Enhancing fault tolerance of wireless sensor networks by changing topology

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Abstract. Wireless sensor networks work by multi hop mode. The increase of intermediate forwarding nodes will bring the packet loss rate increase. In addition, a node which has fault will affect the entire link work. The average number of forwarding node influences the fault tolerance of wireless sensor networks. In order to ensure that wireless sensor networks can work smoothly and prolong the lifetime, the reducing of average number of forwarding node is necessary, namely reducing the average number of hops. The reducing of average hop number of whole network also reduces the packet loss rate and the energy consumption of nodes. The proposed algorithm in this paper cuts down the hops and improves the fault tolerance of wireless sensor networks.

1. Introduction

Wireless sensor networks need fault tolerance to ensure that the network can operate safely, especially for large scale wireless sensor networks. Because the sensor nodes forward a packet by the way of multi hop, the forwarding packet may be lost. A forwarding time is often very short, but the cumulative consumption time of several forwarding cannot be ignored. Too many hops can lead to serious delay, high packet loss rate and bad fault tolerance of wireless sensor networks. Therefore it is important to reduce hop number to improve the safety and the efficiency of wireless sensor networks.

At present, fault tolerance of wireless sensor networks contains detecting the fault boundary, restoring the lost data and modifying the cavity. However, these are the remedy after problems, fault tolerance first needs establishing prevention mechanism. For example, literature [1] proposes a distributed node deployment algorithm to form good connection of wireless sensor networks. But the more common and important problem is how to improve fault tolerance after existing deployment. Minimum connected dominating set is a concept in graph theory. In wireless sensor networks, minimum connected dominating set research mainly focuses on reducing energy consumption to extend network lifetime. Constructing dominating set is as virtual backbone network [2], a method for constructing the dominating set is designed to reduce the energy consumption of network by reducing dominant point number. In the work of [3], the design of dominating set is based on the minimum energy cost. In the work of [4], markov optimization model of minimum connected dominating set is used to extend network lifetime.

The minimum connected dominating set method is used to reduce redundant forwarding node [5]. In the work of [6], the proposed algorithm can go to repair damaged networks by itself if minimum connected dominating nodes become invalid. These methods are related with the minimum connected dominating set about solving fault tolerance problem, but the work has space for further optimization.

Fault tolerance is the ability to maintain performance of wireless sensor networks when node failure. Fault tolerance is an important problem in wireless sensor networks. System has very good
fault tolerance, namely the best preparation for the worst case. The difference from previous work is that we discuss the fault tolerance problem of wireless sensor networks when sensor nodes are deployed randomly. In addition, this paper combines degree and minimum connected dominating set to discuss fault tolerance problem. This paper proposes an algorithm which combines degree and minimum connected dominating set (D-MCDS). D-MCDS algorithm can enhance the fault tolerance of wireless sensor networks.

This paper has three additional sections. The section introduces background and reviews related work. Section 2 analyzes the problem and proposes algorithm. Section 3 evaluates the proposed algorithm. We close in section 4 with a summary.

2. Constructing minimum connected dominating set by degree to enhance fault tolerance

2.1. The related concept

\[ N_i: \text{ node } i \]

\[ R: \text{ node communication radius} \]

\[ D: \text{ average node degree, namely } D = \sum_{i=1}^{N} d_i / N, \text{ where } d_i \text{ is the neighbor number of node } i. \]

\[ C: \text{ connectivity rate, if the maximum node number of sub network is } S, \text{ then the connectivity rate is } S/N, \text{ where } N \text{ is the total number of nodes.} \]

\[ H: \text{ average number of hops, if } h_{ij} \text{ is the edge number of the shortest path connecting two nodes, then} \]

\[ H = \frac{2}{N(N-1)} \sum_{i \neq j} h_{ij} \]

\[ H_{\text{max}}: \text{ the maximum number of hops between any two nodes in network.} \]

2.2. The analysis of building minimum connected dominating set

It is found that the packet loss rate will show an upward tendency with the increase of hop number. Therefore less hops in wireless sensor networks is very important for fault tolerance. This paper studies the minimum connected dominating set to reduce the number of hops in wireless sensor networks, thereby enhancing network fault tolerance.

Promoting node deployment density of wireless sensor networks will increase the connectivity rate. If the connectivity rate reaches 100%, \( S \) is equal to \( N \).

\[ C = \frac{S}{N} \]

\[ N = \sum_{i=1}^{N} d_i \]

\[ H = \frac{2C^2}{S(S-C)} \sum_{i \neq j} h_{ij} \]

\[ P(b < d_i \leq f) = P\left( \frac{b-E(X)}{\sigma} < \frac{d_i-E(X)}{\sigma} \leq \frac{f-E(X)}{\sigma} \right) = \Phi\left( \frac{f-E(X)}{\sigma} \right) - \Phi\left( \frac{b-E(X)}{\sigma} \right) \]

where \( b \) and \( f \) are constant, \( E(X) \) is expectation, \( \sigma \) is standard deviation, \( \Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt \).

Assuming that the confidence level is \( 1 - \alpha \), then

\[ P\left( \frac{d_i-E(X)}{\sigma} < \frac{d_i-E(X)}{\sigma} \leq \frac{f-E(X)}{\sigma} \right) + \alpha = 1 \]

\[ P\left( \hat{d}_i \frac{\sigma}{\sqrt{V}} > E(X) > \hat{d}_i \frac{\sigma}{\sqrt{V}} \right) + \alpha = 1 \]

\[ \text{Hence, the confidence interval for } E(X) \text{ is} \]

\[ \hat{d}_i \frac{\sigma}{\sqrt{V}} \leq E(X) \leq \hat{d}_i \frac{\sigma}{\sqrt{V}} \]

Because the node deployment is random, \( k \) and \( n \) are the number of deployment node, \( k < n \), \( C_n \) is the connectivity rate when deployment node number is \( n \),

\[ C_n + \sum_{k=1}^{n-1} \left( \begin{array}{c} n-1 \\ k-1 \end{array} \right) p^{k(n-k)} C_k = 1 \]

Therefore, the interval of \( C_n \) is
1 + (n + 1)p^{n-1} \leq C_n \leq 1 + \binom{n}{2}p^{2n-3} - np^{n-1} \quad (10)

Connectivity rate is proportional to the average degree of wireless sensor networks. Average number of hops also has connection with connectivity rate. A link which contains too many hops causes the robustness decrease. The degree distribution of random deployment sensor nodes in a region is similar to obey poisson distribution. Because of node communication distance constraint in wireless sensor networks, random deployment nodes form uniform network, the majority of nodes has similar degree.

2.3. Constructing minimum connected dominating set based on degree

The hop number has relation with degree. The bigger average degree of network, the hop number may be smaller. Big degree of a node means large neighbor node number of this node, in other words, this node can dominate more other nodes. This paper constructs minimum connected dominating set based on degree, the steps are as follows:

Step1 Select nodes\{N_1, N_2, ..., N_m\} from the set G, G contains all nodes, degree(N_1)\geq degree(N_2)\geq...\geq degree(N_m);

Step2 If \exists set J=\{N_1, ..., \} , the points in J and \forall N_i have edge in set M=G-J, then enter Step3, otherwise continue to add nodes to set J according to the degree;

Step3 Select the connection point between nodes in set J=\{N_1, ..., \}, all points in J can communicate;

Step4 Check set J, if \exists edge\{N_x, N_y\}, \exists edge\{N_x, N_z\}, \exists edge\{N_y, N_z\} and after the removal of N_y, the point set J and \forall N_i have edge in set M=G-J, then remove N_y.

The proposed algorithm is called minimum connected dominating set based on degree (D-MCDS) algorithm. Minimum connected dominating set is designed to keep nodes dormant state and minimize the intermediate forwarding node number as much as possible. The innovation of the proposed D-MCDS algorithm is that the application of minimum connected dominating set based on degree reduces the redundant forwarding nodes and ensures realizing fault tolerant wireless sensor networks.

3. Simulation

This paper simulates 100 nodes deployment in 200*200 plane, the communication radius of each node is 40, 10 nodes are deployed randomly every time, namely, 10 times complete 100 nodes deployment. We compare D-MCDS algorithm and geographic adaptive fidelity (GAF) algorithm. GAF algorithm divides the monitoring area into several virtual cells, nodes enter corresponding cell according to node position information and each cell elects a cluster head according to cycle.

Fig.1 Comparison of maximum hop number

As shown in Fig.1, the maximum hop number becomes large with the increase of node number. If the node density reaches a certain level, the maximum hop number tends to be stable. It can be found
that the maximum value of D-MCDS algorithm and GAF algorithm for maximum hop number both appear after the network connectivity rate reaches 100%. The reason is that some nodes cannot be connected when node distribution is relatively sparse. Increasing node after full connection creates redundant nodes, so the network has a certain degree of fault tolerance. Certain redundancy is necessary. Sensor nodes density is inverse ratio to the average distance between nodes. So we can observe the relation between reliability and sensor node density.

Fig. 2 Comparison of average hop number

There are two conditions in the simulation experiment. Firstly, the connectivity rate reaches 1 after deploying 40 nodes randomly, the maximum hop number and the average hop number reach the maximum value basically. Secondly, average hop number has a slight downward trend gradually with the increase of node density. In contrast, the connectivity rate of GAF algorithm reaches 1 after deploying 80 nodes randomly. The situation reveals node deployment density is required to achieve a certain density (i.e., when the connectivity rate reaches 1 by random deployment nodes), then the fault tolerance of wireless sensor networks is the weakest. If node density reaches a certain level and connectivity rate reaches 1, then the increase of node density can enhance the fault tolerance of wireless sensor networks. As shown in Fig.2, if the node density is low, the average hop number increases rapidly with the increase of node number. If the node deployment is intensive, the maximum hop number and the average hop number of D-MCDS algorithm are both less than GAF algorithm. The reason is that if the node deployment reaches high density, the influence of the node degree increases rapidly.

4. Conclusion

Because multi hop impacts fault tolerance, reducing the number of hops in wireless sensor networks has realistic significance. This paper explores the impact of hops by minimum connected dominating set based on degree. We analyze the relationship between network hop number and connectivity rate. If sensor nodes are deployed densely, the method of minimum connected dominating set based on degree can effectively decrease the maximum hop number and the average hop number, thereby establishing fault tolerant wireless sensor networks. Future work includes the investigation of the case with different application of large scale wireless sensor networks and the extension of the proposed algorithm to more detailed models of large scale wireless sensor networks.

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