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Research on WSN Topology Algorithm Based on Greedy Shortest Paths

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Abstract: It is a common design in most of the current topology schemes of wireless sensor network that the cluster head nodes can communicate with base station (BS) node directly, which causes that the cluster head nodes consume too much energy and become the bottleneck of network performance. Therefore, a WSN topology algorithm based on greedy shortest paths is proposed in this paper. Firstly, selecting the backbone nodes of the network and constructing the backbone network to transmit messages and allowing the backbone nodes and cluster heads to exist separately. Secondly, the backbone nodes build a single source shortest path routing table based on the greedy algorithm and select the most suitable shortest path to transmit data according to the consumption of the backbone nodes. Thirdly, selecting the cluster heads based on the LEACH protocol, in which the cluster heads is responsible for collecting and compressing the data, selecting the nearest backbone node to transmit the data. It is shown by data calculation and analysis that the proposed topology scheme in this paper has more stable transmission network structure, less burden and less reconstruction frequency, and the cluster heads are only responsible for transferring the processed data to the backbone network. In addition, the cluster head consumption and the overall network consumption are significantly improved compared with LEACH.

Key Words: Greed method, single-source shortest path, topology, backbone network, Wireless Sensor Network.

1 Introduction

The typical feature of wireless sensor network (WSN) is to deploy many nodes in a small area, which can ensure a high enough coverage so that the redundant nodes of the network can prevent the network hole caused by nodes failure, but it also brings some disadvantages. In a relatively crowded network environment, due to the excessive number of nodes' neighbors, there are many communication problems such as the mutual interference of nodes, the possible increase in the number of routes brought by the variety of links, the frequent occurrence of route reconstruction caused by node failure and location change, and the problems brought by the use of different transmission power to communicate with different nodes. Besides, WSN nodes are generally powered by batteries which cannot be replaced, and energy saving is one of the main considerations in network topology design [1] [2]. It is known that the most important goal of topology control is to use energy reasonably and efficiently as much as possible to prolong the lifetime of the whole network while ensuring the connectivity and coverage of the network [3] [4].

It is an important way to reduce the interference between nodes, improve the communication efficiency, adjust the power properly or construct the backbone network through topology control. The backbone nodes in WSN can fuse the collected data and send the results to the data collection node, which can reduce the transmission of messages in the network without forwarding one by one and reduce the energy consumption of the whole network [5]. Moreover, the backbone nodes need to coordinate and manage the work of their own nodes in the cluster, so that the energy consumption is far more than other nodes in the network. In addition, if a fixed node is selected as the backbone node, it will cause the node to die quickly and affect the network life [6]. For security, the frequent communication of one node is easy to cause the problem of single point failure [7]. Therefore, the method of selecting some key nodes periodically is usually used to balance the energy consumption of nodes and maintain the connectivity of the network.

In addition, as a WSN high frequency communication node, the energy problem of cluster head is always the bottleneck of network performance. Most of the clustering algorithms proposed currently have the following disadvantages: 1) in WSN, all cluster heads communicate directly with BS, if the network scale is large and some cluster heads are far away from BS, the cluster heads will have short life because the energy consumption of sending information is directly proportional to the exponent of sending distance (usually the exponent is greater than 2) [9]; 2) because the energy consumption of cluster heads is far greater than other sensor nodes, the energy of cluster head

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nodes will be exhausted quickly, only with the frequent replacement of cluster heads can maintain the network connection, but increase the burden of the network [10]; 3) in most clustering algorithms, cluster members must communicate with cluster heads directly which not only limits the scale of cluster but also increases the burden of cluster heads and faster the death of cluster heads [11].

As above mentioned, the current researches are to integrate the function of the backbone nodes and the cluster heads which are all responsible for data collection, fusion and forwarding, but it does not really solve the problem of energy consumption, they are still high-frequency communication nodes which are easy to cause routing reconstruction. Therefore, this paper proposes a WSN topology algorithm based on greedy shortest paths (TA-GSP). On the one hand, this scheme needs to select backbone nodes of the network, build the backbone network to transmit network data, allow the backbone nodes and cluster heads to exist in same network, in which the cluster heads are only responsible for collecting and compressing its data of the cluster. On the other hand, the backbone nodes build a single source shortest path routing table based on the greedy algorithm and select the most suitable shortest path to transmit data according to the consumption of the backbone nodes. The proposed topology scheme in this paper has more stable transmission network structure, less burden and less reconstruction frequency, and the cluster heads are only responsible for transferring the processed data to the backbone network.

The organization structure of this paper is as follows: section 1 summarizes the background of current algorithms research; section 2 describes the greedy algorithm and the method of greedy shortest paths; section 3 describes the main contents of TA-GSP scheme, including backbone node selection, shortest path construction, cluster head selection, etc.; section 4 analyzes the advantages of TA-GSP scheme through data analysis; section 5 summarizes the work of this paper.

2 Related Work

2.1 Greed Method

The greedy method (GM) [12] always makes the best choice at present which means that the greedy algorithm does not consider the overall optimization and its choice is only the local optimization in a sense. Although greedy algorithm cannot get the global optimal solution for many problems, it still can generate the global optimal solution for some special problems, such as the single source shortest path problem, the minimum spanning tree problem and so on.

The solution process of GM is regarded as a series of choices, in which if an input is selected and the choice should be the best choice (local optimal solution) under the current state. After each choice, the problem of GM will be simplified into a smaller sub problem so that the overall optimal solution can be achieved gradually through the optimal solution of each step.

2.2 Single source shortest path [13]

Given a weighted digraph G = (V, E), where the weight of each edge is a nonnegative real number. The mission is to calculate the shortest path length from a point V_0 (source point) of V to all other vertices and the path length is the sum of the weight of each edge on the path.

Algorithm idea: assume S is the terminal set of the known nodes on the shortest paths, if $V_0 \in S$ initially and its shortest path length is 0, then expand S step by step based on greedy selection. In V-S, select the terminal node x of the shortest path with the minimum path length to join S each time.

Construction principles: for constructing the shortest path with the shortest length, each path must have the minimum length. If i shortest paths have been constructed, the next joining point u must be the end point with the minimum path length in V-S and its length is either an arc (V_0, u) or the middle path that only passes through the vertexes in S and finally reaches u.

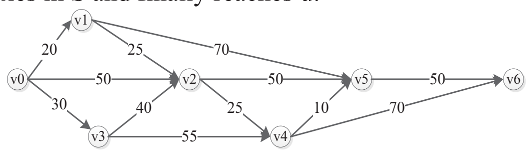

Fig. 1: Single source shortest path example

Figure 1 is an example of single source shortest path. Based on the construction principles of GM, the shortest paths execution traces from the single source node V_0 to each destination node are shown in Table 1.

Table 1: Shortest-paths execution trace

Iteration	Node	S	DIST							Shortest Paths
			0	1	2	3	4	5	6	
Value	--	0	0	20	50	30	∞	∞	∞	v0-v1, v0-v2, v0-v3
1	1	0,1	0	20	45	30	∞	90	∞	v0-v1, v0-v1-v2, v0-v3, v0-v1-v5
2	2	0,1,3	0	20	45	30	85	90	∞	v0-v1, v0-v1-v2, v0-v3, v0-v3-v4, v0-v1-v5
3	3	0,1,3,2	0	20	45	30	70	90	∞	v0-v1, v0-v1-v2, v0-v3, v0-v1-v2-v4, v0-v1-v5
4	4	0,1,3,2,4	0	20	45	30	70	80	140	v0-v1, v0-v1-v2, v0-v3, v0-v1-v2-v4, v0-v1-v2-v4-v5, v0-v1-v2-v4-v6
5	5	0,1,3,2,4,5	0	20	45	30	70	80	130	v0-v1, v0-v1-v2, v0-v3, v0-v1-v2-v4, v0-v1-v2-v4-v5, v0-v1-v2-v4-v5-v6

For the construction of wireless sensor network backbone, each backbone node can be seemed as a single source starting node, and BS and the backbone nodes above the same level can be the destination nodes by establishing the shortest path routing table based on greedy algorithm. The rules are that the backbone nodes firstly will select the shortest path in the routing table when it transmits information upward, and it can select the secondary shortest path in turn to communicate when there are nodes consuming too much and alarming in the current path, which not only keeps the stability of the backbone network, but also avoids a lot of cost caused by frequent network topology updates.

3 TA-GSP

3.1 Network Model

For easy to discuss, the network model of TA-GSP is assumed as follows:

i. It is assumed that the network is static and each cluster member is identical in the configuration of hardware and software, where the network size is N and there are four types of nodes: base station, backbone node, cluster head and common node. The topology structure of WSN designed for TA-GSP is shown in the Figure 2.

ii. It is assumed that BS is equipped with enough hardware and software resources.

iii. The backbone nodes are responsible for transferring the messages from cluster heads to BS along the backbone network. In addition, the backbone nodes can adjust their transmitting power based on the distance of each pair neighbor backbone nodes.

iv. The cluster head are responsible for collecting the data from its members and sending it to the nearest backbone node.

v. The common nodes are responsible for collecting the surrounding environment data and sending the data to their cluster head.

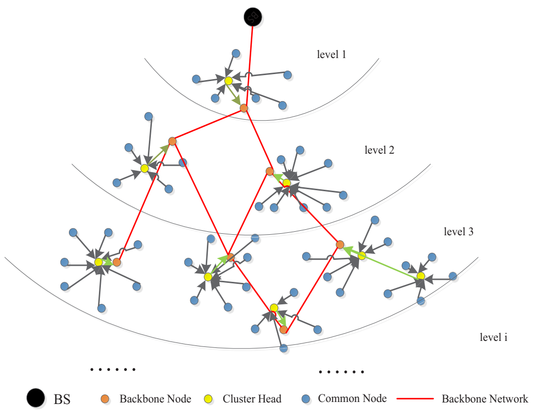

Fig. 2: The topology structure of WSN designed for TA-GSP

3.2 Topology Constructing

(1) Construction of Network Level

Firstly, in the initialization stage of network, BS actively broadcasts the network level construction messages including BS ID and network level, and assumes that the transmission power of BS and common nodes is the same.

$$L_{broadcast} = \{ID_{BS}, l_0 = 0\} \tag{1}$$

Secondly, the neighbor nodes of BS records itself as the first level nodes after receiving $L_{broadcast}$, i.e. level 1, and broadcast down the modified network level construction messages.

$$L_{broadcast} = \{ID_{BS}, l_1 = 1\} \tag{2}$$

Last, if the subsequent nodes receive multiple network level construction messages, selecting the one with the smallest level and adding 1 to the level, i.e. $l_i = l_{i\text{-}1} + 1$, and each network node can belong to the different network level, as shown in Figure 2.

(2) Selection of Backbone Nodes

After the network level is constructed, it is time to select the backbone nodes and construct the backbone network paths. As mentioned before, the biggest difference between TA-GSP and traditional topology schemes is to separate the function of backbone nodes and cluster heads independently, so the main work is to define the selection method of backbone nodes and the route selection method of backbone network paths.

The weight calculation method of backbone nodes is defined as:

$$\text{weight}_1 = \text{a} * \text{degree} + (1 - \text{a}) * \text{energy} \tag{3}$$

degree represents the connectivity of nodes that is the number of neighbor nodes in a hop. The more connectivity the node is, the closer the connection with the neighbor nodes is, it also shows that there are more nodes covering the same area, so that taking the nodes with larger connectivity as the backbone nodes do not affect the monitoring work of the coverage area. Therefore, *degree* as a weight factor can reduce the size of the backbone network, so that as many nodes as possible in the sleep state. In addition, it can get a relatively stable backbone network which is suitable for the network with high stability requirements.

energy represents the residual energy of the node, choosing the *energy* as the weight factor of the backbone nodes selection can make the nodes with more energy enter the backbone network first.

$\text{a} \in [0,1]$, if a = 0, the weight is equal to the energy of the node, and if a = 1, the weight is equal to the connectivity of the node. In different network situation, the best value of a is different, and the best value is related to the global characteristics of the network. Usually, it cannot get the best value of a with only the local information, and the value of a should be determined according to the results of simulation or experiments.

(3) Construction of Backbone Network

Firstly, defining the calculation method of backbone paths weight.

In this paper, the backbone nodes are relatively more stable and durable compared with the cluster heads and common nodes. In order to keep the backbone nodes' life longer, it is assumed that the power of the backbone nodes can be adjusted. It is shown in some literature [1-3] that the energy consumption of the node transmitting is directly proportional to the exponent of transmitting distance (usually the exponent is greater than 2), so that the node with a long distance has a relatively short life.

Based on the above analysis, in order to construct the shortest communication paths, it is necessary to set the consumption weight of each path in the backbone network.

$$\text{weight}_2 = \text{kd}^x, (x \geq 2) \quad (4)$$

weight$_2$ is the weight of backbone network path, i.e. the backbone network edge weight in graph G = (V, E) (the value of red line in Figure 2), *k* is the proportion coefficient, *d* is the distance between adjacent backbone nodes, x is the consumption index, usually x = 3.

For the network with clear coordinates, the distance *d* can be calculated by the coordinates of the backbone nodes.

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (5)$$

Where *d* is the calculated distance (in m), (x1, y1) and (x2, y2) are the coordinates of the adjacent backbone nodes.

For the temporarily spread WSN network, *d* can be calculated by RSSI.

$$d = 10^{\wedge}\left((|RSSI| - A)/(10 * n)\right) \quad (6)$$

Where RSSI represents the received signal strength indication (in dbm), A is the signal strength at 1m between the transmitting end and the receiving end, *n* is the environment attenuation factor, A and n can be set as constants in a specific experimental environment.

Secondly, greedy shortest paths construction method.

According to the first step work of backbone nodes weights calculation, the nodes with better connectivity and residual energy are selected as backbone nodes, and the weight of each path is calculated according to the weight calculation method of backbone network paths in this step.

Since lack of energy in WSN, this paper can construct a single source shortest path method based on GM to build a communication routing table for each backbone node (as shown in Figure 1 and Table 1).

After the routing table is built, the backbone nodes will select the shortest path in the routing table to transmit the information upward. At the same time, it can select the secondary shortest path in turn for communication when there are nodes consuming too much in the current shortest path and alarming.

The pseudo program of greedy shortest paths construction is as follows:

```
INPUT: G= (V, E), V= {1, 2, ..., n}.
OUTPUT: distance from vertex 1 to other vertices in G.
INITIALIZATION: X= {1}; Y←V- {1}; λ [1] ←0.
   for y←2 to n
      if y is the neighbor of 1, then λ[y]←distance [1, y].
        else λ[y]←∞.
      end if
   end for
   for j←1 to n-1
      let y∈Y, making λ[y] is the minimum distance.
         X←X∪{y} {add vertex y to X.}
         Y←Y∪{y} {delete vertex y from Y.}
      for edge (y, m)
         if w∈Y and λ[y]+distance [y, m]<λ[w],
              then λ[w]←λ[y]+distance [y, m],
         end for
 end for
```

In addition, most of the nodes are responsible for maintaining the network connectivity when the network density is low or there are some areas with sparse density in the network. For situation, these nodes are all backbone nodes and the number of their neighbor nodes is small, so there are not more suitable nodes to replace them as the backbone nodes, the backbone nodes are allowed to have the responsibility of cluster heads at this time.

(4) Selection of Cluster Head

At present, the research of WSN cluster topology is based on the cluster heads election mechanism. After the cluster head nodes is elected, other nodes will join the clusters according to certain rules. When some cluster head node energy is insufficient, some strategies are taken to reorganize the cluster. The defects of these schemes are also obvious: 1) the cluster heads is the same as the backbone nodes which will cause the energy of the cluster heads to be exhausted quickly; 2) frequent replacement of cluster heads to maintain the network connection is not conducive to the stable operation of the network topology, which increases the burden of the whole network.

As mentioned before, the biggest difference between TA-GSP and traditional topology schemes is to separate the functions of backbone nodes and cluster heads independently. Cluster heads are only responsible for collecting and processing data which will be handed over to the backbone node nearby for transmission, and the backbone nodes will transmit data according to the greedy shortest paths principle (as the green paths shown in Figure 2). Therefore, the advantages of TA-GSP are that the transmission network structure is stable and the burden is less, and the cluster heads are only responsible for transferring the processed data to the backbone network.

For easy to discuss, LEACH protocol is selected for selecting the cluster heads.

Assume that each common sensor node generates a random number between 0 and 1, and it will be the cluster head if some random number is less than a certain threshold value $T(n)$.

$$T(n) = \begin{cases} 1 - p[r \bmod (\frac{1}{p})] & n \in G \\ 0 & else \end{cases} \quad (7)$$

Where, p is the percentage of desired cluster head nodes, r is the round, G is the common sensor nodes set in last $1/p$ round.

According to LEACH protocol, the non-backbone nodes have a certain probability to act as the cluster heads which will broadcast identity information after selected as the cluster heads. Then, the neighbor nodes will decide to join which cluster according to RSSI and inform the cluster heads.

There is a special case that a remote border node may fail to receive the broadcast signal from the cluster head. For such situation, it only needs to send the monitoring data to the neighbor node with strong signal which will send it to the cluster head for processing, which means that the neighbor node is its default cluster head and this special cluster head is not responsible for processing the data, which can ensure network coverage and connectivity.

Figure 3 is the flow chart of TA-GSP scheme.

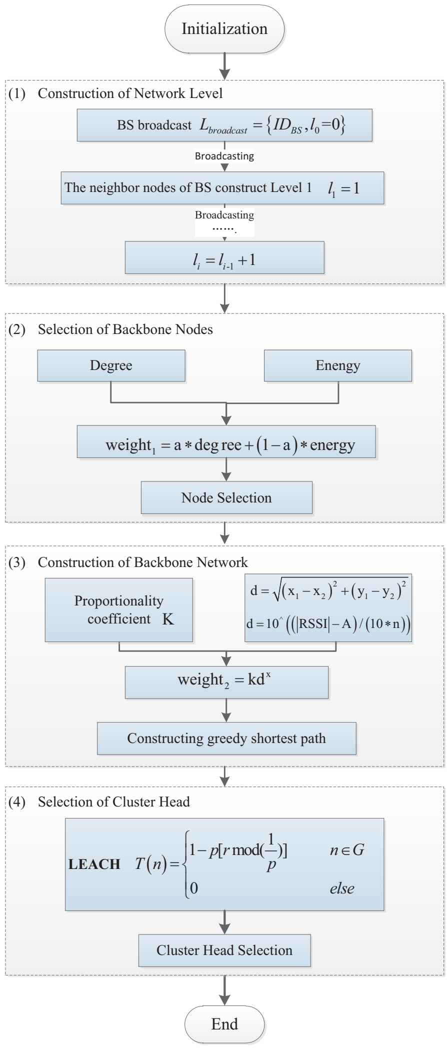

Fig.3: The flow chart of TA-GSP scheme

4 Analysis

(1) Constructing the shortest-path routing table

For the backbone communication routing in Figure 2, the shortest paths routing table is created based on GM. For easy to discuss, it is assumed that the communication radius of common WSN nodes is 50m, while the transmission power of backbone nodes is adjustable and the maximum communication radius of backbone nodes is 50m. For path weight calculation $\text{weight}_2 = kd^x, (x \geq 2)$, assume k = 1, x = 2, $\text{weight}_2 = d^2$. If the distance d is calculated according to RSSI value, the paths' weights of backbone network is shown in Figure 4, and the shortest path routing table of each backbone node is shown in Table 2.

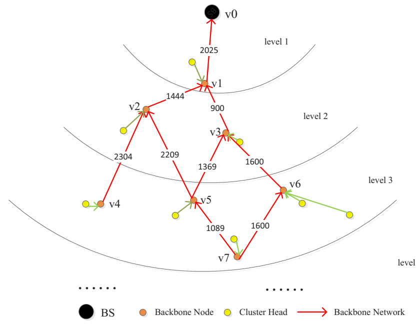

Fig. 4: Backbone path weights

As shown in Table 2, there are multiple paths of v5 and v6. According to the greedy principle, v5 and v6 will select the first shortest path as the backbone transmission path, and the next path will be selected automatically when the energy consumption of current path exceeds the alarming line.

(2) Comparing the energy consumption

WSN energy consumption modules mainly include sensor module, processor module and wireless communication module. With the development of integrated technology, the power consumption of processor and sensor has reached a satisfactory level, so the energy consumption is mainly focused on the wireless communication module. In the communication process, sensor nodes have four states: sending, idle, receiving and sleep. When the node is in the sending state, the energy consumption is the most, the consumption of receiving state and idle state is nearly equal which is slightly less than the sending State (about 0.7-0.8 times of the power consumption of the sending), and the energy consumption in the sleeping state is the least.

In order to simplify the problem, this paper does not consider the actual node energy consumption model and will roughly compare the one round power consumption f1 and f2 between TA-GSP and LEACH. Assume that the network size is N, the number of cluster heads in both schemes is x, the number of backbone nodes in TA-GSP is y, the consumption of common node sending status is A, the consumption of receiving status is 0.7A, and the network level is same. So,

$$f_1 = (N-1-x)*A + (N-1-x)*0.7A + (N-1-x)*\text{level}*1.7A \quad (8)$$

$$f_2 = (N-1-x\text{-}y)*A + (N-1-x\text{-}y)*0.7A + x*A + x*0.7A + y*\text{level}*A \quad (9)$$

Table2: Shortest-paths routing table

Node	DIST 0	1	2	3	4	5	6	7	Shortest Paths
1	2025	0	∞	∞	∞	∞	∞	∞	v1-v0
2	3469	1444	0	∞	∞	∞	∞	∞	v2-v1-v0
3	2925	900	∞	0	∞	∞	∞	∞	v3-v1-v0
4	5773	3748	2304	∞	0	∞	∞	∞	v4-v2-v1-v0
5	4294	2269	2209	1369	∞	0	∞	∞	(1) v5-v3-v1-v0 (2) v5-v2-v1-v0
6	4525	2500	1600	30	∞	∞	0	∞	v6-v3-v1-v0
7	5383	3358	3298	2458	∞	1089	1600	0	(1) v7-v5-v3-v1-v0 (2) v7-v6-v3-v1-v0 (3) v7-v5-v2-v1-v0

For f1, N-1-x is the number of common nodes of LEACH, (N-1-x) * A + (N-1-x) * 0.7A is the consumption of sending information by common nodes and receiving information by cluster heads, (N-1-x) * level * 1.7A is the consumption of sending and receiving information by cluster heads, level is the average number of sending and receiving times between cluster heads, and 1.7A = 1A + 0.7A is the consumption of sending and receiving information once time between cluster heads.

For f2, N-1-x-y is the number of common nodes of TA-GSP, (N-1-x-y) * A + (N-1-x-y) * 0.7A is the consumption of information sent once by common nodes and received by cluster heads, X * a + X * 0.7A is the consumption of the processed information sent to backbone nodes by cluster heads and received by backbone nodes, y * level * A is the consumption of information sent and received between backbone nodes, level is the average number of sending and receiving times between backbone nodes, A = 0.5A + 0.5A is the consumption of sending and receiving information once time between backbone nodes (assume that the power consumption of the backbone nodes is adjustable and the average communication distance is about 2 / 3 radius).

According to the specific settings in Figure 2, assuming N = 1000, x = 8, y = 7, A = 10, level = 6, one round of communication consumption comparison between the two schemes is shown in Figure 5, where the consumption of common nodes of these two schemes is equivalent, but the consumption of the cluster head nodes and the network in TA-GSP is far less than that of LEACH. Although the calculation is not very precise, the power consumption advantage of TA-GSP is obvious, which can greatly improve the life of cluster heads and the network.

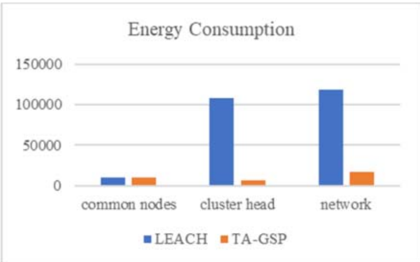

Fig. 5: Comparison of one round energy consumption

5 Conclusion

The main research of WSN topology control is to extend the average life of the network as much as possible ensuring the connectivity and coverage of the network. As the high-frequency communication nodes, the energy problem of cluster heads have always been the bottleneck of network performance. Therefore, this paper proposed a WSN topology algorithm based on greedy shortest paths (TA-GSP), in which the scheme selected the backbone nodes of the network, built the backbone network to transmit network data, allowed the backbone nodes and cluster heads to exist in same network, and the cluster heads were responsible for collecting and compressing its data of the cluster. In addition, the backbone nodes built a single source shortest path routing table based on the greedy algorithm and selected the most suitable shortest path to transmit data according to the consumption of the backbone nodes. TA-GSP scheme has more stable transmission network structure, less burden, less reconstruction frequency and lower requirements for cluster head selection method, and the cluster heads are only responsible for transferring the processed data to the backbone network.

The research focus of TA-GSP is to design the rationality of the network backbone communication path, which do not consider the method of cluster head selection in detail. So, the next work can be combined with related optimization algorithms of the cluster heads, and further rationalize this scheme.

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