Fault-tolerant Topology Control for Heterogeneous Wireless Sensor Networks Using Multi-routing Tree

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***Abstract*—Fault-tolerant topology control is a critical problem in WSNs. It is important for improving network lifetime and reliability. In this paper, we present a novel algorithm FTMRT, which ensures Fault Tolerance by constructing a Multi-Routing Tree. We firstly construct a multi-routing tree of the initial topology, which ensures there are at least k-disjoint paths from each sensor to the set of supernodes. And then each sensor adjusts its transmission power according to the multi-routing tree to form the fault-tolerant network topology. In the topology maintenance phase, topology reconstruction is invoked each time there are some node fail and the supernode connectivity is broken. The effectiveness of the proposed algorithm is validated through simulation experiments.**

Keywords—Heterogeneous wireless sensor networks; topology control; fault-tolerant

I. INTRODUCTION

In recent years, wireless sensor networks (WSNs) have attracted many research attentions for their broad range of potential monitoring and tracking applications [1-3].In most applications, WSNs are deployed under a harsh environment such as forest fire monitoring, search-and-rescue or battlefield where the nodes are susceptible to damage [1-5]. In addition, sensor nodes are battery-powered and it is usually infeasible to recharge the nodes or to replace the failed nodes timely. Therefore, ensuring fault tolerance and minimizing energy consumption are two important issues in wireless sensor networks.

The published works on fault-tolerant topology control can be classified into the algorithms for homogeneous WSNs [4-7] and that for heterogeneous WSNs (HWSNs) [8-11]. All of these algorithms in reference [4-7] constructed k-connected networks to provide alternative routes to ensure networks fault-tolerant. Reference [12] presented the benefits of using HWSNs. If the nodes are properly deployed, heterogeneity can provide a 5-fold increase in the network lifetime. DPV (Disjoint Path Vector) [9] is one of the fault-tolerant topology control algorithm for HWSNs, and its main objective is to assign each sensor's transmission range so that there are at least k-vertex-disjoint paths to supernodes and the total power consumption is minimum. Most of the studies of HWSNs, including DPV algorithm, propose static solutions which can't adapt the topology to the changing network conditions. Unlike the static algorithms, the algorithm ADPV [11] is a recent study which can dynamically adjust the sensor nodes' transmission powers to ensure supernode connectivity in the presence of node failures. Our algorithm FTMRT is also tailored to HWSNs and can adapt the topology to the changing network conditions. FTMRT differs from ADPV by constructing multi-routing tree to ensure k-disjoint paths to the set of supernodes.

The remainder of the paper is organized as follows. The system model is discussed in Section II. In section III, the proposed FTMRT approach is described in detail. Section IV presents simulation analysis and finally Section V concludes the paper.

II. SYSTEM MODEL

A HWSN is composed of several resource-rich supernodes and a large number of low-cost ordinary sensor nodes. We consider a HWSN consisting of M resource-rich supernodes and N low-cost sensor nodes, with $M \ll N$. Let an undirected graph$G = (V, S, E)$ presents the network topology, where $V = \{v_1, v_2, v_3 \dots v_n\}$ denotes the set of sensor nodes, $S = \{s_1, s_2, s_3 \dots s_m\}$ denotes the supernodes set, and $E = \{(v_i, v_j) | v_i, v_j \in V \cap d(v_i, v_j) < Min(R_i, R_j)\}$ presents the set of edges, where $d(v_i, v_j)$ is the Euclidean distance of v_i and v_j, and R_x denotes the transmission range of v_x. A sample

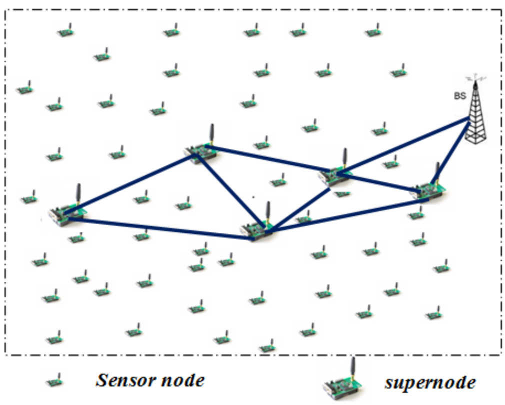


Fig.1. Heterogeneous WSN

HWSNs environment is depicted in Fig.1. Our algorithm aims to construct a fault-tolerant network topology and minimize the energy consumption. We assume that each sensor can adjust its transmission range as required, and the maximum transmission range is R_{max}. And we assume that the supernodes are not energy constrained and they can directly communicate with a base station or other supernodes [9,11]. We also have the following definitions:

Definition 1 (1-hop neighbor). Let $N^1(x_i)$ denotes the 1-hop neighbors of x_i, where x_i can be a supernode or a sensor node. For $\forall v_j \in N^1(x_i)$, $\mathrm{dis}(x_i, v_j) \le \min(R_i, R_j)$.

Definition 2 (power consumption). $\forall v_i, v_j \in V$, the minimum necessary transmission power, sending a message from v_i to v_j, can be computed through formula (1):

$$C_{ij} = \alpha \times d^{\beta}(v_i, v_j) \qquad (1)$$

Where α is a constant, n is the path loss factor and $d(v_i, v_j)$ is the Euclidean distance between v_i and v_j.

Definition 3 (multi-routing tree) An undirected graph is a multi-routing tree if it meets the following conditions:

- Each node holds a level value. Let $\mathrm{Lev}_{\sup\_i}$ and Lev_i denotes the level of supernode s_i and sensor nodes v_i separately, and the initial value of which is 0. If $Lev_i = 0$, it can be redefined as formula (2).

$$Lev_i = \begin{cases} 1, & v_i \in N^1(s_j) \\ M, & v_i \in N^1(v_j) \cap \mathrm{Lev}_j = M-1 \end{cases} \qquad (2)$$

- For $\forall v_i$, if $Lev_i = 1$, then v_i has several supernodes as its father node and uncle nodes. If $Lev_i = M (M \ge 2)$, v_i has one father $Father_i$ and k-1 uncle $Uncle_{ix}$, and $\mathrm{Lev}_{Father_i} = M-1 \cap \mathrm{Lev}_{Uncle_{ix}} = M-1$.
- All the nodes in level 1 are the roots of a subtrees. The edges that link to node v_i and all its sons only belong to one subtree.

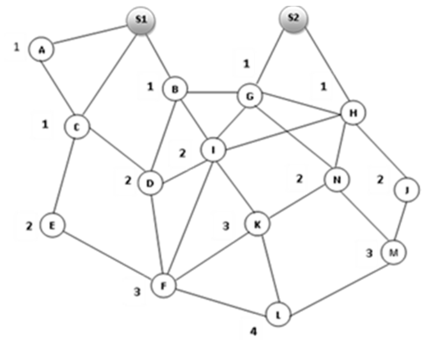
III. Topology Construction Using Multi-routing Treee

In this section, a distributed k-fault-tolerant topology control scheme FTMRT is proposed. The FTMRT algorithm involves two phases: fault-tolerant topology construction phase and topology reconstruction phase, and the second phase is invoked each time the supernode connectivity is broken.

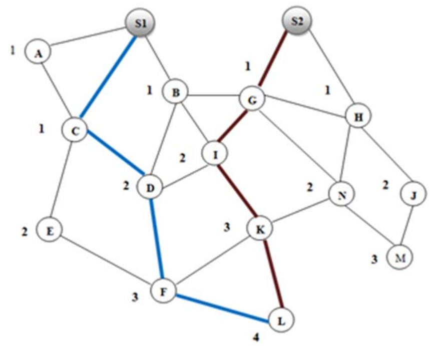
A. *Construction of Fault-tolerant Network Topology*

The construction process of fault-tolerant network topology will be handled as follows:

- Step 1: Level value assignment. For each supernode or sensor node, the initial value $Lev_x = 0$. The process of level assignment is initiated by the supernodes. Each supernode broadcasts a message DL to its sensor neighbors, which contains ID and the level of the supernode. When v_i receives such a message, it will reset $Lev_i = 1$. Then the process continues. That is to say, when a node v_j receives a DL from v_k, where $Lev_k = m$, it first check its own Lev_j. If $Lev_j = 0$, v_j will reset $Lev_j = m + 1$, otherwise, drop the message. The process continues until for $\forall v_i \in V$, $Lev_i > 0$. As shown in Fig.2 (a), S1,S2 are supernodes and A,B,C…N are sensor nodes. After the level assignment process, each node is assigned a level value.
- Step 2: Multi-routing tree construction. In this phase, each sensor node chooses a father node and k-1 uncle nodes among its upstream neighbors. For $\forall v_i \in V$, where $Lev_i = \mathrm{m}$, the set of upstream neighbors US_i can be defined as : $\mathrm{US}_i = \{(v_j) | \mathrm{Lev}_j = (\mathrm{m}-1) \cap \mathrm{d}(v_i, v_j) \le \min(R_i, R_j)\}$. Node v_i chooses the nearest node from US_i as its father and chooses the uncle nodes from the rest nodes in a similar manner. If the selected father v_j has been the father of another node whose root node is the same with v_i, node v_i have to reselect another appropriate node as its father node to avoid the two paths intersection. The process will continue until all the sensors have been assigned a father and (k-1) uncle nodes.
- Step 3: Adjusting nodes transmission range. After constructing the multi-routing tree, each node adjusts its transmission range to reach the neighbors which are in its k disjoint paths to form the fault-tolerant network topology. Fig.2 (b) shows the network topology, where k=2.The path $\{\mathrm{L-K-I-G-S2}\}$ is one of the paths from L to supernode set. For node F, the nearest node among level 2 is I, but node I has been the father of



(a) Level value assignment



(b)Fault-tolerant network topology

Fig.2. Construction of fault-tolerant network topology

node K, so F choose node D as its father node to avoid two paths intersect.

B. Topology Restruction

In the topology maintenance phase, once the network's supernode connectivity is broken, FTMRT starts topology reconstruction process. When node v_i finds one of its neighbors v_j fails, it will check if v_j is its father node or one of the uncle nodes. If v_j is not the father or uncle node, node v_i does not deal with the fault. Otherwise, node v_i will start the reconstruction process of the disjoint paths to supernode set. The process will be handled as follows:

- Step 1: v_j is the father node of v_i. If the fault node v_j is the father node of v_i, node v_i will reselect a new father node among its uncle nodes. At the same time, v_i will select a new uncle node among US_i. And if there is no more neighbor in US_i, v_i will adjust its transmitting power to add one uncle node. As shown in Fig. 3 (a), node I, which is the father node of K, fails to transmit data. Node K starts to select a new father node among its uncle nodes. As shown in Fig.3 (b), K selects N as its new father. The path $(L-K-N-H-S2)$ replaces $(L-K-I-G-S2)$ as the new path from L to the set of supernode. In addition, node K should reselect an uncle node among its neighbors in level 2 to ensure there are 2 disjoint paths to the supernode set. If such neighbors exist, K will select the nearest node as its uncle. Otherwise, node K will adjust its transmitting power to the nearest node v_m, which meets the following mathematical expression: $(\mathrm{Lev_m} = Lev_K - 1) \cap (\mathrm{d(K, v_m)} > \mathrm{d(K, N)}) \cap (\mathrm{d(K, v_m)} > \mathrm{d(K, O)}) \cap (\nexists \mathrm{v_n} \in \mathrm{V} \cap \mathrm{d(K, v_n)} < \mathrm{d(K, v_m)})$
- Step 2: v_j is the uncle node of v_i. If v_j is the uncle node of node v_i, v_i will select another uncle to ensure k-disjoint paths between v_i and the set of supernode. The method of selecting uncle node is the same as that described in step 1.

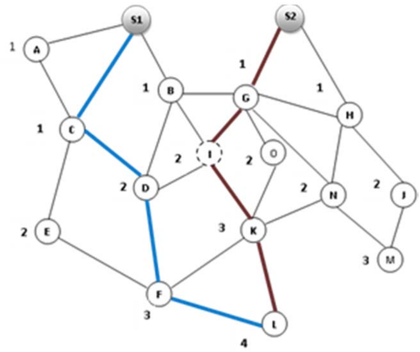
IV. Simulation Analysis

The simulation environment, performance metrics, and experimental results are discussed in the subsection.

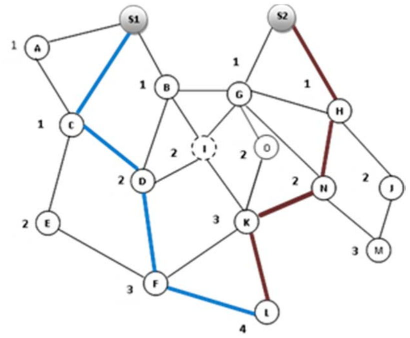
A. Experiment Setup and Performance Metrics

The simulation experiment is conducted in MATLAB environment. In our experiments, the sensors are randomly placed in a 600m × 600m area. The number of sensors 'n' is varied from 100 to 300 and the number of supernodes 's' is set to 5% or 10% of n. The initial sensor transmission range R_{max} is varied from 100 to 180 and k is set to 2. In our experiment, each individual simulation experiment involves 40 different topologies and the average result is reported, and we compared FTMRT with DPV [9] and DATC with 1-hop local neighborhood (h=1) [8].

We use Total Transmission Power and Node Failure Tolerance as the performance metrics.



(a)failure occurrence



(b) Disjoint paths reconstruction

Fig.3. Topology reconstruction

- Total transmission power: is the sum of transmission power of all the sensors. We assume a simple path loss model, where the path loss factor β = 2, and compute the transmission power of each sensor using the simple formula $p_i = R_i^2$. Thus, the total transmission power TP can be expressed as formula (3).

$$\mathrm{TP} = \sum_{i=1}^{n} R_i^2 \tag{3}$$

- Node failure tolerance: After the fault-tolerant construction algorithm execution, there are still some sensors having no uncle node, that is to say, if the father fails, these nodes cannot transmit data to supernodes. Let Num_{f-un} denotes the number of the nodes, which have both father node and uncle node, and 'n' denotes the number of sensors. Thus, the node failure tolerance NFT can be computed as formula (4).

$$\mathrm{NFT} = Num_{f-un}/n \tag{4}$$

B. Result Analysis

Because of space limitations, here only shows the results of $s = 0.05 \times n$.

In our experiments, we set the path loss factor β = 2. According to the reference [13], for $\forall v_i, v_j$, if node v_x falls into the cover region of v_i and v_j, the transmission power will

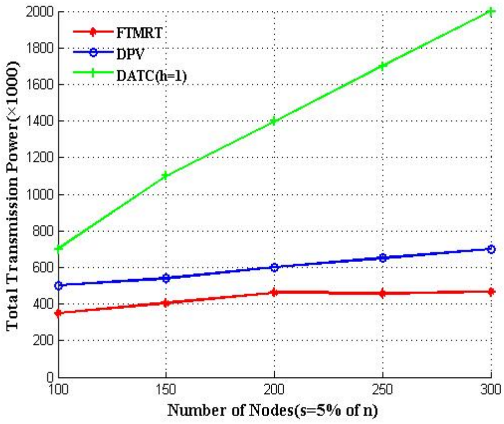


Fig.4. Total transmission power (s=5% of n)

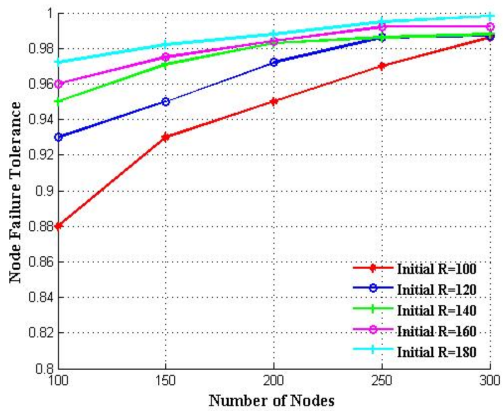


Fig.5. Node failure tolerance

meets the following expression $C_{ij} > C_{ix} + C_{xj}$. If $Lev_x = Lev_j = Lev_i + 1$, we reset $Lev_j = Lev_x + 1$. Thus we can reduce some nodes' transmission range to reduce total energy consumption. Because of space limitations, the optimization of FTMRT algorithm will be described in detail in our future work. Fig.4 shows the total transmission power of s=5% of n. We can observe that FTMRT obviously outperform the algorithm DPV and DATC (h=1) in terms of the metric total transmission power. With the increase of the number of nodes, the change of total energy consumption of algorithm FTMRT is not obvious. This is because the sensors' transmission range becomes much small as the network gets denser.

Fig.5 shows node failure tolerance of algorithm FTMRT with the initial transmission range varied. We can observe that with the increasing of initial transmission range, the topology failure tolerance rate increases. And the node failure tolerance increases as the number of sensors in the networks increases. When the initial transmission is more than 140m, the node failure tolerance reaches more than 95%.

Therefore, we can conclude that our algorithm FTMRT is outperforms the DPV algorithms and DATC (h=1) algorithm. And the simulation experiments verify the validity of our algorithm.

V. CONCLUSIONS

In this study, we present FTMRT, a distributed fault-tolerant topology control algorithm for HWSNs. The FTMRT algorithm consists of two phase: topology construction phase, and topology maintenance phase. During topology maintenance phase, once there is a father node or an uncle node fails, FTMRT will reconstruct fault-tolerant topology. Our goal is to ensure the network topology fault-tolerant and energy efficient. The simulation results confirm the effectiveness of FTMRT. In the future, we will further optimize the algorithm through optimize the level assignment strategy.

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