_1 within time steps ($T_1 = |E|$) to avoid the agent being trapped in an infinite loop when exploring the action space. If the time step T_1 is greater than the total number of links $|E|$, it is considered that the agent fails to find the path and gets the maximum penalty of $-|V|$; Otherwise, the agent will be rewarded according to the weighted network; Among them, ζ_1, ζ_2 and ζ_3 is an adjustable weight, which can adjust the weight of different performance parameters. In this paper, due to the priority of network energy saving and load balancing ζ_1 greater than ζ_2, ζ_3 and satisfy $\zeta_1, \zeta_2, \zeta_3 \in [0, 1]$

In this regard, a routing energy saving algorithm based on minimum spanning hyper tree is implemented for wireless sensor networks.

4 Experiment

4.1 Experimental design

This paper uses MATLAB software to search data set in Google dataset, The simulation research is carried out on the. In the same environment configuration, compared with the single hop, cluster head spanning tree algorithm of the nodes in the cluster, the weight of the cluster head spanning tree represents the communication consumption of the two nodes. 100 nodes are randomly generated and randomly distributed over 100 m × 00 m flat area. The experimental parameters are shown in Table 3:

Table 3: Simulation experiment parameters

parameter	**Corresponding value**
Cluster head probability	0.05
E_0/ Joule	0.2
E_{elec} /(nJ/bit)	50
$\varepsilon_{fs}/\left(\text{pJ/bit/m}^2\right)$	10
$\varepsilon_{mp}/\left(\text{pJ/bit/m}^2\right)$	0.0013
E_{DA}/bit/ signal	5
Control package length	32
Packet length	4000
Coordinate of	convergence node (0,0)

According to the above parameters, experimental verification is carried out.

4.2 Performance evaluation of wireless multi hop network

In wireless multi hop networks, according to the difference in the number of paths, the network performance evaluation model can be divided into single path performance evaluation model and multi path performance evaluation model. The single path performance evaluation model analyzes the indicators of a single path. The performance evaluation model of multiple paths can evaluate the overall performance when multiple paths are transmitted in the network. This section introduces the performance evaluation models of single path and multiple paths in wireless multi hop networks respectively.

(1) Performance indicators of single path

This section analyzes various indicators in a path, uses path efficiency to evaluate path utilization, and uses standard energy per bit (r') to evaluate the energy consumption of wireless multi hop networks, using the transmission time per bit (T_{tran}) to measure the speed of data transmission. The relevant definitions of these performance indicators will be given in the following description.

Path efficiency

Path efficiency describes the degree of redundancy of a path. The higher the path efficiency, the less network space this path occupies. In this paper, the path efficiency (η) is defined as: Euclidean distance between source node and destination node (l) ratio to the actual distance of the path. See Formula (20) for details.

$$\eta=\frac{l}{\sum_{i=1}^{k} d_i}=\frac{l}{\beta \bar{d}} \tag{20}$$

In this formula, where β refers to the number of hops of a path, $\bar{d}$ indicates the average distance per hop. In this paper, we consider that the path efficiency of linear networks is 1 .according to formula (19), the hops of a path can be expressed as formula (21).

$$\beta=\frac{l}{\eta \bar{d}} \tag{21}$$

(2) Transmission time per bit

In wireless multi hop networks, the transmission speed between the source node and the destination node is not only related to various channel parameters, but also affected by the hop distance. This section uses the transmission time per bit to represent the end-to-end transmission speed of the network. When a path transmits data (the amount of data transmitted is Q Bit), the transmission time of each hop can be obtained from Formula (22).

$$T_i=\frac{Q}{\lambda_i}=\frac{Q}{B \log 2\left(1+\frac{P d_i^{-2}}{n_0 B}\right)} \tag{22}$$

Wherein, the i of the transmission speed of transmissions is λ_i. The transmission time per bit refers to the total time consumed by transmitting unit data and paths, which can be expressed as Formula (23).

$$T_{\text{tran}}=\frac{\sum_{i=1}^{\beta} \frac{Q}{B \log 2\left(1+\frac{P d_i^{-2}}{n_0 B}\right)}}{Q}=\sum_{i=1}^{\beta} \frac{1}{B \log 2\left(1+\frac{P d_i^{-2}}{n_0 B}\right)} \tag{23}$$

We believe that the time required for the node to receive data is equal to the transmission time of each bit, then Formula (24) setup.

$$T_{\text{rcep}}=T_{\text{tran}} \tag{24}$$

Among them, T_{tran} indicates the receiving time of each bit of path transmission data.

(3) Standard energy per bit

Standard energy per bit refers to the energy consumed for each bit transmitted during data transmission. It is usually used to measure the energy efficiency performance of data transmission. A lower standard of energy per bit represents achieving data transmission with less energy, resulting in higher energy efficiency performance. On the contrary, a higher standard of energy per bit indicates that data transmission is achieved with more energy transmitted, resulting in lower energy efficiency performance.This paper assumes that all nodes have the same power to send and receive data. Combining Formula (23) and Formula (24), the energy per bit (γ, the total energy consumption of transmitting and receiving unit data) can be expressed as formula (25).

$$\gamma=\gamma_{\text{tran}}+\gamma_{\text{rcep}}=P T_{\text{tran}}+P T_{\text{rcep}}=2 p\left(\sum_{i=1}^{\beta} \frac{1}{B \log 2\left(1+\frac{P d_i^{-2}}{n_0 B}\right)}\right) \tag{25}$$

Among them, γ_{tran} and γ_{rcep} respectively represents the energy consumed by transmitting and receiving 1-bit data.

The energy per bit transmitted is greatly affected by the path efficiency. By normalizing the path efficiency, we call such energy per bit standard energy per bit (γ') and use it to estimate the energy change of the path. Combining Formula (16) and Formula (21), γ' can be expressed as formula (26).

$$\gamma' = \gamma\eta = 2P\eta\left(\sum_{i=1}^{\beta}\frac{1}{B\log 2\left(1+\frac{Pd_i^{-2}}{n_0 B}\right)}\right) \tag{26}$$

(2) Performance indicators of multiple paths

The evaluation indicators in the previous section describe the performance of a path. This section mainly discusses various performance indicators in the network when using the transmission scheduling model to schedule the transmission in multiple paths.

The total energy consumed by transmitting the same data in path A is $E.E$ can be expressed as formula (27).

$$E = \sum_{x=1}^{m}\sum_{y=1}^{n_x} PT_{\text{con }xy} \tag{27}$$

Among them, m refers to the number of concurrent transmission sets, n_x refers to the number of x concurrent transmission set schedules that contain transmissions. $T_{con_{xy}}$ indicates that the schedule is in the concurrent transport sets of x, the transfer of the duration of y.

Network concurrent throughput when using k paths to transmit data (C) is Formula (28).

$$\text{C} = \frac{Q}{T_{\text{all}}} = \frac{Q}{\sum_{x=1}^{m} T_{\text{con}_x}} \tag{28}$$

Among them, T_{con_x} indicates the duration of concurrent transport sets of x.

(3) Network Concurrent Throughput $\boldsymbol{B_t}$

In order to verify the energy-saving effect of the wireless sensor network routing method proposed in this article, the concurrent throughput of the network is used as the indicator for verification. The specific calculation formula is:

$$B_t = \frac{N_{bb}}{T_{rr}} \tag{29}$$

Among them, N_{bb} represents the number of network concurrency, and T_{rr} represents the average response time.

4.3 Experimental results

4.3.1 Standard energy per bit

Figure 6 shows the change of average switch energy consumption of each algorithm with traffic intensity. The average switch energy consumption of all algorithms increases with the increase of traffic. Among them, the method in this paper shows the minimum power consumption, saving at least 10 W to 15 W for the average energy consumption of switches in the Fat Tree topology, followed by NMU and SRASA-R algorithms. Because DDPG-R is limited to select actions in the four shortest paths, and other performance parameters are considered, it is only a little better than the traditional SPF algorithm; Figure 6 shows the link saving rate of each algorithm changes with traffic intensity. The link saving rate of this method is at least 3.2% higher than that of other algorithms. This is because this paper optimizes the edge weight of the Spanning tree based on the transmission energy, residual energy and consumption rate to select appropriate intermediate nodes. A routing model is established, in which the Deep reinforcement learning agent calculates the optimal path of each source destination request to optimize the energy utilization.

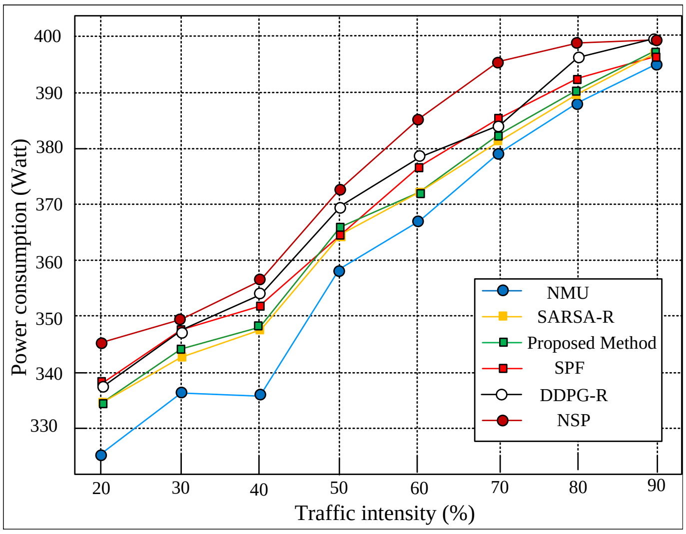

Figure 6: Average energy consumption of switch changes with traffic intensity

4.3.2 Transmission time per bit

Figure 7 shows the average path length of each algorithm changes with traffic intensity, and SPF shows the minimum average path length. This is because SPF simply considers the shortest path and does not consider other indicators; DDPG-R was the second; The method in this paper is very close to the algorithm considering the shortest path, because with the increase of traffic, the shortest path may be overloaded, so some flows must be routed to longer paths; NMU mainly considers that the network link utilization is at a high level as far as possible, so the average path length is the largest.

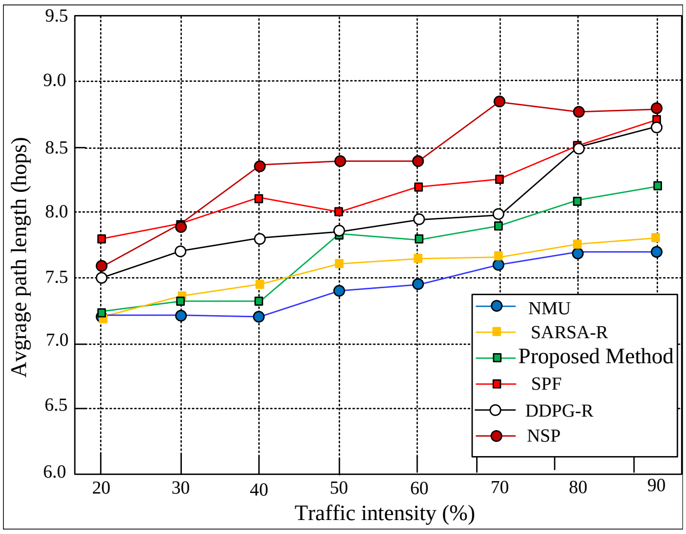

Figure 7: Average path length changes with flow intensity

4.3.3 Network concurrency throughput

Figure 8 shows the change of throughput of each algorithm with traffic intensity. NMU mainly considers that the network link utilization is as high as possible, so the average throughput is the largest. The throughput of this method is 2 to 3Mbps less than that of the best performing NMU. In general, the throughput of NMU, this method and SARSA-R is larger than that of SPF, NSP and DDPG-R which focus on the shortest path.

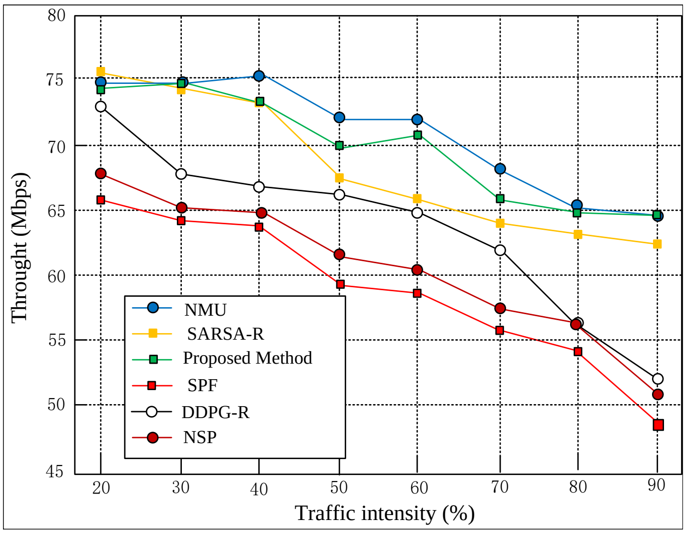

Figure 8: Network throughput changes with traffic intensity

Figure 9 shows the delay of each algorithm changes with the traffic intensity. The NSP algorithm does not exceed the maximum load due to the selection $U_{\max}$ the shortest path of is the best in terms of delay. Because the link delay is taken into account, the results of this method are prior to those of NSP and NMU algorithms; SPF algorithm only considers the shortest path and performs worst in terms of delay. This is because this method clusters sensor nodes through LEACH, and constructs a Minimum spanning tree within the cluster and between cluster heads to avoid channel competition, improve transmission efficiency, and effectively reduce link delay.

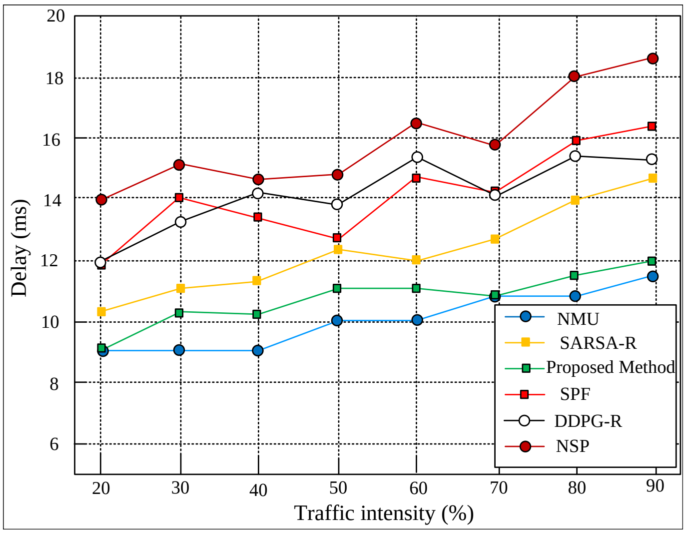

Figure 9: Network average delay changing with traffic intensity

5 Conclusion

Effective routing is crucial for energy constrained wireless sensor networks (WSNs) to maximize their lifespan. This paper proposes a new energy-saving routing algorithm based on Minimum spanning tree. The main conclusions are as follows:

(1) The sensor nodes are clustered by LEACH, and a Minimum spanning tree is constructed within the cluster and between cluster heads to avoid channel competition and improve transmission efficiency.

(2) The edge weight of Spanning tree is optimized based on transmission energy, residual energy and consumption rate to select appropriate intermediate nodes.A routing model is established, in which the Deep reinforcement learning agent calculates the optimal path of each source destination request to optimize the energy utilization.

(3) Compared with existing methods, the average switching energy is reduced by $10 - 15$ W, indicating the effectiveness of this method in achieving energy-saving goals.

(4) The throughput is high because it avoids overloading the shortest path and the average path length is close to the shortest path algorithm.

In a word, the routing algorithm based on Minimum spanning tree successfully realizes the energy efficiency of wireless sensor networks while maintaining the network QoS performance. It provides an efficient and adaptive solution suitable for resource limited wireless sensor networks. Further work includes testing on real sensor datasets and hardware test benches. The routing method can also be extended to other wireless self-organizing networks.

Although this method has achieved many achievements, there is room for progress in improving energy efficiency and reducing network transmission energy consumption, which is also my future research direction.

Author contributions

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