QoS Topology Control in Ad Hoc Wireless Networks

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Abstract—**This paper discusses the energy efficient QoS topology control problem in ad hoc wireless networks. Given a set of nodes in a plane, end-to-end traffic demands and delay bounds between node pairs, the problem is to find a network topology that can meet the QoS requirements and the maximum transmitting power of nodes is minimized. We consider two cases of the problem: 1) the traffic demands are not splittable, and 2) the traffic demands are splittable. For the former case, the problem is formulated as an integer linear programming problem. For the latter case, the problem is formulated as a mixed integer programming problem, and an optimal algorithm has been proposed to solve the problem.** (*Abstract*)

Keywords—*ad hoc wireless networks*; *energy management*;*QoS provision*; *QoS routing*; *topology control* (*key words*)

I. INTRODUCTION

An ad hoc wireless network is a special type of wireless networks that does not have a wired infrastructure to support communication among the wireless nodes. In multi-hop ad hoc networks, communication between two nodes that are not direct neighbors requires the relay of messages by the intermediate nodes between them. Each node acts as a router, as well as a communication end-point. There are many modern network applications that require QoS provisions in ad hoc networks, such as transmission of multimedia data, real-time collaborative work, and interactive distributed applications.

Extensive research has been done on QoS provisions in ad hoc networks, such as QoS routing or admission control [1-4]. Most of the existing works deal with resource allocation (e.g., scheduling or buffering) or routing for QoS requests. However, the construction of a network topology that can overall meet QoS requirements has not been studied in the literature. In multi-hop ad hoc networks, on-line QoS provisions, such as end-to-end bandwidth and delay, are highly dependent on the network topology. Without a proper configuration of the topology, some nodes in the network could be easily over-loaded and it might be impossible to find a QoS route during the operation of the network.

The topology of an ad hoc network can be controlled by some "controllable" parameters such as transmitting power and antenna directions. Topology control is to allow each node in the network to adjust its transmitting power (i.e., to determine its neighbors) so that a *good* network topology can be formed. An issue often associated with topology control is energy management. In ad hoc wireless networks, each node is usually powered by a battery equipped with it. Since the capacity of battery power is very much limited, energy consumption is a major concern in topology control. To increase the longevity of such networks, an important requirement of topology control algorithms is to achieve the desired topology by using minimum energy consumption.

In this paper, we study the energy efficient QoS topology control problem. Given a set of wireless nodes in a plane and QoS requirements between node pairs, our problem is to find a network topology that can meet the QoS requirements and the maximum transmitting power of nodes is minimized. The QoS requirements of our concern are traffic demands (bandwidth) and maximum delay bounds (in terms of hop counts) between end-nodes at the application level. With the network configured in such a topology, as many as possible QoS calls can be admitted at run-time and the network life time can be prolonged.

II. RELATED WORK

There are some research works that have already been done on topology control for ad hoc wireless networks. The earlier works of topology control can be found in [5, 6]. In [6], Hou *et al.* studied the relationship between transmission range and throughput. An analytic model was developed to allow each node to adjust its transmitting power to reduce interference and hence achieve high throughput. In [5], a distributed algorithm was developed for each node to adjust its transmitting power to construct a reliable high-throughput topology. Minimizing energy consumption was not a concern in both works.

Recently, energy efficient topology control becomes an important topic in ad hoc wireless networks. Most of the works have been focused on the construction and

maintenance of a network topology with good (or required) connectivity by using minimal power consumption. Lloyd *et al.* gave a good summary of the works in this type in [7]. They use a 3-tuple <M, P, O> to represent topology control problems, where "M" represents the graph model (either directed or undirected), "P" represents the desired graph property (e.g., 1-connected or 2-connected), and "O" represents the minimization objective (e.g., MinMax power or Min total power). The NP-completeness of this kind of problems has been analyzed and several algorithms have been proposed. In [8], two centralized optimal algorithms were proposed for creating connected and bi-connected static networks with the objective of minimizing the maximum transmitting power for each node. Additionally, two distributed heuristics, LINT (local information no topology) and LILT (local information link-state topology), were proposed for adaptively adjusting node transmitting power to maintain a connected topology in response to topological changes. But, neither LINT nor LILT can guarantee the connectivity of the network. Li *et al.* proposed a minimum spanning tree based topology control algorithm that achieves network connectivity with minimal power consumption [9]. A cone-based distributed topology control method was developed in [10]. Basically, each node gradually increases its transmitting power until it finds a neighbor node in every direction (cone). As the result, the global connectivity is guaranteed with minimum power for each node. Huang *et al.* extended this work in [10] to the case of using directional antennas [11]. Marsan *et al.* presented a method in [12] to optimize the topology of Bluetooth, which aims at minimizing the maximum traffic load of nodes (thus minimizing the maximum power consumption of nodes).

There are a lot more works on energy efficient communication in ad hoc wireless networks, such as in [13, 14]. Singh *et al.* studied five different metrics of energy efficient routing in [14], such as minimizing energy consumed per packet, minimizing variance in node power levels, minimizing cost per packet, and so on. Kawadia *et al.* proposed a clustering method for routing in non-homogeneous networks [15], where nodes are distributed in clusters. The goal is to choose the transmit power level, so that low power levels can be used for intra-cluster communication and high power levels for inter-clusters. In [16], Wieselthier *et al.* studied the problem of adjusting the energy power of each node, such that the total energy cost of a broadcast/multicast tree is minimized. Some heuristic algorithms were proposed, namely the Broadcast Incremental Power (BIP), Multicast Incremental Power (MIP) algorithms, MST (minimum spanning tree), and SPT (shortest-path tree). The proposed algorithms were evaluated through simulations. Wan *et al.* in [17] presented a quantitative analysis of performances of these three heuristics.

So far, there is no published work that considers how to meet the overall QoS requirements through topology control. In this paper, we address the problem of topology control that can meet the QoS requirements and the maximal power of nodes in the system is minimized.

III. SYSTEM MODEL AND PROBLEM SPECIFICATION

We adopt the widely used transmitting power model for radio networks: $p_{ij} = d_{i,j}^{\alpha}$, where p_{ij} is the transmitting power needed for node i to reach node j, $d(i, j)$ is the distance between i and j, and α is a parameter typically taking a value between 2 and 4.

The network is modeled by $G = (V, E)$, where V is the set of n nodes and E a set of undirected edges. Each node has a bandwidth capacity B, and a maximal level of transmitting power P. The bandwidth of a node is shared for both transmitting and receiving signals. That is, the total bandwidth for transmitting signals plus the total bandwidth for receiving signals at each node shall not exceed B. Let p_i denote the transmitting power of node i. We assume that each node can adjust its power level, but not beyond some maximum power P. That is, $0 \leq p_i \leq P$ for $1 \leq i \leq n$. The connectivity between two nodes depends on their transmitting power. An edge $(i, j) \in E$ iff $p_i \geq d^{\alpha}(i, j)$ and $p_j \geq d^{\alpha}(i, j)$.

From the network model, we can see that the network topology can be controlled by the transmitting power at each node and the topology directly affects the QoS provisions of the network. If the topology is too dense (*i.e.*, nodes have more neighbors), there would be more choices for routing, but the power consumption of the system would be high. On the other hand, if the topology is too loose (*i.e.*, with less edges), there would be less choices for routing (hence, some nodes could be over-loaded) and the average hop-count between end-nodes would be high. Our goal is to find a balanced topology that can meet end-users QoS requirements and has minimum energy consumption.

Let $\lambda_{s,d}$ and $\Delta_{s,d}$ denote the traffic demand and the maximally allowed hop-count for node pair (s, d), respectively. Let $P_{max} = \max\{p_i \mid 1 \leq i \leq n\}$. The topology control problem of our concern can be formally defined as: given a node set V with their locations, $\lambda_{s,d}$ and $\Delta_{s,d}$ for node pair (s, d), find transmitting power p_i for $1 \leq i \leq n$, such that all the traffic demands can be routed within the hop-count bound, and P_{max} is minimized.

We consider two cases: 1) end-to-end traffic demands are not splittable, i.e., $\lambda_{s,d}$ for node pair (s, d) must be routed on the same path from s to d; 2) end-to-end traffic

demands are splittable, i.e., $\lambda_{s,d}$ can be routed on several different paths from s to d.

We assume each node can transmit signals to its neighbors in a conflict free fashion. Thus, we do not consider signal interference in this paper. There are many MAC (medium access control) layer protocols [18, 19] or code assignment protocols [20, 21] that have been proposed to avoid (or reduce) signal interference in radio transmissions.

IV. TOPOLOGY CONTROL WITH TRAFFICS NON-SPLITTABLE

Given:

- V, set of n nodes and their locations.

- B, the bandwidth of each node.

- $\lambda_{s,d}$, traffic demands for each node pair (s, d).

- $\varDelta_{s,d}$, maximally allowed hop-count for node pair (s, d).

- P, maximally allowed transmitting power of nodes.

Variables:

- $x_{i,j}$, boolean variables, $x_{i,j}=1$ if there is a link from node i to node j; otherwise, $x_{i,j} = 0$.

- $x_{i,j}^{s,d}$, boolean variables, $x_{i,j}^{s,d}=1$ if the route from s to d goes through the link (i, j); otherwise $x_{i,j}^{s,d} = 0$.

- $P_{\max}$, the maximum transmitting power of nodes.

Optimize:

- Minimize the maximum transmitting power of nodes.

$$Min \ P_{\max} \qquad\qquad (1)$$

Constraints:

- Topology constraints:

$$x_{i,j} = x_{j,i} \qquad \forall i, j \in V \qquad (2)$$

$$x_{i,j} \le x_{i,j'} \quad d(i,j') \le d(i,j) \ \ \forall i, j, j' \in V \quad (3)$$

- Transmitting power constraint:

$$P \ge P_{\max} \ge d_{i,j}^{\alpha} x_{i,j} \quad \forall i < j, \ i, \ j \in V \quad (4)$$

- Delay constraint:

$$\sum_{(i,j)} x_{i,j}^{s,d} \le \varDelta_{s,d} \qquad\qquad \forall (s,d) \qquad (5)$$

- Bandwidth constraint:

$$\sum_{(s,d)} \sum_{j} x_{i,j}^{s,d} \lambda_{s,d} + \sum_{(s,d)} \sum_{j} x_{j,i}^{s,d} \lambda_{s,d} \le B \ \ \forall i \in V \ (6)$$

- Route constraints:

$$\sum_{j} x_{i,j}^{s,d} - \sum_{j} x_{j,i}^{s,d} = \begin{cases} 1 & \text{if } s = i \\ -1 & \text{if } d = i \quad \forall i \in V \ (7) \\ 0 & \text{otherwise} \end{cases}$$

$$x_{i,j}^{s,d} \le x_{i,j} \qquad \forall \ i, j \in V \qquad\qquad (8)$$

- Binary constraint:

$$x_{i,j} = 0, or \ 1, \ x_{i,j}^{s,d} = 0, or \ 1 \quad \forall i, j \in V, (s,d) \quad (9)$$

Remarks:

- Constraint (2) ensures that each edge corresponds to two directed links.

- Constraint (3) ensures that nodes have broadcast ability. That is, the transmission by a node can be received by all the nodes within its transmitting range. This feature can be represented by the links in the network as: for node i, if there is a link to j (*i.e.*, $x_{i,j} = 1$), then there must be a link to any node j' (*i.e.*, $x_{i,j'} = 1$) when $d_{i,j'} \le d_{i,j}$, which is constraint (3).

- Constraint (4) determines the maximum transmitting power among all nodes.

- Constraint (5) ensures that the hop-count for each node-pair does not exceed the pre-specified bound.

- Constraint (6) ensures that the total transmission and reception of signals at a node do not exceed the bandwidth capacity of this node. The first term at the right hand side of inequality (6) represents all the outgoing traffics at node i (transmitting) and the second term represents all the incoming traffics (reception).

- Constraints (7) and (8) ensure that the validity of the route for each node-pair. Since traffics are not splittable, $x_{i,j}^{s,d}$ represents that the entire traffics of (s,

d) go through link (i, j) if it is in the route from *s* to *d*. The availability of bandwidth along the route is ensured by constraint (6).

The problem of QoS topology control for non-splittable has now been formulated as an integer linear programming problem (ILP) (1)-(9), which is NP-hard in general. There are several tools that can be employed to compute the solution to this problem. After computing out $x_{i,j}$ for $1 \le i, j \le n$, the transmitting power of node *i* can be determined by the distance to its furthest neighbor. We use a user-defined toolbox called matlog (http://www.ie.ncsu.edu/kay/matlog) in Matlab 6.5 to solve the problem for experiment purpose. The experimental results are presented in section 6.B.1.

V. TOPOLOGY CONTROL WITH TRAFFICS SPLITTABLE

When the network is in operation, the traffics between a node-pair may take different routes due to congestion or failures in the network. In this subsection, we consider the case that the traffic demands can be split. That is, the flow going through a path is no longer an integer.

A. Formulation

Given:

- All the parameters in the formulation of non-splittable case remain the same.

Variables:

- $x_{i,j}$ and P_{max} remain the same as above.

- $f_{i,j}^{s,d}$, variables representing the amount of traffics of node pair (*s, d*) that go through link (*i, j*).

Optimize:

- Minimize the maximum power of nodes.

$$Min \ P_{\max} \qquad (10)$$

Constraints:

- Topology constraints:

$$x_{i,j} = x_{j,i} \qquad \forall i, j \in V \qquad (11)$$

$$x_{i,j} \le x_{i,j'} \text{if } d(i, j') \le d(i, j) \ \forall i, j, j' \in V \quad (12)$$

- Transmitting power constraint:

$$P \ge P_{\max} \ge d_{i,j}^{\alpha} x_{i,j} \qquad \forall i < j, \ i, \ j \in V \qquad (13)$$

- Bandwidth constraint:

$$\sum_{(s,d)} \sum_{j} f_{i,j}^{s,d} + \sum_{(s,d)} \sum_{j} f_{j,i}^{s,d} \le B \qquad \forall i \in V \qquad (14)$$

- Routes constraints:

$$\sum_{j} f_{i,j}^{s,d} - \sum_{j} f_{j,i}^{s,d} = \begin{cases} \lambda_{s,d} & \text{if } s = i \\ -\lambda_{s,d} & \text{if } d = i \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in V \quad (15)$$

$$f_{i,j}^{s,d} \le f_{i,j}^{s,d} x_{i,j} \qquad \forall \ i, j \in V, (s,d) \qquad (16)$$

- Variables constraints:

$$\begin{aligned} x_{i,j} &= 0, or1 \\ f_{i,j}^{s,d} &\ge 0, \quad \forall i, j \in V, (s,d) \end{aligned} \qquad (17)$$

Remarks:

- The objective and most of the constraints are the same as the non-splittable case.

- Constraint (15) is for flow conservation along all the routes for node pair (*s, d*).

- There is no delay constraint in the above formulation, because the traffics between a node pair can be routed via several different paths.

The QoS topology control problem with traffics splittable has now been formulated as a mixed integer programming problem in $(10) - (17)$.

B. Our Solution

Our problem is to find the network topology such that all traffics can be routed and the maximal node power is minimized. In the case where traffics are splittable, our solution consists of two major steps: 1) increment node power to connect two nodes that have the shortest Euclidean distance among the unconnected node-pairs; 2) check if the traffics can be routed on the topology constructed in step 1. If so, the topology is found; otherwise repeat steps 1 and 2.

Because traffics are splittable, the problem in step 2 can be transformed to a variant of the multi-commodity flow problem, that is, for a given network topology, to route commodities on the network such that the maximal load of nodes is minimized. Since we assumed all nodes have the same bandwidth capacity, the objective of

minimizing the maximal node load would lead to the optimal routing to accommodate the traffics.

We first consider the QoS routing problem for a given network topology.

1) QoS Routing Problem

Given a network graph G and traffic demands between node pairs, route these traffics in this graph, such that the maximum node-load in the system, denoted by $L_{\max}$, is minimized. This problem can be formulated as the following:

$$MinL_{\max} \qquad (18)$$

$$\sum_j f_{i,j}^{s,d} - \sum_j f_{j,i}^{s,d} = \begin{cases} \lambda_{s,d} & \text{if } s = i \\ -\lambda_{s,d} & \text{if } d = i \quad \forall i \in V \\ 0 & \text{otherwise} \end{cases} \qquad (19)$$

$$\sum_{(s,d)} \sum_j f_{i,j}^{s,d} + \sum_{(s,d)} \sum_j f_{j,i}^{s,d} \le L_{\max} \quad \forall i \in V \qquad (20)$$

$$f_{i,j}^{s,d} \ge 0, \quad \forall i, j \in V, (s,d)$$
$$L_{\max} \ge 0 \qquad (21)$$

Note that: $\forall (s,d), f_{i,j}^{s,d} = 0, if (i,j) \notin E(G)$

Function (18) is the objective, which is to minimize the maximum node load. Constraint (20) obtains the maximum node load in the network. When any request cannot be routed due to the disconnection of the network, it will report an error of disconnection.

This is a linear programming (LP) problem. The optimal solution can be found in polynomial time $O((|E|t)^{3.5})$, where $|E|$ is the number of edges in graph G, and t is the number of node pairs which have non-zero traffic. We use Matlab 6.5 to compute the LP problem.

The next, we integrate this QoS routing algorithm with the energy efficient topology control.

2) Energy Efficient QoS Topology Control Algorithm

The basic idea of the algorithm is to sort all node pairs (in fact, only the node pairs that can be reached within the maximal transmitting power P are considered) in ascending order according to their Euclidean distance. Each time the pair of nodes that have the shortest distance and have not yet had a link between the two nodes are picked and their power is increased until they can reach each other. Then, the QoS routing algorithm runs on the network to see if the requested traffics can be all routed. This operation is repeated until the QoS topology is found, or all nodes already reached their

maximal power P (the topology that can meet the QoS requirements does not exist in this case).

Input: node set V with their locations, $\lambda_{s,d}$ for node-pair (s, d), and bandwidth capacity B.

Output: power levels p for all nodes in V.

a) sort all node-pairs with $d^\alpha(i,j) \le P$ ($i<j$) in ascending order according to $d(i,j)$.

b) pick up the node-pair with closest distance but not yet connected and increase the power to make them connected to get a new graph G.

c) run the QoS routing algorithm on G to obtain $L_{\max}$. If $L_{\max} \le B$, then stop; otherwise repeat (b) and (c).

In step (b), it stops if all nodes already reach power P and an error of no solution is reported in this case. To reduce the number of times of calling the QoS routing algorithm in step (c), we use the binary search method to find the QoS topology, instead of adding an edge each time and running the routing algorithm.

In this algorithm, the node power is gradually increased until the required topology is formed. It is not difficult to see that the maximum node energy needed to form the required topology is minimum, provided the number of power-levels of a node is finite. Furthermore, the topology found in step (b) and (c) is minimum in the sense that it has the least number of edges that are added-in among all the possible topologies that can meet the QoS requirements. This is because the routing produced by our QoS routing algorithm (formulated in (18) − (21)) is also optimal in the sense that the maximum node-load in the topology is minimum. That is, given a topology, if our routing algorithm cannot route all traffic demands without letting any node exceed its bandwidth capacity, there is no solution on this topology (i.e., the topology needs more edges to split traffics off). Therefore, when traffic demands are splittable, our algorithm can find the optimal solution to the energy efficient QoS topology control problem.

VI. EXPERIMENTS

A. Simulation Setup

The simulations are conducted in a 30×30 two-dimensional free-space region. The co-ordinates of the nodes are randomly and uniformly distributed inside the region. All nodes have the same bandwidth capacity $B = 500$. The value of α in the transmitting power function is set to 2, i.e., $p_{ij} = d_{i,j}^\alpha$ for $\alpha = 2$.

The set of requests $R = \{(s, d, \lambda_{s,d})\}$ are generated by using the Poisson function (i.e., the requests originating from a node follow the Poisson distribution). For each node, we use the random Poisson function with the mean value $\lambda = 1$ to generate a number k, which is the number of requests originating from this node. The destinations of the k request are randomly picked from the other nodes. The traffic demand $\lambda_{s,d}$ for a pair of nodes (s, d) is assigned by a random function of a normal distribution with variance equal to $0.5\lambda_m$, where λ_m is the mean value of the normal distribution function (i.e., the average bandwidth demand per request).

B. Simulation Results and Analysis

1) Topologies for non-splittable traffic versus splittable traffic

The first experiment is to compare the topologies for the two cases of traffic non-splittable and splittable. Fig.1 shows the topology of a network with 6 nodes and 6 requests. The 6 nodes are randomly dispersed in a 30×30 two-dimensional region. The bandwidth capacity of nodes, i.e., B, is set to 500. The source, destination, and traffic demand of the 6 requests are generated in the same way as described in subsection VI.A. The average traffic amount per request (i.e., λ_m) is 150, which is $0.3B$. The details of the requests and the computed routing information are in Tab.1.

For comparison, Fig.2 is the topology for the case where traffics are splittable and the topology is computed by using the method described in section V. The input for Fig.2 is the same as Fig.1. Tab.2 shows the routing and traffic distribution in the topology of Fig. 2. Comparing Fig.1 with Fig.2, we can see that the topology for non-splittable case has a long distance edge (1, 3) in Fig.1, which results in a much higher P_{max} than the splittable case. The topology for splittable case has more short edges, which helps splitting the traffic off among multiple routes. Note that: Fig. 1and Fig.2 are topologies which remove the redundant edges, i.e., no traffic edges.
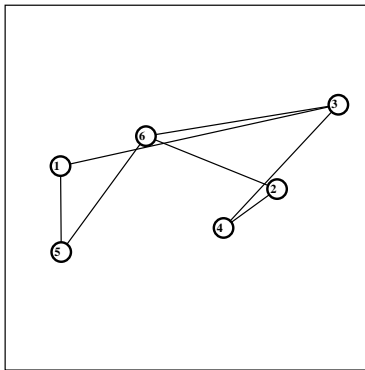

Figure 1. Topology of six nodes and six requests for non-splittable case

TABLE.1. THE QoS REQUESTS AND THEIR ROUTES FOR FIGURE1

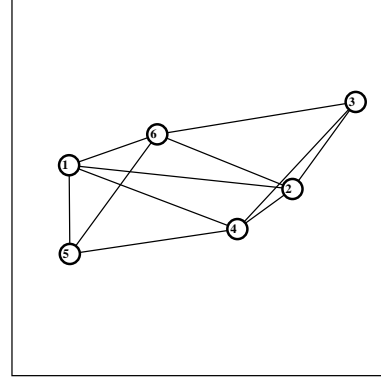| s	d	$\lambda_{s,d}$	route
2	4	148.6403	2→4
3	4	142.2603	3→4
5	1	152.0183	5→1
5	3	137.897	5→6→3
1	3	155.6549	1→3
6	2	163.5291	6→2

Figure 2. Topology of six nodes and six requests for splittable case

TABLE 2. THE QoS REQUESTS AND THEIR ROUTES FOR FIGURE2

| s	d		splitted	route
2	4		134.0611	2→4
			6.7199	2→1→5→4
			5.9452	2→1→4
			1.9141	2→3→4
3	4		142.2603	3→4
5	1		152.0183	5→1
5	3		82.1792	5→6→3
			38.3595	5→4→3
			8.2598	5→1→2→3
			4.7424	5→1→6→3
			4.3561	5→1→4→3
1	3		61.2726	1→2→3
			41.9292	1→6→3
			24.8259	1→4→3
			15.0018	1→5→6→3
			12.6254	1→5→4→3
6	2		145.41	6→2
			7.3976	6→5→1→2
			6.5375	6→1→2
			4.1839	6→3→2

2) Topologies versus traffic load

This experiment shows how the topology changes as the increase traffic demands. The network topology is dictated by the traffic demands once node locations are given. Fig.3 shows the topology changes as the increase of λ_m. For the clarity of drawing, only 10 nodes are used in this experiment. When λ_m is relatively small (to B), the topology does not change much (as seen from Fig.3a and Fig.3b). When λ_m reaches a certain threshold ($\lambda_m = 0.1B$), the number of edges in a topology increases in a fast speed (which can also be evidenced in Fig.4). The topology in Fig.3d is almost saturated due to the high traffic load in the network. It has been observed that about 50% of the cases have no solution (i.e., no such a topology that can meet the QoS demands) when λ_m reaches $0.3B$.
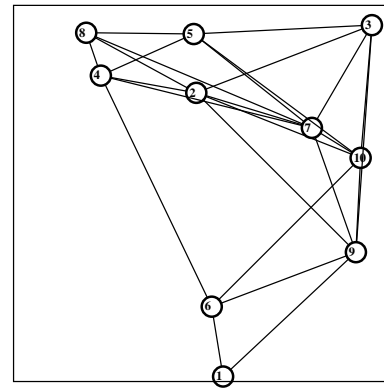
The third experiment is to analyze the generated topologies. In this experiment, 20 nodes are distributed in the 30×30 region to form an ad hoc network. Fig.4 –6 show how the node-degree, node-load, and node-transmitting-power change, respectively, as the changes of λ_m. From Fig.4 - 6, the following observations can be made:
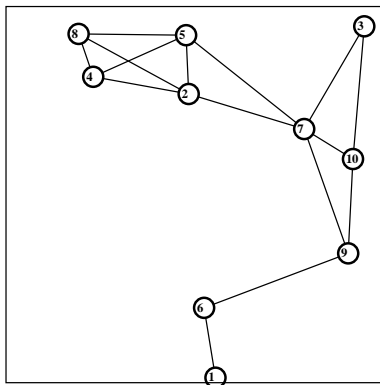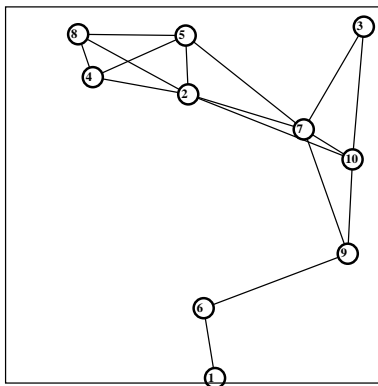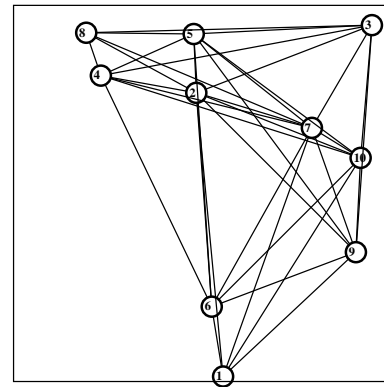
(c)

(d)

Figure3. The network topology for (a) $\lambda_m = 0.02B$; b) $\lambda_m = 0.1B$; c) $0.2B$ d) $\lambda_m = 0.32B$.

1) Node degrees increase slowly when λ_m is small (in fact, the topology has little change before λ_m reaches $0.05B$), as shown in Fig.4. When λ_m is greater than $0.075B$, it is observed the node degrees increase quickly. After λ_m reaches $0.2B$, it starts to have "no solution" cases, and the simulation results become unstable due to the drop out of the "no solution" samples.

2) The QoS routing algorithm is very effective in load-balancing. From Fig.5, we can see maximum node load, L_{max}, becomes closer to the average node-load, L_{avg}, when the load in the network gets heavier, and the increase of L_{max} slows down quickly and becomes quite stable after λ_m reaches $0.1B$.
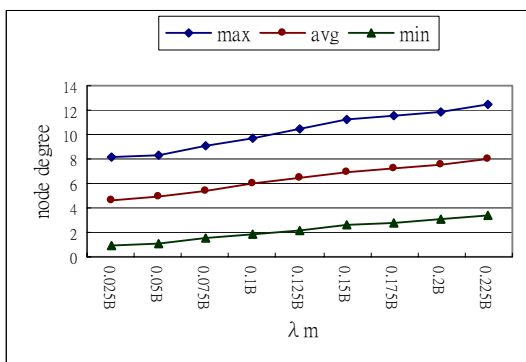
(a)

(b)

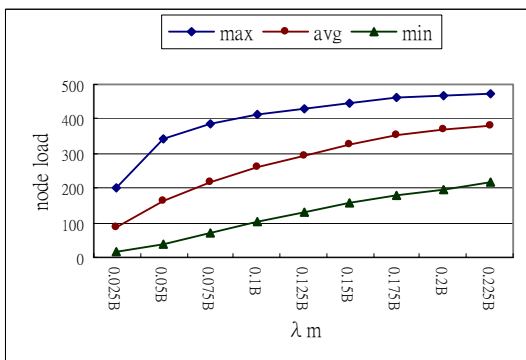Figure 4. Node-degrees versus λ_m
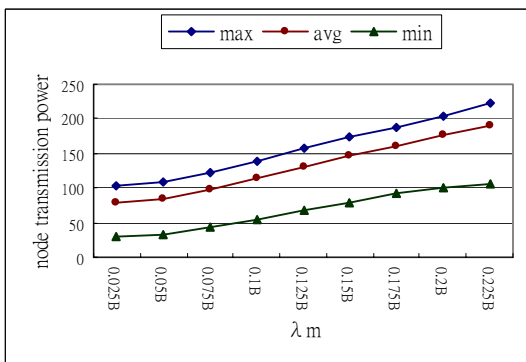

Figure 5. Node-load versus λ_m

Figure 6. Node-transmitting-power versus λ_m

3) Fig.6 shows that our topology control method is very effective in balancing the uses of node transmitting power. We can see the maximal node power, P_{max}, is constantly quite close to the average node power, P_{avg}. The shows that the topology generated by our method uses short edges and avoids using long distance edges. This feature of balancing the use of node power extends greatly the lifetime of the network.

VII. CONCLUSIONS

We have discussed the energy efficient QoS topology control problem. This is the first time in the literature that topology control is studied regarding to QoS provisions. Both cases of traffic splittable and non-splittable have been considered. For the former case, we considered both bandwidth and delay bound as QoS requirements. The problem has been formulated as an integer linear programming problem. For the latter case, we considered only the bandwidth requirement, and the problem has been formulated as a mixed integer programming problem. A polynomial time algorithm has been proposed to compute the optimal solution.

The problem discussed is a static configuration problem. The traffic demands are assumed to be known in prior. By configuring a good QoS topology, QoS requests can be best served in the system (i.e., less requests will be blocked). However, due to the dynamics and the unpredictability of network traffics, a QoS request can still be blocked no matter how good the topology is. In a dynamic environment where nodes are mobile and traffics are dynamic, the proposed topology control algorithm can be run periodically to keep the topology optimal in the sense that it balances the node energy consumption and, at the same time, meets users QoS requirements.

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