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Study of Topology Optimization Algorithm of Wireless Mesh Backbone Networks based on Directional Antenna

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Abstract

In order to improve serious signal interference and energy consumption of wire mesh backbone network due to omni-directional antenna communication mechanism, a topology control optimization algorithm in wireless mesh backbone networks based on directional antenna is proposed. At first, this algorithm used Delaunay graph model to quickly find gateway node by position information of network nodes. Then, in view of the relationship between network transmission distance and the node degrees, it optimizes the network topology structure and lines. In order to improve the transmission rate of wireless mesh network and solve new interference and energy loss problem after adjusting Delaunay graph to achieve a gateway deployment of wireless mesh network using directional antenna, the algorithm reduces wireless links that the transmission distance is too long and energy consumption is higher, and defines the upper limit of the number of directional antenna on routing nodes. The simulation results show that this algorithm can minimize the number of gateway and the shorten network transmission distance from route node to gateway node. This algorithm can effectively decrease the deployment cost and interference by using less antennas and promote the network performance at the same time.

***Keywords**: wireless mesh networks; directional antenna; gateway deployment; Delaunay graph; topology optimization*

1. Introduction

Wireless mesh network(WMN) is a kind of new network transmitting signal through multiple hops wireless channel, and has broad applications in many fields [1]. It combines several advanced technologies such as multi-channel, multi-card and multi-rate, and can effectively improve network performance. To obtain a satisfied performance of WMN, an adaptable deployment method for various applications is essential.The deployment optimization of wireless mesh backbone network(WMBN) is one of the key problems of the research of WMN which directly affects the performance of the whole WMN[1].

At present, most wireless data transmission technology is based on omni-directional antenna because of its wide coverage. It is too much interference in the WMN, however, low spatial reuse while using Omni-directional antenna which restricts the performance of WMN. In order to improve the performance of WMN, some researchers use directional antennas to deploy network nodes in wireless mesh networks to reduce the interference and increase the network throughput [2]. A wireless mesh employing directional antenna can greatly extend courage and improve spatial reuse of wireless channels [3]. But the directional antenna technology has its own problems, such as much cost of directional antenna more than the one of omni-directional antenna, the mutual interference between directional beam, *etc*., which makes the WMN deployment based on directional antenna technology difficult.

This paper mainly studies the deployment problem of WMBNs from the aspects of gateway deployment. By using Delaunay triangulation as network topology, we propose a

Delaunay graph-based topology control optimization algorithm of WMBNs using directional antenna. The remainder of this paper is organized as follows. Section 2 briefly describes previous works related to the deployment optimization methods of WMN. Section 3 gives problem descriptions and network model. A topology control optimization algorithm in wireless mesh backbone networks based on directional antenna is presented in Section 4. The performance evaluation of the algorithm is presented in Section 5 and some concluding remarks are given in Section 6.

2. Related Works

The gateway deployment optimization of WMN is a hot issue by the attention of researches, and has made some achievements. The problem of Gateway deployment optimization with multi-objective in WMN is known to be NP-complete problem [4]. In order to optimize the WMN's topology and decrease the interference, some researchers have gained some achievements. To minimize the number of gateway and make load balance between gateways, Wu *et al*. [5] proposed a gateway placement optimization algorithm for load balancing in wireless mesh networks, which is greedy algorithm based on the weight of the load of network. Drabu *et al*. [6] used heuristic algorithms to solve gateway placement optimization problem of WMN, and presented a near optimal heuristics algorithm for gateway placement. Seyedzadegan *et al* [7]. put forward a novel algorithm for the gateway placement problem in WMBNs. The algorithm placed a minimum number of IGWs to satisfy quality of service (QoS) requirements.

Recently, the research about WMN using directional antenna is mainly focused on the MAC layer while research on network deployment is just at the beginning. Under directional antenna, a reasonable topology control mode can increase the effect of WMN routing, so that improve the transmission rate packet, fairness and reduce end to end delay [8]. Kandasamy *et al*. [9] studied the improvement of WMN using directional antennas. Each node in the network is equipped with a 4-beam antenna array and forms a grid network topology. Then researchers analyzed the gain of throughput, delay and fairness of network on this topology. Hiraku *et al*. [10] analyzed the performance of WMN using sector antenna, noting that the problem, such as hidden and exposed terminal, "Deafness", which is due to the use of directional antennas could be solved by using sector antenna. Liu *et al*. [11] proposed a topology control method for multi-channel multi-radio wireless mesh networks that use directional antennas. A similar structure is proposed in [12] under the 802.11s standards. Antennas covering a fixed area are deployed on nodes in order to have a full coverage. Based on this topology, a mechanism is proposed to reduce the cost of routing. Li *et al*. proposed a novel optimizing WMN deployment algorithm based on directional antennas and Delaunay triangulation is proposed in [13]. By removing redundant triangle edge, the network topology is simplified and the number of directional antenna deployed on nodes is reduced which make deployment costs reduce. Wu *et al*. studied the gateway deployment problem of WMBN using directional antenna in [14]. A heuristic algorithm based on the capacity of node is proposed to minimize the number of gateways and both the average hops and maximum hops between any mesh router and its closest gateway. Wang *et al* [3] addressed how to jointly optimize topology,routing and channel assignment, and proposed a simple and implementable joint optimization heuristic which is based on interactive LP rounding guarantee to converge. Using Delaunay triangulation, Zhang *et al*. [15] presented a topology control algorithm of WMN based on tolerance region, which can simplify the operation of routing in dynamic scenarios and increase the network throughput.

However, because the nodes of network topology are randomly distributed, the directional antenna communication in wireless network topology control technology still exists link angle is too small and the distance between nodes may be too short,which results in a large channel interference appears between directional antennas. So, it is certain research significance to research on topology control technology for WMNs based on directional antenna. In this paper, we will study a topology control optimization method of WMBN based on directional antenna which combines computational geometry and topology of WMN.

3. Problem Descriptions and Network Model

3.1. Problem Descriptions

As it is known, the gateway node (GW) is the key node to connect the whole WMN to the Internet, so the GW requires higher performance and reliability to ensure the normal operation of the network. In addition, the position of GW in the network also affect the performance of the entire network, and it relates to network delay, network throughput and other network performance. So, we need to be deployed under multiple constraints.

In this paper, the multi-gateway WMBN in which each node is deployed appropriate number of directional antennas is optimized. Taking into account meeting users’ request for bandwidth and network performance, WMBN is divided into disjoint clusters. The gateway deployment algorithm reasonably select a node as a gateway to reduce the deployment costs and the delay from mesh router (MR) to gateway(MR-GW), and also need to balance the load between gateways and control the media competition between nodes at same time. Since the cost of the GW is larger than MR, the number of gateways can be used to represent the cost of gateway deployment. The delay of MR-GW is equivalent to the path length of MR-GW. Therefore, the goal of our algorithms is to minimize the number of gateways and the path length of the MR-GW. Besides, the load balance among gateways and the node contention controlling are achieved through a reasonable division of total traffic of MR and the constraint of the number of node that attach to some gateway.

The researchers have found that Delaunay triangulation (DT) has many desirable properties, so it is widely used in the deployment of wireless network like wireless sensor network [15-17]. It can increase network coverage and minimize network deployment costs, and ensure that the generated network topology as uniform as possible. However, in all the graph formed by triangulation net formed by drawing, the minimum angle of triangulation net formed by Delaunay triangulation is maximum. Therefore, the average degree of the graph nodes is lower.

An initial dealaunay topology graph is shown in Figure 1. As can be seen from the Figure 1, the small angle and long side of the topology is the most important issues affecting the deployment. The small angle needs more directional antenna, resulting in the increase of deployment costs. The long side needs require larger transmission power to ensure connectivity, causing new interference problem. Figure 2 is topology after initial optimization and removing part of the long side. In Figure 2, the node No. 12 is designated as a gateway node, the solid lines represent the shortest path tree connected to the gateway node and the dashed lines represents the remaining original Delaunay topology edge which we will adjust it as an alternative set of directional antenna.

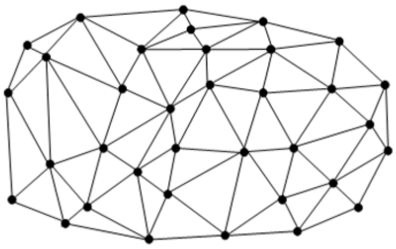

Figure 1. Dealaunay Topology Graph

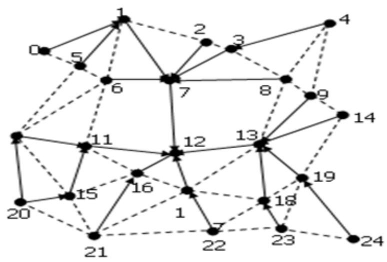

Figure 2. Topology Graph after Initial Optimization

As a result of the same transmission power, using Delaunay triangulation to deploy WMN network based on directional antennas will lead to larger transmission distance of some nodes, so as to cause new interference and energy consumption. Therefore, we need to adjust the cover range of nodes by controlling the transmission power, so that the average connection of nodes in the network is maintained at an acceptable range, which reduces network interference.

Therefore, the research question of this paper is described as follows:(1) choose reasonable nodes as gateway in order to reduce deployment costs and delay of MR-GW;(2) optimize WMBN topology of WMBN and achieve both optimization goals: minimizing the number of GW and the path length of MR-GW.

3.2. Network Model

We model an wireless mesh backbone network as an undirected Delaunay graph G (V, E), $V=\{v_1,v_2,\ldots,v_n\}$ is the set of n network nodes, representing MRs and GWs. E is the set of link in the network. The coordinates of a node can be represented by (x, y). The Euclidean distance between node v_i and v_j is $L(i,j)=\sqrt{(x_i,x_j)^2+(y_i,y_j)^2}$, setting that the maximum transmission distance of directional antenna is L_{max}, in order to reduce the interference between antennas, setting a minimum distance between nodes is L_{min}. Therefore, the radio link set $E=\{(v_i,v_j)|L_{min}\leq L_{min}(i,j)\leq L_{max}\ ,i\neq j\}$, and the adjacency matrix of G is:

$$A=\begin{pmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,n} \end{pmatrix} \tag{1}$$

where $a_{i,j}$ represents whether there is a radio link between nodes v_i and v_j, if $(v_i,v_j)\in E$, then $a_{i,j}$=1, otherwise $a_{i,j}$=0. The link distance between nodes is expressed as ω which is equal to the Euclidean distance between the two nodes, the gateway node is set as V_G and the non-gateway nodes represent a collection V_{NG}.

Vector $Z=\{z_1,z_2,\ldots, z_n\}$ represents that which node is selected as a gateway, when a node v_i is selected as the gateway, $z_i = 1$, otherwise $z_i = 0$. T_i denotes the maximum traffic of node v_i. In this paper, the WMN is divided into several clusters, and each cluster has only one gateway (cluster's head) serving the nodes inside the cluster. Cluster C is a sub graph of G, $C(V',E')\subseteq G(V,E), V'\subseteq V, E'\subseteq E$, C_g represents the cluster whose root node is gateway v_g and $|C_g|$ denotes the node number of C_g. $\lambda(i,j)$ indicates that the node v_i connects to the gateway v_j via a or multi-hop, $\delta(i,j)$ represents the shortest distance between node v_i and v_j with single hop or multi-hop, T_g represents the maximum traffic of gateway v_g, S represents the maximum number of nodes inside the cluster. A_{bad} denotes angle between directional antennas that prone to create interference, that is bad angle. $a(i,j,k)$ represents an angle which vertex is v_i and two sides are (v_i,v_j) and (v_i,v_k). D_{maxP} is the maximum number of directional antennas deployed on each node, $d(i)$ is the degree of note v_i, *pre* is the priority of each nod. The priority of gateway node is the highest, and the farthest node from the gateway node has the lowest priority.

According to the above settings, the formulation of this paper's model is given below:

Optimization goal:

$$\min \sum_{i=1}^{n} z_i \tag{2}$$

$$\min \sum_{i}^{n} \sum_{j}^{n} \delta(i,j) * \lambda(i,j) \tag{3}$$

Subject to：

$$\sum_{v_j \in V_G} \lambda(i,j) = 1, \forall v_i \in V_{NG} \tag{4}$$

$$|C_g| \le S \tag{5}$$

$$\sum_{i=1}^{S} T_i \le T_g, v_i \in C_g \tag{6}$$

$$\forall a(i,j,k) > A_{bad} \tag{7}$$

$$d(i) \le D_{max}, \quad v_i \in V_{NG} \tag{8}$$

In this model, the objective (2) means that a minimum number of nodes selected as the gateway among n nodes is achieved. And the objective (3), the total distance of MR-GW is minimized. These two objectives are subjected to the following constraints. Equation (4) ensures that each node v_i is attached to only one gateway v_j. Inequality (5) guarantees that the number of nodes inside each cluster is within maximum number S. Inequality (6) ensures the gateway maximum traffic capacity as the upper bound of the traffic in each cluster. Inequality (7) represents any angle existing in network topology should be less than bad angle. Inequality (8) represents the number of directional antennas of other routing nodes outside the gateway node is less than the maximum number of directional antennas deployed on each node.

4. Our Algorithm

4.1. Algorithm Descriptions

The gateway deployment optimization problem is treated as a linear programming problem. According to the centrality of graph theory, we propose a gateway deployment algorithm based on Delaunay graph. According to the closeness centrality of graph theory, tightness is a kind of measurement of centrality of a node in a graph. In the analysis of a network, tightness of a node is defined as the reciprocal of the total path of the node to other nodes. Therefore, the closer to the center a node is, the smaller total path of the node to other nodes it has. This algorithm design idea is: in the sub-graph subjected to the constraint of traffic flow and the number of nodes that gateway serve, we figure out the central node or nodes close to the center through greedy algorithm to achieve the shortest path MR to the gateway, and then achieve the shortest total MR-GW distance of the whole network. Another objective of the proposed algorithm is to achieve the minimum number of gateways based on a reasonable network division of network traffic flow subjected to the QoS constraints.

Our gateway deployment algorithm based on Delaunay graph for WMN is described as follows:

Step1: Collect the network information (including the maximum traffic flow and coordinates of nodes), and then we get the Delaunay topology of WMN according to this information. The overall traffic flow of the network is calculated to decide whether the network is divided.

Step2: According to breadth-first traversal principle, it began to traverse the nodes in the graph from the node in the lower left corner. When the traffic flow of traversed node reaches maximum limit of gateway or the number of traversed node reaches *S*, the Delaunay sub graph is formed.

Step3: The center coordinates of the sub graph are found out based on the coordinates of nodes in the sub graph so that can get the Euclidean distance of each node to the center point and the shortest three nodes are found out. The one of these three nodes has the shortest total distance to other nodes is selected as the gateway of the sub graph. The traversed nodes are removed from the adjacency matrix.

Step4: Repeat Step2 and Step3 in the rest of the adjacency matrix until all gateways needed in the network are selected.

Step5: Obtain the connections of each node in Delaunay sub graphs and gateway node according to the position of the selected gateway node. Setting A_{bad} and D_{max}.

Step6：Traverse the topology of various sub-clusters in the entire network, find out all triangle which interior angles is less than A_{bad}, and remove the edge opposite the maximum angle in these triangle. Thus, we can get the initial optimization topology.

Step7：Take the gateway of each Delaunay sub-graph as the root node of the tree, the distance from the gateway as the priority *pre*. and connect Delaunay sub-graph nodes except the gateway node to the tree. When connected, select only those nodes which *pre* is highest and its degree is not greater than D_{max}. If the degree of optimal node is greater than Dmax, then select sub-optimal node to connect.

Step8：Repeat Step7 until all nodes in each Delaunay sub-graph have been traversed and connected. Finally, we get a network topology based clustering.

Step9：If the degree of all nodes are not larger than D_{max}, we can add redundant paths through the network in order to increase the reliability and redundancy of the network.

4.2. Instance Description of Algorithm

In this section, we use a instance to describe the execution process of the algorithm. To simplify the demonstration, we only use a Delaunay sub-graph for instance. The topology of the instance is shown in Figure 3, and the hexagram node represents the gateway node. Obviously, there are many links which angle is to small in whole topology, and these links will have too much interference between the directional antenna. So, it is necessary to optimize these links.After using the our algorithm to optimize the angle of these links, the optimized topology is shown in Figure 4. Optimization results shows that links have been improved and effectively reduced the communications interference between directional antenna.

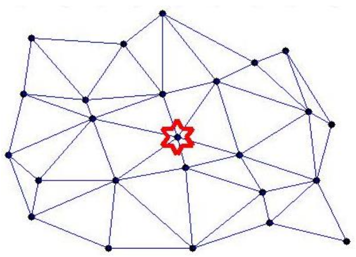

Figure 3. Delaunay Sub-graph

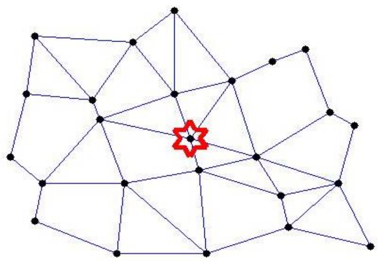

Figure 4. Topology Graph after Optimizing Bad-angle

However, the degree of some nodes is still higher, the number of antennas on these nodes are also larger. Thus, we also need to limit the degree of these nodes and make MR-GW distance to a minimum. The further optimized result is shown in Figure 5. After optimization, the degree of each node is not greater than D_{max}, the number of antennas deployed on each node is reduced and the MR-GW is also shorter. To further ensure network connectivity, our algorithm adds a certain amount of redundancy side (as shown in Figure 6). Obviously, after the algorithm optimization, network topology has the minimal MS-GW, and has ensured redundancy of the network at same time.

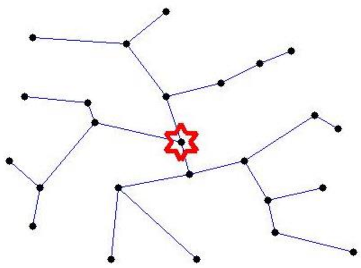

Figure 5. Topology after re-connection

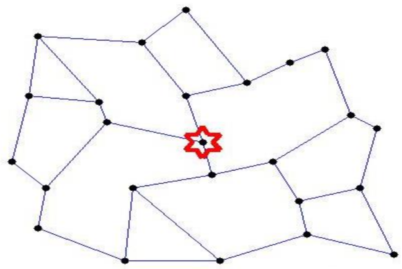

Figure 6. Topology after Adding Redundant Edges

5. Performance Analysis and Simulation Result

5.1. Experimental Environment and Parameters setting

In simulation experiment, the A_{bad} is set at 30 degrees, the D_{max} of each node is 3. Each node communicates with the gateway node with the shortest path. All nodes are randomly and uniformly distributed so that the distance between the nodes is approximately equal which make us use total number of MR-GW hops to represent the total MR-GW distance. In order to simplify the calculation, we set that all MR node's local traffic is 1 and the maximum traffic T_g of gateway v_g is 25. The maximum traffic of gateway is equal to the maximum number of nodes it serves, which means the cluster' s maximum number of node is 25.

The random deployment algorithm and ILA (Improved Liu's Architecture) algorithm proposed in [6] are used as comparison algorithms in experiment. The simulation is done using MATLAB tool.

5.2. Simulation Result and Performance Analysis

Experiment 1 is to compare deployment results obtained by three algorithms taking the total number of network hops as a measure. Firstly, Delaunay graph is generated according to the coordinates of nodes. Then, we find the location of gateway by our algorithm. ILA algorithm and random algorithm respectively and compare the total MR-GW hops of them. The simulation result is shown in Figure 7.

As can be seen from Figure 7, when the number of nodes increases, the total MR-GW hops of our algorithm is always less than the one of random algorithm and ILA algorithm. With the number of nodes increases, the difference becomes more apparent. Experimental result indicates that our algorithm is still better than the comparison algorithm after optimizing network deployment.

Different maximum traffic of gateway also has influence on the MR-GW hops. We keep the WMN stay 100 nodes and the network topology steady, and then investigate the relation between the maximum traffic of gateway and the total MR-GW hops. Figure 8 gives the simulation result.

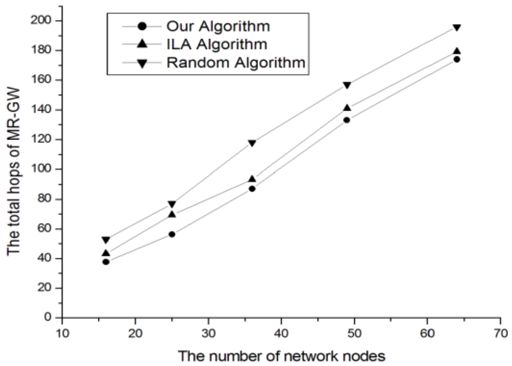

Figure 7. Comparison Results of the Total MR-GW Hops

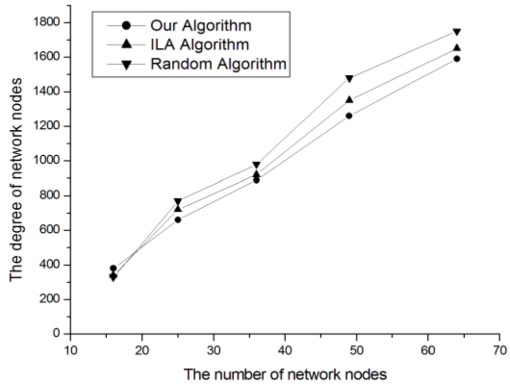

Figure 8. Comparison Result of Network Nodes' Degree

In Figure 8, with the maximum traffic of gateway T_g increases, the total MR-GW hops also increases. The reason is that the algorithm limits the number of nodes of cluster with T_g. While T_g is small, less nodes are in the cluster which make the number of cluster increase so that the total MR-GW hops reduces; when T_g increases, more nodes are in the cluster and the number of clusters increases which results in the increase of the total MR-GW hops. As shown in Figure 2, when T_g increases from 25 to 30, the total MR-GW of hops has no apparent increase. That is because the network is divided based on T_g which make the number of gateway is $\lceil n/T_g \rceil$. That's the minimum number of gateway that satisfies user's requirement within the load capacity of gateways. So whether T_g is 25 or 30, the number of gateways is 4 and the total MR-GW hops has no significant increase.

Taking the product of node degree and transmission distance as an evaluation standard, we also compare the performance of the three algorithms, and comparison result is shown in Figure 9.

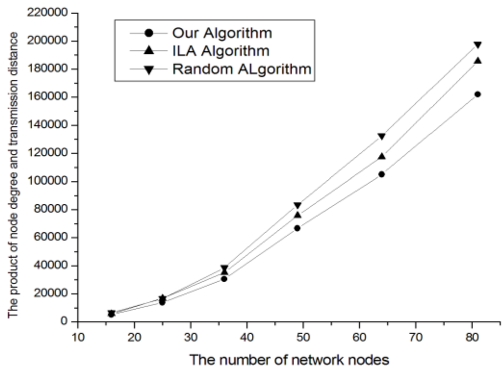

Figure 9. Comparison in Product of Degree and Transmission Distance

The simulation result show that the products of our algorithm is significantly less than ILA algorithm and random algorithm. It is because the algorithm proposed in this paper is based on the transmission distance as a priority objective, so each node can be connected to the path closest to GW. In the case of GW's degrees are not limited, the GWs can be connected with all adjacent nodes which distance to GW is shortest, such that it increase the communication path of MR-GW for each node and significantly reduce the transmission distance. But, its cost is to increase the degree of GW.

6. Conclusion

Combining transmission characteristics of directional antenna and advantages of Delaunay triangle graph, this paper proposes a new deployment algorithm to optimize gateway deployment and topology of WMBNs based on directional antenna. While network connectivity is guaranteed, the algorithm reduces wireless links that the transmission distance is too long and energy consumption is high to improve the transmission rate and reduce energy consumption of WMN. The cost of WMN deployment can be effectively reduced by limiting the number of directional antennas deployed on nodes of WMN. The simulation shows that the algorithm proposed in this paper achieves the minimum number of gateways and the shortest total MR-GW distances while guaranteeing the requirement of user within the load of gateway. This algorithm can effectively optimize topology of WMN and solve the problem of the interference between the directional antenna.

Acknowledgements

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