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# An Improved Directed Diffusion Routing in Wireless Sensor Networks

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**Abstract:** In order to bring the potential advantages of directed diffusion routing into full play in wireless sensor networks, the minimum hop routing (MHR) protocol based on directed diffusion is improved, and the MLN (MHR based on Lowest Level Neighbors) routing protocol is presented. In the MLN, by limiting the gradient level width of directed diffusion gradient field, the connectivity of logical topology in wireless sensor networks is enhanced, so that the reliability of data aggregation is improved. At the same time, by changing the data-packet forwarding rule of hop-by-hop in the MHR to the rule of data-packet being priority forwarded by the lowest-level neighbors in the MLN, the real-time performance and the energy efficiency of data aggregation are improved on the premise of high data aggregation reliability. The theoretical analysis and simulation results validate that the MLN routing protocol not only enhances the connectivity, but also improves the comprehensive performances of directed diffusion routing in wireless sensor networks.

**Keywords:** Wireless Sensor Networks, Directed Diffusion, Gradient Level Width, Connectivity, Network Performance

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## 1. Introduction

Information sensing, information transportation, information processing and information application are the main tasks of wireless sensor networks (WSN), and among them, the information transportation is the bottleneck hindering the large scale practical application of wireless sensor networks. Due to the particularity of the application mode, the behavior of information transportation has directional characteristics in wireless sensor networks [1]. The Directed Diffusion (DD) routing protocol not only adapts to the directional characteristics of information transportation, but also has the potential advantages of the shortest path, the minimum time delay and the minimum energy consumption [2], so it is considered as the milestone of the research on wireless sensor networks. The directed diffusion routing protocol based on hop, namely the Minimum Hop Routing (MHR) protocol is the typical example of DD protocols, but

its potential advantages have not been brought into full play because of some defects, so it has not been massively popularized and applied in wireless sensor networks up to now. Through the analysis of MHR protocol in wireless sensor networks, it is found that the actual wireless sensor networks are often heterogeneous, and the defects are found to be mainly in the following two aspects. One of them is that the stable period of directed diffusion gradient field (DDGF) is short because of the network's fast changing physical topology, so the real-time connectivity of network's logic topology is very poor, and the reliability of information transportation is very poor, too. The other of them is that the routing controlling granularity is too coarse, so that there exist the situations of high degree of repeated information transportation and large instantaneous data volume, this does not adapt to the wireless sensor network's characteristics of strictly limited resources and sharing contention channel, and influences the lifecycle of network and the real-time performance of information

transportation [3]. The traditional directed diffusion routing protocol MHR should be improved because of the above defects restricting the potential advantages to be taken into full play in wireless sensor networks.

The rest of this paper is organized as follows. The sect. 2 introduces the related works, the sect. 3 describes the MLN network model and performance improvement analysis, the sect. 4 gives the simulation analysis, and the sect. 5 concludes the whole paper.

## 2. Related Works

The literature [2] put forward a directed diffusion routing protocol based on directed diffusion gradient value of hop in wireless sensor networks, namely MHR protocol. The MHR protocol divides its running process into two stages. The first stage is the query-packet delivery phase initiated by the SINK node (the data collection node, namely the gateway node), and the other stage is the data-packet delivery phase from some one source node to the SINK. The directed diffusion gradient field based on hop is set up hop-by-hop in the query-packet delivery phase, and then the demanded data-packet is aggregated to the SINK node hop-by-hop through the directed diffusion gradient field set up in the stage of query-packet delivery. The behavior characteristics of the traditional MHR network are analyzed in the literature [3]. The literature [4] analyzes the defects of the traditional MHR network, and finds that the data flow in the different gradient levels is extremely non-uniform when the source node with different geometric distance to the SINK. When a source node is near to the inner boundary of a gradient level, the number of data-packet copies is large, so the energy efficiency of data aggregation is poor, and the real-time performance of data aggregation also is poor because the channel contention leads to the information collision. However, when a source node is near to the outer boundary of a gradient level, the number of data-packet copies is rare, and the node which meets the conditions of data-packet receiving and forwarding often locates in the transition region of a wireless communication channel [5], this leads to poor link quality, so the reliability of data aggregation is very poor, and the phenomenon that the data-packet can't be successfully aggregated to the SINK often appears. The literature [6] presents a wireless sensor network's data gathering mechanism based on fine-grain gradient, namely FGS (Fine-grain Gradient Sinking mechanism). In the FGS network, the data-packet is not aggregated according to the gradient value of hop, but according to the fine-grain gradient value, so the aggregation of data-packet occurs almost only between the nearest neighbors, and the advancing distance per step almost only equals the average node spacing, so the reliability of data aggregation is high. But the hop number of data aggregation in FGS is too more, and the time delay of data aggregation is too large. The literatures [7-11] study the connectivity based on topology control in wireless sensor networks, but the influence of the specific routing rule on connectivity is not considered. The literature [12] discusses the method of congestion control for directed diffusion routing

based on cross layer optimization, but lacks of concrete measures to improve the network congestion and time delay.

In this paper, the traditional MHR protocol is improved, and the MLN (MHR based on Lowest Level Neighbors) protocol is presented. Firstly, the connectivity problem of the directed diffusion routing wireless sensor networks is solved, then the refinement of routing controlling granularity is discussed and solved. All these works aim to gradually overcome the defects of traditional directed diffusion routing protocol, optimize the network's comprehensive performances, and promote the large-scale practical application of directed diffusion wireless sensor networks.

## 3. MLN Network Model and Performance Improvement Analysis

### 3.1. Directed Diffusion Gradient Field of the MLN Network

In the MHR network, the reliability of data aggregation is closely related to the gradient level width of directed diffusion gradient field, and the data aggregation may be not reliable if the gradient level width is wider than the effective communication radius of the node locating near the outer border in the someone gradient level. For the convenience of description, a two-dimensional serial number  $(i, j)$  is assigned to each node in the network, and among them, the serial number of the SINK node is specified as  $(0, 0)$ . Considering the discrete distribution characteristics of nodes, some signs are introduced in this paper. Among them,  $R(i, j)$  represents the actual communication radius of node  $(i, j)$ ,  $R_e(i, j)$  represents the effective communication radius of node  $(i, j)$ , and  $K_G (K_G \leq 1)$  represents the average gradient level width coefficient for limiting the gradient level width of directed diffusion gradient field in wireless sensor networks.

The model of directed diffusion gradient field is related to the directed diffusion gradient value  $H(i, j)$  of node in the network, and the setting up process of DDGF is just the process that each node  $(i, j)$  obtains its directed diffusion gradient value  $H(i, j)$ . Before the directed diffusion gradient field is set up, the directed diffusion gradient value of the SINK is assigned as  $H(0, 0) = 0$  and the others are assigned as  $H(i, j) = \infty$ . The setting up process of directed diffusion gradient field is started with the SINK transmitting the query-packet, and then the subsequent neighbor nodes join into the directed diffusion gradient field hop-by-hop in the direction of the directed diffusion gradient value  $H(i, j)$  increasing by one. In order to improve the reliability of data aggregation in wireless sensor networks, the MLN network limits the gradient level width of its directed diffusion gradient field, and assigns the gradient level width coefficient as  $K_G < 1$ , this can be conveniently realized by limiting each-node's transmitting power in the setting up process of directed diffusion gradient field, namely, the actually used communication radius of node  $(i, j)$  equals to  $K_G * R(i, j)$  when the node  $(i, j)$  transmits the query-packet. The setting up process of DDGF is started with SINK transmitting the query-packet. After the subsequent node  $(i, j)$  has received the

query-packet and updated its directed diffusion gradient value  $H(i, j)$ , the node  $(i, j)$  updates the query-packet with the new  $H(i, j)$  and forwards the query-packet with  $K_G * R(i, j)$  as the transmitting radius, then the node  $(i', j')$  in the coverage area of node  $(i, j)$ 's transmitting radius  $K_G * R(i, j)$  updates its directed diffusion gradient value  $H(i', j')$  and forwards the query-packet according to the formula (1) if the conditions are satisfied, otherwise doesn't change its  $H(i', j')$  and discards the query-packet.

$$H(i', j') = H(i, j) + 1, \text{ if } d_{(i,j)}(i', j') \leq K_G * R(i, j)$$

and

$$H(i', j') > H(i, j) + 1 \quad (1)$$

Among them, the  $d_{(i,j)}(i', j')$  represents the geometric distance from the node  $(i', j')$  to the node  $(i, j)$ .

But in the MHR network, the gradient level width coefficient is assigned as  $K_G = 1$ , namely, the updating rule of the directed diffusion gradient value of node  $(i', j')$  follows the formula (2).

$$H(i', j') = H(i, j) + 1, \text{ if } d_{(i,j)}(i', j') \leq R(i, j)$$

and

$$H(i', j') > H(i, j) + 1 \quad (2)$$

The model of DDGF looks like a series of concentric circles taking the SINK node as the center as shown in the Figure 1. The concentric circles in the Figure 1 (a) represent the directed diffusion gradient field of the MHR network, and the concentric circles in the Figure 1 (b) and the Figure 1 (c) represent the directed diffusion gradient field of the MLN network. From the graph, the number of gradient levels is corresponding increased after the gradient level width has been limited in the MLN network.

### 3.2. Data Aggregation in the MLN Network

Compared with the MHR network, the data aggregation model of the MLN network is improved mainly in the following three aspects.

1) In the MLN network, although the transmitting power of node is restricted to limit the gradient level width in the setting up process of directed diffusion gradient field, but in order to ensure the reliability of data aggregation, the full power of each node is used in the process of data aggregation.

Theorem 1: After limiting the gradient level width, the coverage areas of the nodes which participate in the data-packet forwarding become larger than the full gradient level width when the same source node aggregates the data-packet.

Proof: Assumed that the geometric distance from the source node  $(i_s, j_s)$  to the SINK is  $d_{\text{SINK}}(i_s, j_s)$ , the full gradient level width of directed diffusion gradient field  $F_1$  is  $W_1$ , and the limited gradient level width of directed diffusion gradient field  $F_2$  is  $W_2$ , moreover there is  $W_1 > W_2$ .

In the directed diffusion gradient field  $F_1$ , the directed

diffusion gradient value of the source node  $(i_s, j_s)$  can be estimated as  $H_1(i_s, j_s) \approx d_{\text{SINK}}(i_s, j_s) / W_1$ , the node  $(i, j)$  which participates in forwarding the data-packet should satisfy the condition  $d_{\text{SINK}}(i, j) + d_{(i_s, j_s)}(i, j) \leq H_1(i_s, j_s) * R$  ( $R$  is the average communication radius of nodes), namely the data-packet forwarding nodes locate in the ellipse region with  $C_1 = 2H_1(i_s, j_s) * R - d_{\text{SINK}}(i_s, j_s)$  as the long axis,  $D_1 = \sqrt{(H_1(i_s, j_s) * R)^2 - (d_{\text{SINK}}(i_s, j_s))^2} / 2$  as the short axis, and the SINK node and the source node  $(i_s, j_s)$  as the focuses.

However, in the directed diffusion gradient field  $F_2$ , the directed diffusion gradient value of source node  $(i_s, j_s)$  can be estimated as  $H_2(i_s, j_s) \approx d_{\text{SINK}}(i_s, j_s) / W_2$ , the node  $(i, j)$  which participates in forwarding the data-packet should satisfy the condition  $d_{\text{SINK}}(i, j) + d_{(i_s, j_s)}(i, j) \leq H_2(i_s, j_s) * R$ , namely the forwarding nodes locate in the ellipse region with  $C_2 = 2H_2(i_s, j_s) * R - d_{\text{SINK}}(i_s, j_s)$  as the long axis,  $D_2 = \sqrt{(H_2(i_s, j_s) * R)^2 - (d_{\text{SINK}}(i_s, j_s))^2} / 2$  as the short axis, and the SINK node and the source node  $(i_s, j_s)$  as the focuses.

Because of  $W_1 > W_2$ , leading to  $H_1(i_s, j_s) < H_2(i_s, j_s)$ ,  $C_1 < C_2$ , and  $D_1 < D_2$ , at the same time, the focuses of the two ellipses, namely the SINK node and the source node  $(i_s, j_s)$ , are the same. So the region area of forwarding nodes in  $F_2$  contains the region area of forwarding nodes in  $F_1$ , namely the region area of forwarding nodes in  $F_2$  is larger.

The theorem is proved.

According to the theorem 1, the nodes' coverage area is increased after limiting the gradient level width of directed diffusion gradient field, so as that the reliability of data aggregation is improved.

2) The data-packet forwarding rule of the MHR protocol is modified in order that nodes can participate in forwarding the data-packet reliably as much as possible. By the Theorem 1, limiting gradient level width increases the coverage area of the data-packet forwarding nodes and improves the reliability of data aggregation. But the routing rule in the MHR network requires that only the neighbor nodes with the lower directed diffusion gradient value by one can receive and forward the data-packet, namely hop-by-hop forwarding rule, so if the gradient level width is too narrow, the number of nodes which participate in forwarding the data-packet may be decreased on the contrary, and the reliability of data aggregation may be even worse in some cases. In order to ensure high reliability of data aggregation, the data-packet forwarding rule of the MHR protocol is modified to allow all the neighbor nodes in the lower gradient levels to participate in forwarding the data-packet in the MLN network, namely low-hop forwarding rule. In low-hop forwarding rule, when node  $(i, j)$  transmits or forwards the data-packet, if the node  $(i', j')$  is in the coverage area of node  $(i, j)$ 's communication radius and satisfies the conditions in the Formula (3), the node  $(i', j')$  is allowed to receive and forward the data-packet. The data-packet forwarding label of node  $(i', j')$  in the MLN network is marked as follows.

$$H_D(i', j') = 1, \text{ if } d_{(i,j)}(i', j') \leq R(i, j)$$

and

$$H(i', j') \leq H(i, j) - 1 \quad (3)$$

But the data-packet forwarding rule in the MHR network is described as the Formula (4).

$$H_D(i', j') = 1, \text{ if } d_{(i,j)}(i', j') \leq R(i, j)$$

and

$$H(i', j') = H(i, j) - 1 \quad (4)$$

3) In the premise of ensuring the reliable delivery of data-packet, the number of data-packet copies should be reduced to decrease the collision probability. If the nodes satisfying the forwarding rule are more, the reliability of data aggregation is higher. But if the forwarding nodes are too more, not only the energy consumption is larger, but also the time delay of data aggregation resulted from higher collision probability is larger, and this influences the network's comprehensive performances. In order to optimize the network's comprehensive performances in the premise of ensuring the reliability of data aggregation, only the neighbor nodes satisfying the low-hop forwarding rule and in the lowest hop gradient level are allowed to forward the data-packet preferentially, namely lowest-hop-forwarding rule. At the same time, the forwarding behavior of the subsequent nodes in other gradient levels is cancelled if the data packet has been forwarded successfully. In the ideal case, the lowest-hop-forwarding rule is described as the Formula (5).

$$H_D(i', j') = 1, \text{ if } d_{(i,j)}(i', j') \leq R(i, j)$$

and

$$H(i', j') = \min\{H(i, j)\} \quad (5)$$

The differences between the MHR network and the MLN network are shown in the Figure 1 (a) ~ Figure 1 (b). The Figure 1 (a) is for the traditional MHR network, in the figure, the directed diffusion gradient value of the source node 'source' is marked as 'h4', when node 'source' transmits data-packet, the nodes with the directed diffusion gradient value 'h3' and in the coverage area of node 'source' can participate in receiving and forwarding the data-packet, and the receiving and forwarding region is marked as vertical-line shadow in the Figure 1 (a). The Figure 1 (b) is for the MHR network with the limited gradient level width, in the figure, the directed diffusion gradient value of node 'source' is increased to 'h7' because the gradient level width is decreased. When node 'source' transmits data-packet, the nodes with the directed diffusion gradient value 'h6' and in the coverage area of node 'source' can participate in receiving and forwarding the data-packet, and the receiving and forwarding region is marked as vertical-line shadow in the Figure 1 (b). The Figure 1(c) is for the MLN network, in the figure, the directed diffusion gradient value of node 'source' is increased to 'h7' because the gradient level width is decreased to the same with the Figure 1 (b). When node 'source' transmits data-packet, the nodes with the directed diffusion gradient value 'h6' or 'h5' and in the coverage area of node 'source' can participate in

receiving and forwarding the data-packet if according to the low-hop forwarding rule, and the potential receiving and forwarding region is marked as vertical-line shadow in the Figure 1 (c), however if according to the lowest-hop-forwarding rule, only the neighbor nodes in the 'h5' gradient level can receive and forward the data-packet preferentially, namely the nodes in the grid shadow area in the Figure 1 (c) can receive and forward the data-packet preferentially, and the forwarding behavior of the nodes in the 'h6' gradient level may be cancelled if the data packet has been successfully delivered.

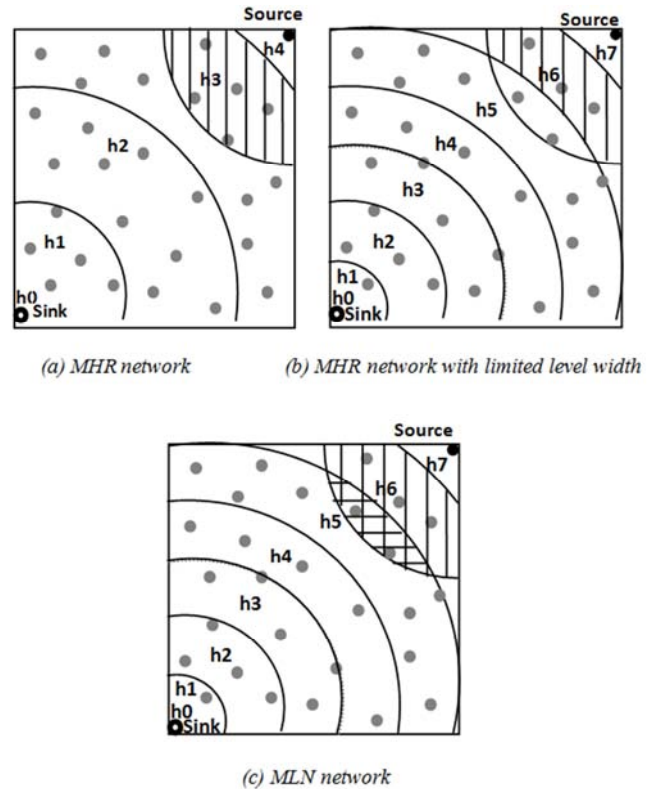


Figure 1. MHR network and MLN network.

### 3.3. Analysis of Network's Performance Improvement

For someone node, the gradient situations of the neighbors under its rated power communication radius is different with the full gradient level width after the gradient level width of directed diffusion gradient field is limited. If the directed diffusion gradient value of someone node is 'h', then its low-level-end neighbors may be located in the gradient levels from 'h-1' to 'h-L', and the 'L' is the number of its low-level-end gradient levels covered by the 'one hop' communication radius of the node. The 'L' is adaptively generated in the setting up process of directed diffusion gradient field, and generally larger than one. The logical topology with limited gradient level width can guarantee that the node has enough reliable low-level-end neighbors, and can reduce the breakage of data aggregation links resulted from the asymmetry of effective communication radius, node energy attenuation and node slowly moving, so that it can improve the reliability of data aggregation. But the

transmitting power to establish the directed diffusion gradient field can't be too small, otherwise the downlink inaccessible phenomenon of query-packet appears, and isolated nodes come into being. For the source node with the directed diffusion gradient value of 'h', the neighbors in the 'h-1' gradient level are allowed to receive and forward the data-packet in the MHR network. But in the MLN network, the neighbors in the gradient levels from 'h-L' to 'h-1' are allowed to receive and forward the data-packet, and the neighbors in the gradient level of 'h-L' are priority to receive and forward the data-packet, at the same time, the data-packet forwarding behavior of subsequent nodes in the gradient levels from 'h-L-1' to 'h-1' may be suppressed, so the data-packet may be needed to forward only by the neighbors locating in the gradient level of 'h-L'. Therefore in the MLN network, not only there are enough potential forwarding nodes, but also there are actual forwarding nodes as little as possible, and the hop count of data aggregation may be not increased. Compared with the MHR network, the MLN network's comprehensive performances are improved.

### 4. Simulation Analysis

The simulation scenarios are as follows. The network nodes are randomly distributed in the plane rectangular region of 300m\*300m according to the approximate uniform distribution model, the average communication radius  $R$  of nodes is equal to 50m, and the node density  $\xi$  of network is equal to 0.005/m<sup>2</sup>, the average node spacing  $d$  is equal to 15m, the dispersion coefficient of actual node's communication radius  $K_R$  is equal to 0.5, the average gradient level width coefficient  $K_G$  is equal to 0.1~1. The following three types of network with different data-packet forwarding rule are simulated.

1) The traditional MHR network with full gradient level width and adopting the hop-by-hop forwarding rule, marked as 'MHR'.

2) The network with the limited gradient level width and adopting the low-hop forwarding rule, marked as 'MHR+MLN'.

3) The network with the limited gradient level width and adopting the lowest-hop forwarding rule, marked as 'MLN'.

In the simulation, the uplink (marked as 'UP') number of node, the downlink (marked as 'DOWN') number of node, the hop number of data aggregation, and the number of

forwarding nodes in the process of data aggregation are compared. Among them, the number of uplinks and the number of downlinks are used to reflect the reliability of data aggregation, the hop number of data aggregation is used to reflect the real-time performance, and the number of forwarding nodes is used to reflect the energy consumption and the collision probability. The purposes of simulation are to compare the connectivity when different gradient level width utilized, and the improvement degree of network's comprehensive performances before and after the protocol is improved.

Because of the different environment in the different location or with the different energy for different node, the node's actual communication radius may be different. In the simulation, the actual communication radius of node  $(i, j)$  is random assigned as follows.

$$R(i, j) = R + K_R * R * (\text{rand}(0,1) - 0.5) \tag{6}$$

The smallest communication radius may be as follows.

$$R_{\text{MIN}} = R - 0.5 K_R * R \tag{7}$$

In order to limit the gradient level width, the employed communication radius of node  $(i, j)$  is as the formula (8) when it transmits the query-packet.

$$R_1(i, j) = K_G * R(i, j) \tag{8}$$

Then, the theoretically average gradient level width of directed diffusion gradient field is as follows.

$$W_F = K_G * R \tag{9}$$

In order to retain the potential advantages of the MHR network such as the shortest path and minimum time delay, the node's rated power is utilized when transmitting data-packet, so the actually utilized communication radius of node  $(i, j)$  when transmitting data-packet is as follows.

$$R_D(i, j) = R(i, j) \tag{10}$$

Due to the discreteness of node distribution, the average effective communication radius of nodes under rated power is estimated as follows.

$$R_S \approx R - d \tag{11}$$

The main results of simulation are shown in the table 1~2.

Table 1. The number of broken chain nodes and data aggregation hop.

gradient level width coefficient $K_G$	number of broken chain nodes			hop number of data aggregation	
	MHR-DOWN	MHR-UP	MLN-UP	MHR	MLN
0.1	440	441	431	0	0
0.2	440	441	431	0	0
0.3	440	441	431	0	0
0.4	5	6	1	0	0
0.5	0	1	1	20	10
0.6	0	1	1	17	13
0.7	0	3	3	14	14
0.8	0	13	13	12	12
0.9	0	34	34	10	10
1.0	0	55	55	10	10

Table 2. The number of logical links and data-forwarding nodes.

gradient level width coefficient $K_G$	number of node's average logical links				number of data-forwarding nodes	
	MHR-DOWN	MHR-UP	MHR+MLN-UP	MLN-UP	MHR	MLN
0.1	0	0	0	0	0	0
0.2	0	0	0	0	0	0
0.3	0	0	0	0	0	0
0.4	1.49	5.29	12.63	2.12	0	0
0.5	2.18	6.88	11.66	3.00	393	80
0.6	3.03	8.02	10.65	3.86	369	189
0.7	3.90	8.32	9.83	4.68	353	183
0.8	4.94	8.13	8.83	5.64	317	167
0.9	5.80	7.48	7.73	6.00	206	239
1.0	7.23	7.19	7.27	6.56	291	303

The Figure 2~Figure 7 are the figures of simulation results according to the table 1~2. The number of broken chain nodes under different gradient level width is shown in the Figure 2. According to the Figure 2, the number of broken chain nodes ( $N_{\text{MHR-DOWN}}/N_{\text{MHR-UP}}/N_{\text{MLN-UP}}$ ) is very large when the gradient level width coefficient is  $K_G < 0.3$ , this is because the target gradient level width is less than the average node spacing, namely the limited power to transmit the query-packet is too small and almost no node is in the coverage area in the setting-up process of directed diffusion gradient field, so almost all nodes have not been joined into the directed diffusion gradient field. The number of broken chain nodes ( $N_{\text{MHR-DOWN}}/N_{\text{MHR-UP}}/N_{\text{MLN-UP}}$ ) is very small when the gradient level width coefficient is  $0.3 < K_G < 0.7$ , this is because the target gradient level width is greater than the average node spacing and less than the average effective communication radius under the rated power. When the gradient level width coefficient is  $K_G > 0.7$ , the number of downstream broken chain nodes  $N_{\text{MHR-DOWN}}$  is kept small, but the number of upstream broken chain nodes  $N_{\text{MHR-UP}}/N_{\text{MLN-UP}}$  tends to increase, and this is because the target gradient level width is wider than the average effective communication radius under the rated power. It is obvious that the average gradient level width coefficient  $K_G$  should be valued in the range of  $d \sim R_c$  to reduce the broken chain nodes. At the same time, it is found that the number of broken chain nodes of the MLN network is no more than the MHR network, and the connectivity of the MLN network is better.

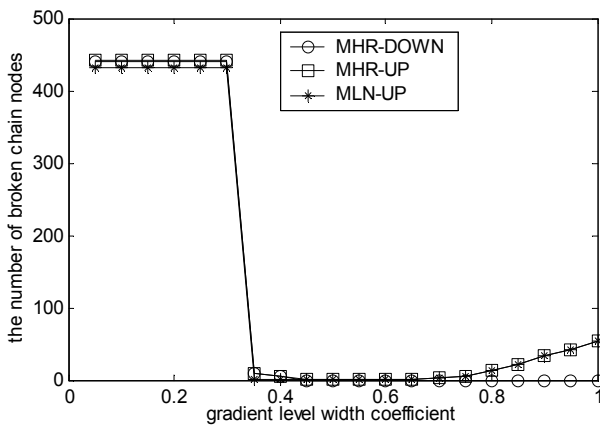


Figure 2. The number of broken chain nodes.

The average number of node's logical communication links under different gradient level width coefficient is shown in the Figure 3. According to the Figure 3, the average number of node's logical communication links ( $L_{\text{MHR-DOWN}}/L_{\text{MHR-UP}}/L_{\text{MLN+MHR-UP}}/L_{\text{MLN-UP}}$ ) almost is zero when the gradient level width coefficient is  $K_G < 0.3$ , this is because the target gradient level width is less than the average node spacing. When the gradient level width coefficient is  $K_G < 0.3$ , the average number of node's downstream links in the MHR network and the average number of node's upstream links in the MLN network are monotone increased with the increasing of the gradient level width coefficient  $K_G$ , and the average number of node's upstream links in the MHR network or in the MHR+MLN network is increased firstly and then decreased with the increasing of the gradient level width coefficient  $K_G$ . For the average number of upstream links, there are  $L_{\text{MLN+MHR-UP}} > L_{\text{MHR-UP}} > L_{\text{MLN-UP}}$  when the gradient level width coefficient is  $0.3 < K_G < 1$ , this shows that the number of node's potential upstream links is increased and the reliability of data aggregation is improved after the gradient level width is limited. When the gradient level width coefficient is limited to  $K_G = 1$ , the directed diffusion gradient field with full width gradient levels is set up, and the average number of upstream links in the MLN network or the MHR network is basically same,  $L_{\text{MHR-DOWN}} \approx L_{\text{MLN+MHR-UP}} \approx L_{\text{MHR-UP}} \approx L_{\text{MLN-UP}}$ .

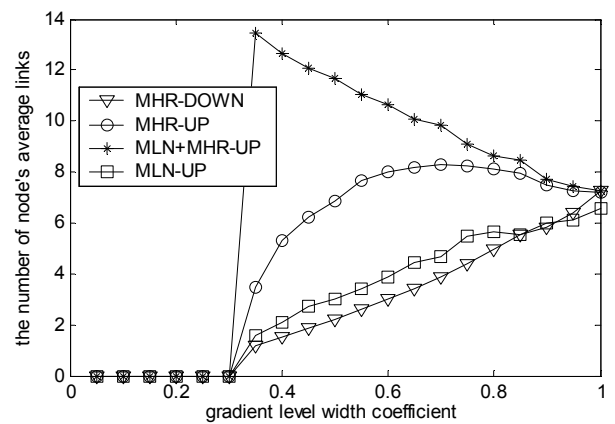


Figure 3. The number of node's average logical links.

The situation of data aggregating links of some one source node in the MHR network with the gradient level width coefficient  $K_G = 0.5$  is shown in the Figure 4. The

Figure 4 shows that the data aggregating links are enough to guarantee the high reliability of data aggregation when the gradient level width is properly limited, but this may lead to high energy consumption and high collision probability resulted from over repeated transmission of the data-packet.

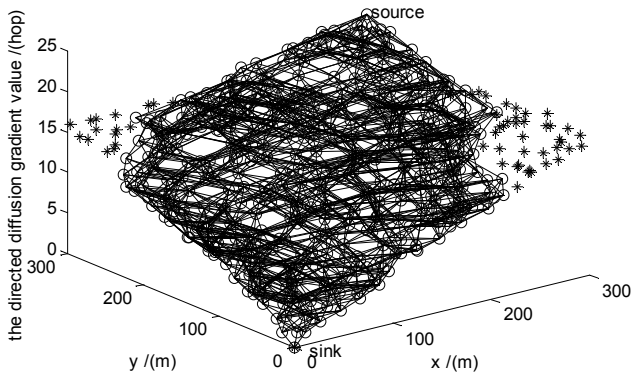


Figure 4. The data aggregating links in MHR network ( $K_G=0.5$ ).

The situation of data aggregating links of the same source node as above in the MLN network with the gradient level width coefficient  $K_G=0.5$  is shown in the Figure 5, compared with the MHR network shown in the Figure 4, the number of data aggregating links is significantly reduced, this indicates that the energy consumption and collision probability are decreased in the MLN network.

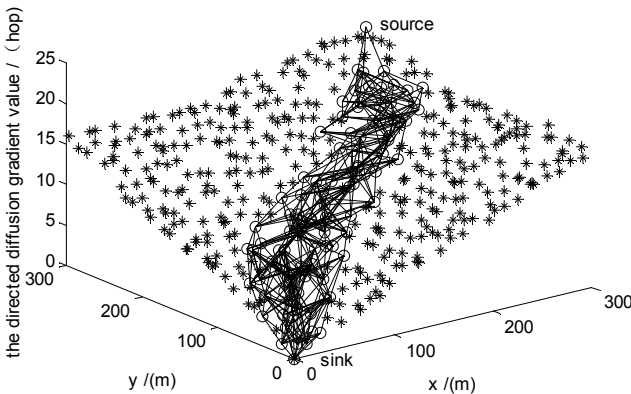


Figure 5. The data aggregating links in MLN network ( $K_G=0.5$ ).

The total hop number of data aggregation from the source node to the SINK node in the MHR network and the MLN network are respectively shown in the Figure 6. According to the Figure 6, we find that the data aggregating hops of the MLN network is less than the MHR network when the gradient level width is limited, this improves the real-time performance of data aggregation. However, compared with the traditional MHR network ( $K_G=1$ ), the total hop number of data aggregation of the MLN network ( $K_G<1$ ) may be slightly larger, this is because the gradient level width is limited, and just is the cost of improving the data-aggregating reliability.

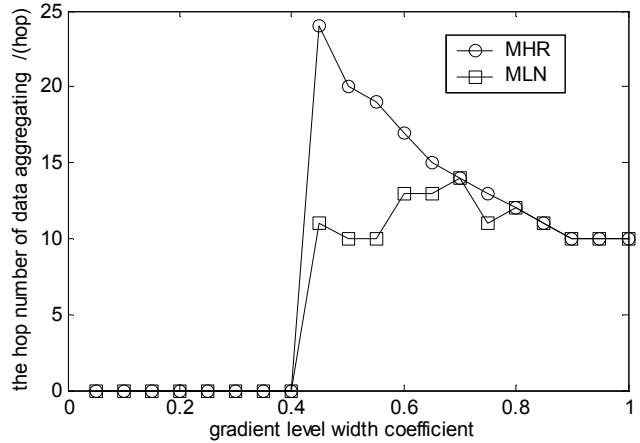


Figure 6. The hop number of data aggregation.

The number of forwarding nodes in the process of data aggregation from the same source node as above to the SINK vs. the gradient level width coefficient  $K_G$  in the MHR network and the MLN network are respectively shown in the Figure 7. According to the Figure 7, it is visible that the energy consumption and collision probability are decreased in the MLN network because the number of forwarding nodes is reduced obviously.

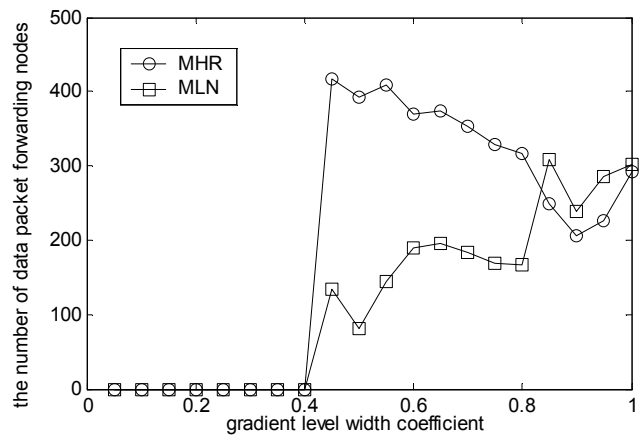


Figure 7. The number of data-packet forwarding nodes.

## 5. Conclusions

The directed diffusion routing protocol in wireless sensor networks has a series of potential advantages, but because of the inherent characteristics of wireless sensor networks, the superfine routing controlling granularity don't adapt to the dynamic topology structure and the uncertainty of parameters, and however, the super-coarse routing controlling granularity leads to the high degree of duplicate transmission of data-packets and influences the network's comprehensive performances, so the proper balance of routing controlling granularity should be considered. The research shows that the reliability of data aggregation is improved by limiting the gradient level width of directed diffusion gradient field, and the time-delay of data aggregation and the energy consumption are reduced by changing the forwarding rule of

data-packets from the hop-by-hop forwarding rule of the MHR network to the lowest-hop forwarding rule of the MLN network. It is predicated that the network's comprehensive performances will be further improved if the relevant parameters are optimized according to the actual application scenarios of wireless sensor networks.

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