Fast Message Dissemination Tree and Balanced Data Collection Tree for Wireless Sensor Network

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Abstract—**Topology control is a fundamental technique in Wireless Sensor Network (WSN), which forms the underlying topology for routing and other protocols by power control and neighbor selection. In recent years, various topology control algorithms with very different design goals have been proposed, and all of them try to form one optimized topology for all types of communications. Such solution makes a serious mistake by neglecting the fact that different communications have very different requirements.**

The most common communications in WSN are broadcast and data collection. For broadcast or message dissemination, the first priority is to spread the message throughout the network as quickly as possible. As for data collection, multi-factors should be taken into account, such as link length, hops to base station, node degree. With the very different goals, it is not possible to solve all those problems simultaneously with just one topology.

In this paper, we propose a approach, which contains a Fast Dissemination Tree (FDT) and a Balanced Data Collection Tree (BDCT) to fulfill the requirements of the above two communications, i.e. message dissemination and data collection. And analysis and simulation proves that our method has a better performance when compared to the existed ones.

Index Terms—**topology control, message dissemination tree, data collection tree, load balance, robustness**

I. INTRODUCTION

Wireless Sensor Network (WSN) is known for its capability for remote sensing and monitoring. During the past years, various applications of WSN [1], such as battle field monitoring [2], wild animal observation and protection [3] and volcano studies [4], have been put into practice. Among those applications or systems, data collection is the most basic mission of WSN. Besides data collection, message dissemination or broadcast is also necessary for network setup after deployment or reconfiguration after node failure or departure.

Topology control is one of the most fundamental and important techniques in WSN, which deals with sensor nodes' power control and the network structure. And there are several different design goals of topology control [5], such as minimum energy consumption, low interference, small node degree, connectivity and planarity. In recent years, various topology control algorithms with very different considerations have been proposed.

However, to the best knowledge of ours, among those proposed algorithms, usually one "final" or "optimal" topology is formed, which is inappropriate for the reason that there are two different communication types in WSN, message dissemination and data collection. Moreover, the robustness of the topology is sometimes neglected; most of the algorithms deal with node failure by simply reset the whole network, which is a high cost behavior, in terms of energy consumption. Still some try to establish several disjoint routes [6] between sensor nodes and Base Station (BS) or nodes and nodes to improve the network robustness, which is not an easy job.

To solve the above said problems, in this paper, we present a novel tree-based topology control algorithm which contains Fast Dissemination Tree (FDT) for

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message broadcast and Balanced Data Collection Tree (BDCT) for data collection.

The rest of the paper is organized as follow. Firstly, we give brief introduction of well-known topology control algorithms and related works. Secondly, assumptions and notations used are described. After that, the detail of FDT and BDCT is discussed. At last, conclusion is drawn based on simulation result under both worst and average cases.

II. Related Works

In this section, we give a brief introduction to topology control algorithms, which we believe are the most typical ones, some may even considered to be the state of art.

As above discussion, different topology control algorithms have their own design goals, however, no matter what, the ultimate design goal is the same, to prolong the network lifetime with preserving network connectivity and fulfilling the coverage requirement.

Moreover, there are different classification standards. For example, the resulting topology is flat or hierarchical; topology control is done by node power control or node activation control; the design is based on theoretic hypothesis or actual environmental parameters and so on.

We give some specific examples of topology control algorithms, which go as follow.

The simplest topology control strategy is called Unit Disk Graph (UDG), in which all sensor nodes using their maximum power to communicate with each other thus all possible communication links are preserved. Though it is not a wise choice for underlying topology, it is considered to be the origin or benchmark for all topology control algorithms.

Other approaches based on Graph theory, such as Relative Neighbor Graph (RNG) [7], Gabriel Graph (GG) [8] and Minimum Spanning Tree (MST), are introduced to eliminating redundant links and construct a resulting topology with better performance than UDG. Take Localized Minimum Spanning Tree (LMST) [9] for example, which is based on neighbor information within one-hop distances and can be executed in a distributed manner.

Besides the above methods, there are more examples. In [10]-[13], interference is taken into account. In [14], the author tries to improve the robustness of the network by specially designed edge weight function, which contains link length and hops to BS. In [15]-[16], Quality of Service (QoS) is the main consideration. In [17], keeping some redundant links is used as a way to improve the network's tolerance to node failure and network capacity. The problem of how to maximizing network capacity is also discussed [18]. In [19], the benefit of topology control is explored in a practical indoor test platform using Packet Reception Rate (PRR) as index of link quality.

Unlike the above mentioned examples, some researchers endeavor to form a hierarchical network by partitioning the network into several disjoint parts or clusters, and each cluster has one selected cluster head and several cluster members. The cluster head is responsible for inter-cluster communication, and all cluster members only communicate with their own cluster head in a TDMA (Time Division Multiple Access) manner. And cluster head election is executed periodically in order to balance energy consumption. The most famous algorithm of this kind is LEACH [20].

For space limitation, there are still many topology control algorithms, which we have no time to explore here. For those, who are interested in this research area, [21]-[22] can be good references.

Though after years of study, there are still many open problems waiting for solution in this area, some of them are discussed in [23].

III. Network Model and Assumptions

In this Section, we give an introduction to notations and assumptions used throughout the paper. Although, some of them are widely accepted ones, for completeness, we still include them here, which go as follows.

1) The network topology is abstracted as undirected graph, in which sensor nodes are represented by vertices and communication links are represented by edges.
2) Every node has a unique ID, for the *i*th node, its ID would be i, and BS' ID is set to 0.
3) Sensor nodes are randomly deployed in 2D plane and can be located by its coordination (x_i, y_i).
4) The hops to BS of node i is represented as hop_i, the hop of BS is set to 0 and largest hops to BS is represented as $hop_{\max}$.
5) Every node has the same maximum communication range, a.k.a Critical Transmission Range, which is represented by CTR.
6) The distance or link length between nodes can be estimated by received signal strength or some other methods like GPS (Global Positioning System), and the distance between node i and node j is d_{ij}.
7) There is a communication link L_{ij} between node i and node j, if and only if $d_{ij} \leqslant CTR$ and $d_{ji} \leqslant CTR$, or to say only bidirectional links are accepted.
8) The BS has unlimited power supply. And sensor nodes have the same initial battery level $E_{\max}$, moreover, as the energy drains out, node i's remain energy is represented by E_i.

Besides the above, planarity and interference is not an issue here, because they can be overcame by physical layer techniques, such as Frequency Hopping Spread Spectrum (FHSS) and Frequency Division Multiple Access (FDMA).

IV. Algorithm Descriptions

Our algorithm forms two topologies, FDT and BDCT. FDT is used for message dissemination in initialization or re-configuration phase, and BDCT is used for data collection based on the information gathered in building of FDT.

A. FDT

FDT aims to deliver control messages as quickly as possible, and neighbor information is not available in the discovering phase, so using maximum power and choosing the nearest neighbor becomes the natural choice. The detail of FDT goes as follows.

Step 1: BS broadcasts a beacon message and fires the timer, hop information and BS' identity are contained in the beacon message. After that it waits for reply until the timer exceeds the setting threshold T_w.

Step 2: Any node i ($i \neq 0$), sets its hop as $hop+1$ and marks the sender of the received beacon message as its parent when it receives a beacon message. In cases that several beacon messages are received, the node j will be chosen as i's parent if and only if for any sender node k, there is $hop_j < hop_k$, or $hop_j = hop_k$ and $d_{ij} \leq d_{ik}$.

Step 3: After processing beacon message, node i sends two kinds of messages with its maximum power. One is the reply message with its own node ID i and its parent's ID j, once j receives this reply message, it includes i in its children list. Another is the new beacon message with updated hop information, its own ID and its residual energy. At last, it fires the timer and waits for reply.

Step 4: Step2-3 will be repeated throughout the network, until timer expires.

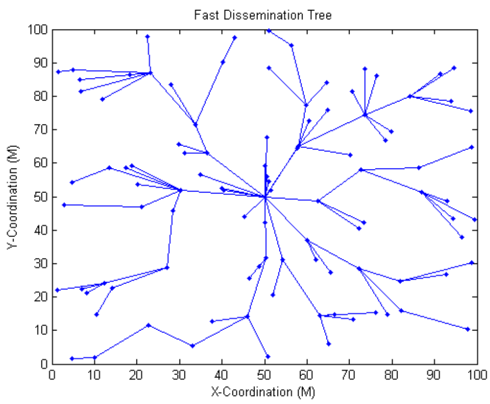

Figure 1. A Sample of Fast Dissemination Tree (Region size 100M*100M, CTR=20)

A dissemination tree can be formed by the above steps. A sample of FDT is shown in Fig.1, in which BS is placed in the center and 100 sensor nodes are randomly deployed in the region. It is not hard to tell that every node has a path of least hops to BS in FDT, which makes it a good choice for message dissemination and network initialization. Once FDT is established, then each node only waits for its children's replies when it needs to broadcast a message.

Moreover, every node has the knowledge of neighboring nodes within its *CTR* after the execution of FDT, including ID, hops to BS, left energy and location, which will be used in construction of BDCT.

B. BDCT

The objective of BDCT is to achieve a balance among different design goals, namely link length, hops to BS, remaining energy and robustness. Moreover, a simple method is provided to improve the network's tolerance to node failure. With the above features, BDCT is suitable for data collection when the network reaches a stable state.

Based on the acquired neighbor information in the formation of FDT, every node can run the BDCT algorithm separately to decide its parent node. The selection of parent node is based on the link weight, which is computed by (1), and the computation of λ and E is illustrated in (2) and (3).

$$Weight_{ij} = E_{ij}((1-\lambda_{ij})*(hop_i+1)+(\lambda_{ij}*D_{ij})), hop_i < hop_j \quad (1)$$

$$\lambda_{ij} = 1 - \frac{hop_i}{hop_{\max}} \quad (2)$$

$$E_{ij} = 1 + \frac{E_{\max}}{E_i} \quad (3)$$

The factor λ is introduced to balance energy consumption between nodes closer to BS and nodes have a longer distance to BS, based on the observation of funneling effect [24], i.e. nodes closer to BS exhaust their energy more quickly than those have further distance to BS. So it is reasonable to assign a larger transmission for those who have a longer distance to BS.

The factor E_{ij} makes nodes with less left energy undertake less packet relay duty, thus achieving a more even energy depletion rate among sensor nodes.

A severe drawback of tree based topology is that once a parent node fails, then all its children lose connection with BS. Take Fig. 2 for example, once node i fails, node j and node k lose connection with BS.

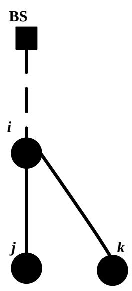

Figure 2. Parent Node Failure Causes Disconnection

A common solution for this problem is to trigger topology reconstruction once node failure is detected, but this is a highly cost behavior in terms of both energy and time. There are some other researchers try to deal this problem with establishing multiple paths (*k*-path) between BS and every sensor node, however, to find independent paths also suffers from high computational complexity, which limits its application.

How to increase the tolerance of node failure without suffering from high energy cost? Mother Nature gives her answer, a very simple and straight forward solution, a spider web, which contains radial paths to the center and bypasses. In case of broken radial thread, the vibration caused by prey can be conducted to the spider through bypass and other radial thread, which is shown in Fig. 3 If node i fails, its child, node q re-route to BS by Side Path (SP) L_{qp}.

We adopt the idea of SP, the red dotted line in Fig. 4, to maintain the network connectivity when node failure occurs. Of course, SP cannot be effective in all cases, if there are too many node failures, periodical adaptation or re-initialization is still needed. However, with SP functions as a complimentary mechanism, the execution frequency of topology reconstruction can be dramatically decreased.

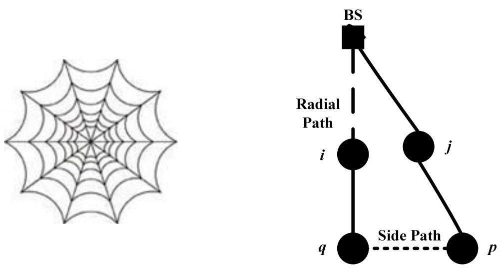

Figure 3. An Illustration of Side Path

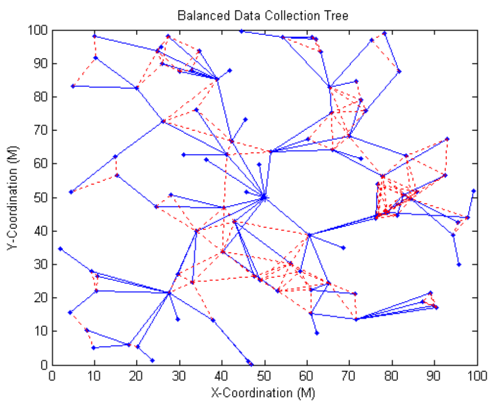

Figure 4. A Sample of Balanced Data Collection Tree

Based on the given link weight computation function and the concept of SP, the detail of BDCT can be given, which go as follows.

Step 1: Every node i calculates a link weight using (1) for all of its neighbor nodes.

Step 2: The node j, which has the smallest link weight and satisfies $hop_j + 1 = hop_i$, is chosen as i's parent. And node i's transmission power is set to include node j in its communication range.

Step 3: SPs are established between node i and other neighbor node k ($k \neq j$) within its transmission range.

By the above steps, a tree topology for gathering sensed data to BS can be generated. An example topology by executing BDCT algorithm is shown in Fig. 4. For simplicity and without loss of generality, each node is assigned with a random energy level from 0 to E_{max} in the example. And other parameters are the same as the setting of Fig. 1.

V. Analyses and Simulation

Because the analysis of FDT is quiet straightforward, we focus on the analysis and simulation of BDCT in this section. In FDT, node i chooses nearest node j to be its parent which has the smallest hops to BS, which makes the broadcast message can be received and relayed as quickly as possible.

Some widely accepted criteria, like link length which determines the energy consumption in single transmission, hops to BS which influences the delay of data collection and node degree which has great influence on the balance of energy consumption, are chosen for comparison. Moreover, robustness is also compared by the number of critical node. Node i is said to be a critical node, once i fails, the network would no longer be a connected one.

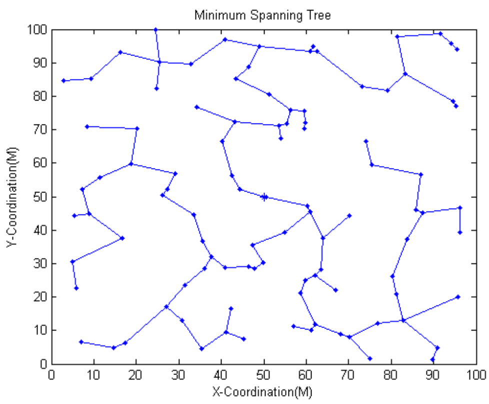

Figure 5. A Sample of MST (100 nodes randomly deployed, CTR=20, BS coordination (50, 50))

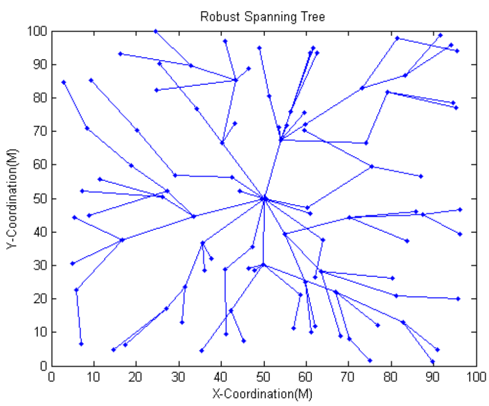

Figure 6. A Sample of RST (100 nodes randomly deployed, CTR=20, BS coordination (50, 50))

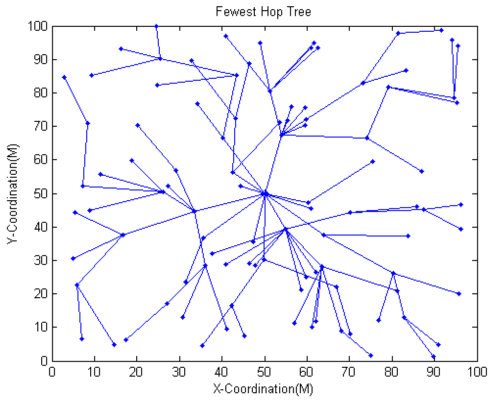

Figure 7. A Sample of FHT (100 nodes randomly deployed, CTR=20, BS coordination (50, 50))

After the setup of comparison standard, we select several most typical algorithms for comparison, which are listed in below.

1) MST, which has the shortest link length. Although, there are distribution edition of MST such as LMST [9], MST does have the best performance. A sample topology derived under MST is shown in Fig. 5.
2) RST [14], which is believed to has a better tolerance for node failure and departure. A sample topology derived under RST is shown in Fig. 6.
3) FHT (Fewest Hop Tree), in which every node has the least hop path to BS as described in [14]. The FHT and FDT are similar but the difference is that FHT only considers hops to BS, whereas FDT takes both hops to BS and link length between parent and child into consideration. A sample topology derived under FHT is shown in Fig. 7.

TABLE I.
PARAMETERS SETTINGS

Parameter	Value
Deploy Region	(0, 0) ~ (100, 100)
CTR	20M
BS Location	(50, 50)
Number of Nodes	100 ~ 200
Energy of BS	Infinite
Initial Energy of Nodes	2J
Residual Energy of Nodes	0 ~ 2J

Simulation is carried out under parameter settings described in Table I. Performance in both average and worst cases is compared, and the results (based on average value of 10 experiments) are shown Fig.8 to Fig. 13.

As the simulation result shows, MST do have advantages in link length, but it also has severe disadvantages that the hops to BS is too long (see Fig.10 and Fig.11), which inevitably leads to serious transmission delay. For such reason, MST would not be an option for practical use. This is pretty much the case for a lot of topology control methods, which show advantages in some indexes or under certain conditions, but shows terrible performance in others.

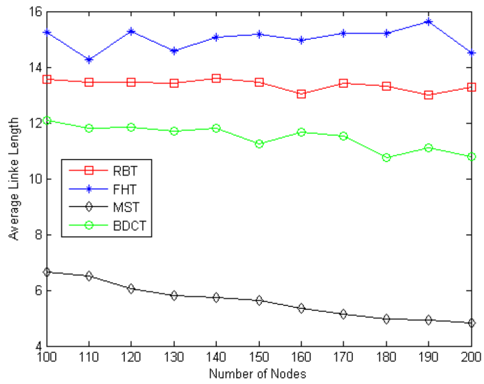

Figure 8. Comparison of Average Link length

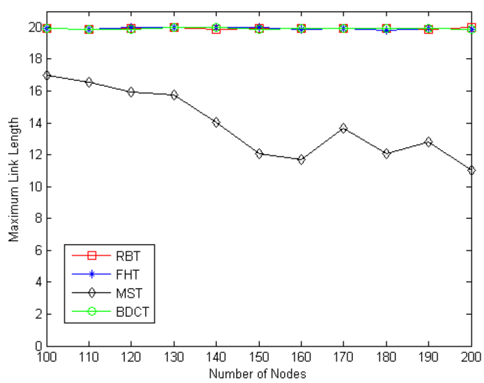

Figure 9. Comparison of Maximum Link length

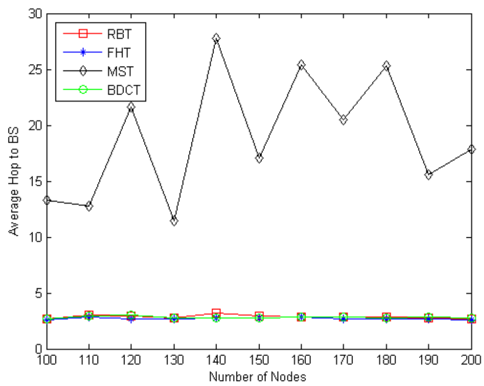

Figure 10. Comparison of Average Hops to BS

For the rest three, in terms of link length, hops to BS and node degree, BDCT's performance is slightly better than FHT and RST. And it also has a better tolerance to node failure due to the existence of SP, which greatly reduces the number of critical node (see Fig.13).

What cannot be seen from the above simulation result is that BDCT helps balance energy consumption between nodes. Because the setting of its link weight function, it tends to choose node with more left energy to be parent node, and thus helps balancing energy consumption throughout the whole network, which in turn prolongs the lifetime of nodes and thus the whole network.

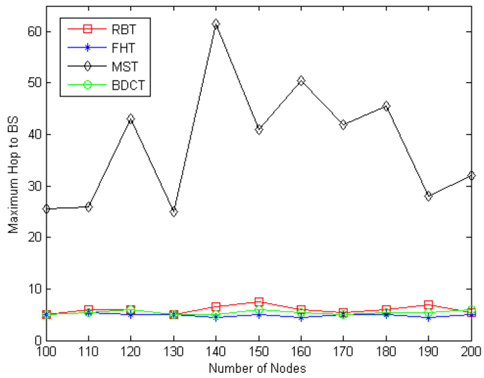

Figure 11. Comparison of Maximum Hops to BS

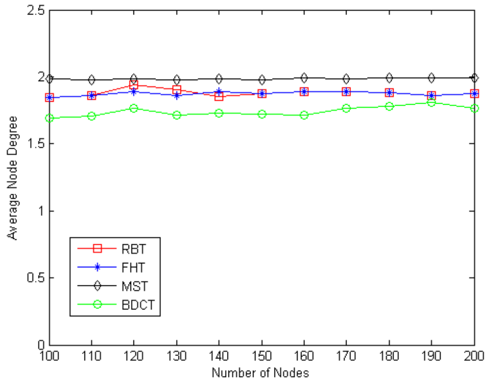

Figure 12. Comparison of Average Node Degree

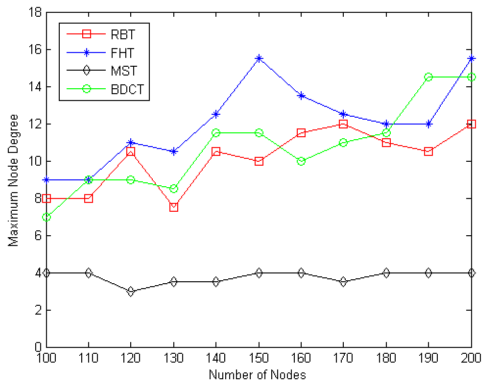

Figure 13. Comparison of Maximum Node Degree

VI. CONCLUSION

Due to the fact that there are different types of communications in WSN, different topology control method should be provided for different requirements. For such reason, a novel tree-based topology algorithm is proposed, which contains two parts, FDT for fast message dissemination and BDCT for efficient data collection. And it is proved by analysis and simulation that our method has a better performance than several well-known algorithms.

Future research can be conducted in combining topology control with sleep strategy and coverage configuration to achieve a better outcome.

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