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QoS Topology Control for Nonhomogenous Ad Hoc Wireless Networks

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This paper discusses the energy-efficient QoS topology control problem for nonhomogenous ad hoc wireless networks. Given a set of nodes with different energy and bandwidth capacities in a plane, and given the 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 energy utilization of nodes is minimized. Achieving this objective is vital to the increase of network lifetime. 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.

1. INTRODUCTION

An ad hoc wireless network is a special type of wireless network 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 meet overall QoS requirements has not been studied in the literature. In multihop 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 overloaded and it might be impossible to find a QoS route upon the arrival of a QoS request. To the best knowledge of the authors, there is no published work so far that addresses the problem of forming the topology for nonhomogenous wireless networks to meet the QoS requirements.

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.

Most of the existing works on topology control for wireless ad hoc networks assume homogenous network environment where nodes have the same bandwidth and energy capacities. However, this assumption on network homogeneity does not always hold in practice. Non-homogenous networks are more general, where nodes can have different bandwidth or energy capacities. For example, the wireless devices carried on vehicles usually have much larger batteries (as well as bandwidth capacities) than the devices carried by persons. The algorithms for homogenous networks, usually, cannot be directly applied to non-homogenous networks.

In this paper, we study the problem of QoS topology control for non-homogenous ad hoc wireless networks. Given a set of wireless nodes in a plane where nodes have different maximal transmitting powers and bandwidth capacities, and given QoS requirements between node-pairs, our problem is to find a network topology that can meet the QoS requirements and minimize the maximal power utilization ratio of nodes. 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. The power utilization of a node is the actual power consumption divided by the energy capacity of the node. The objective of minimizing the maximal power utilization of nodes would balance the power consumption of all nodes, which would avoid the situation that some nodes run out of energy faster than others. The lifetime of the network which is defined as the period of time before any node in the network runs out of its energy can, thus, be prolonged.

2. 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 [5] Hou and Li 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 [6], 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 achieving an objective on energy consumption. Lloyd et al. gave a good summary of the works in this type in [7]. They use a 3-tuple $\langle M, P, O\rangle$ 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., Min-Max 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 biconnected 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 in [9] a minimum spanning-tree-based topology control algorithm that achieves network connectivity with minimal power consumption. 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 a 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). Cheng et al. presented two heuristics—MST heuristic and increment power heuristic—to assign transmit power to each node to form strong connected topology in [13]. The problem of QoS topology control for homogenous wireless networks was first studied in [14], and an algorithm was proposed to form the network topology that meets the system QoS requirements and the maximal transmitting power of the nodes is minimized. All the works mentioned above assume the homogenous environment of wireless networks.

There are a lot more works on energy-efficient communication in ad hoc wireless networks, such as in [15, 16]. Sing et al. studied five different metrics of energy-efficient routing in [16], such as minimizing energy consumed per packet, minimizing variance in node power levels, minimizing cost per packet, and so on. Kawadia and Kumar proposed a clustering method for routing in non-homogeneous networks [17], where nodes are distributed in clusters. The goal is to choose the transmit power level, so that low-power levels can be used for intracluster communication and high-power levels for interclusters. In [18], 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 [19] presented a quantitative analysis of performances of these three heuristics.

So far, there is no published work that addresses the issue of meeting QoS requirements through topology control for non-homogenous wireless networks. In this paper, we discuss the QoS topology control problem for non-homogenous wireless networks.

3. SYSTEM MODEL

We adopt the widely used transmission power model for radio networks, $p_{ij} = d_{i,j}^{\alpha}$, where p_{ij} is the transmission power needed for node i to reach node j, $d_{i,j}$ is the distance between i and j, and α is a constant typically taking a value between 2 and 4. The general transmission power model, $p_{ij} = C_j d_{i,j}^{\alpha}$, where C_j's are different will be studied later in the paper.

The network is modeled by a directed graph $G = (V, E)$, where V is the set of n nodes and E a set of directed edges. Each node i has a bandwidth capacity B_i, and a maximal level of transmitting power P_i. 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 node i will not exceed B_i. We also assume each node can adjust its transmitting power level. Let p_i denote the transmission power that node i chooses, $0 \le p_i \le P_i$. A directed edge $(i, j) \in E$ if and only if $p_i \ge d_{i,j}^{\alpha}$.

From the network model, we can see that the network topology can be controlled by the transmission power at each node and the topology directly affects the QoS provisions of the network. If the topology is made loose to save energy consumption (which results in a topology with less edges), the QoS requirements may not be met due to bandwidth overloading at some gateway nodes. If the topology is made dense to meet the QoS requirements (in this case, some nodes have to link far away neighbors), some nodes may run out of energy quickly due to long-distance transmission. We are to find a balanced topology that meets 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. For node i, we define a power utilization ratio $R_i = p_i/P_i$. Let $R_{\max} = \max\{R_i \mid 1 \le i \le n\}$. In the design of ad hoc wireless networks, an important objective is to increase the lifetime of the network, which is defined as the period of time before any node in the network runs out of its energy. Since the nodes in the system are non-homogenous, they have different battery capacities. For each node, R_i represents the actual level of power consumption relative to its energy capacity. Nodes with a higher R_i will run out of energy faster when their transmission time are the same. Therefore, minimizing $R_{\max}$ would increase the lifetime of the network.

The topology control problem of our concern can be formally defined as follows: given a node set V with their locations and each node i with B_i and P_i, and given $\lambda_{s,d}$ and $\delta_{s,d}$ for each node-pair (s, d), find transmitting power p_i for $1 \le i \le n$, such that all the traffic demands can be routed within the hop-count bound, and $R_{\max}$ is minimized.

We consider two cases: (1) end-to-end traffic demands are not splittable, that is, $\lambda_{s,d}$ for node-pair (s, d) must be routed on the same path from s to d; (2) end-to-end traffic demands are splittable, that is, $\lambda_{s,d}$ can be routed on several different paths from s to d. In the following, we formulate the topology control problem under the two separate cases.

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 [1, 20] or code assignment protocols [13, 21] that have been proposed to avoid (or reduce) signal interference in radio transmissions.

4. TOPOLOGY CONTROL FOR NONSPLITTABLE TRAFFICS

Variables

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

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

(iii) p_i, transmission power for node i.

(iv) $R_{\max}$, the maximum power utilization of all nodes.

Optimize

Minimize the maximum power utilization of nodes:

$$\text{Min } R_{\max}. \tag{1}$$

Constraints

(i) Topology constraint:

$$x_{i,j} \le x_{i,j'} \quad \text{if } d(i, j') \le d(i, j)\ \forall i, j, j' \in V. \tag{2}$$

(ii) Transmission power constraint:

$$P_i \ge p_i \ge d_{i,j}^{\alpha} x_{i,j} \quad \forall i, j \in V, \tag{3}$$

$$R_{\max} \ge \frac{p_i}{P_i} \quad \forall i \in V. \tag{4}$$

(iii) Delay constraint:

$$\sum_{(i,j)} x_{i,j}^{s,d} \le \delta_{s,d} \quad \forall (s, d). \tag{5}$$

(iv) Bandwidth constraint:

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

(v) Flow conservation:

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

(vi) Route validity:

$$x_{i,j}^{s,d} \le x_{i,j} \quad \forall i, j \in V. \tag{8}$$

(vii) Binary constraint:

$$\begin{gathered} x_{i,j} = 0 \text{ or } 1, \qquad x_{i,j}^{s,d} = 0 \text{ or } 1, \\ P_i \ge 0, \quad R_{\max} \ge 0 \quad \forall i, j \in V, (s, d). \end{gathered} \tag{9}$$

Remark 1. Constraint (2) ensures that nodes have broadcast ability. That is, the transmission by a node can be received by all the nodes within its transmission range. This feature can be represented by the links in the network as follows: 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 (2).

Remark 2. Constraint (3) ensures transmission power of each node does not exceed its power bound.

Remark 3. Constraint (4) determines the maximum power utilization ratio among all nodes.

Remark 4. Constraint (5) ensures that the hop-count for each node-pair (s, d) does not exceed the prespecified bound.

Remark 5. 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 left-hand side of inequality (6) represents all the outgoing traffics at node i (transmitting) and the second term represents all the incoming traffics (reception). Although this constraint does not preclude the case of simultaneous transmission and reception at a node, it is applicable to the usual case where a node is equipped with only one set of transceivers and cannot transmit and receive at the same time.

Remark 6. Constraint (7) is for flow conservation. Since traffics are not splittable, $x_{i,j}^{s,d}$ is either 0 or 1, representing that either the entire traffics of (s, d) go through link (i, j) or none does. This constraint states that the entire traffics for (s, d) originate at node s and sink at node d, and at any intermediate node the (s, d) traffic entering this node must be equal to the traffic exiting this node.

Remark 7. Constraint (8) ensures the validity of the route for each node-pair, stating that there is traffic flowing directly from node i to node j only when there exists a link (i, j).

Notice that the topology constructed by the above formulation is directed. To make the topology undirected (or bidirectional), we can simply add another constraint: $x_{i,j} = x_{j,i}$ for all $i, j \in V$.

The problem for nonsplittable case has been formulated as an integer linear programming (ILP) problem, which includes total $n(n-1)(T+1)+(n+1)$ variables, where T is the number of node-pairs, and n is the number of nodes. We know the ILP is NP-hard in general. There are some tools available to solve ILP problems with small sizes due to the high complexity. We use the *lp_solve* (ftp://ftp.es.ele.tue.nl/pub/lp_solve) and Matlab 6.5 to solve the problem for experimental purposes. The experimental results are presented in Section 6.2.1.

5. TOPOLOGY CONTROL FOR SPLITTABLE TRAFFICS

The topology control is a static planning problem. In the on-line situation, we can always route the traffics between a node-pair through different paths from time to time, or even for concurrent requests. 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.

5.1. Formulation

Variables

(i) $x_{i,j}$ and $R_{\max}$ remain the same as the nonsplittable case.

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

Optimize

Minimize the maximum-power utilization of nodes:

$$\text{Min } R_{\max}. \qquad (10)$$

Constraints

(i) Topology constraint:

$$x_{i,j} \le x_{i,j'} \quad \text{if } d(i, j') \le d(i, j)\ \forall i, j, j' \in V. \qquad (11)$$

(ii) Transmission power constraint:

$$P_i \ge p_i \ge d_{i,j}^{\alpha} x_{i,j} \quad \forall i, j \in V, \qquad R_{\max} \ge \frac{p_i}{P_i} \quad \forall i \in V. \qquad (12)$$

(iii) Delay constraint:

$$\frac{1}{\lambda_{s,d}} \sum_{(i,j)} f_{i,j}^{s,d} \le \delta_{s,d} \quad \forall (s, d). \qquad (13)$$

(iv) Bandwidth constraint:

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

(v) Flow conservation:

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

(vi) Route validity:

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

(vii) Variables constraints:

$$x_{i,j} = 0 \text{ or } 1, \qquad f_{i,j}^{s,d} \ge 0, \quad p_i \ge 0, \quad R_{\max} \ge 0 \quad \forall i, j \in V, (s, d). \qquad (17)$$

Remark 8. The objective and most of the constraints are the same as the nonsplittable case.

Remark 9. In the delay constraint (13), the delay is calculated as the average hop-count of multiflows between two nodes. This representation of the delay constraint is reasonable, because in splittable case, traffics between a node-pair can be routed via several different paths and a bound on average delay provides a good delay guarantee for network applications.

Remark 10. Constraint (15) is for flow conservation along all the routes for node-pair (s, d). Notice that the entire traffics for (s, d) (i.e., $\lambda_{s,d}$) is now split into multiple flows (i.e., $f_{i,j}^{s,d}$).

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

5.2. *Our solution*

5.2.1. *Load-balancing QoS routing*

Let L_i denote the bandwidth utilization ratio of node i, defined as

$$L_i = \frac{b_i}{B_i} = \frac{\sum_{(s,d)} \sum_j f_{i,j}^{s,d} + \sum_{(s,d)} \sum_j f_{j,i}^{s,d}}{B_i}, \tag{18}$$

where b_i is the actual bandwidth usage of node i.

Let $L_{\max} = \max\{L_i \mid 1 \le i \le n\}$, the maximum bandwidth utilization in the system.

Load-balancing QoS routing problem

Given a network topology, and traffic demands between node-pairs, route these traffics in the network such that the maximum bandwidth utilization $L_{\max}$ is minimized.

This problem can be solved in polynomial time by transforming it to a variant of multicommodity flow problem, where fractional flows are allowed. It can be formulated as follows:

$$\text{Min}\, L_{\max}, \tag{19}$$

$$\sum_j f_{i,j}^{s,d} - \sum_j f_{j,i}^{s,d} = \begin{cases} \lambda_{s,d} & \text{if } s = i \\ -\lambda_{s,d} & \text{if } d = i \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in V, \tag{20}$$

$$\sum_{(s,d)} \sum_j f_{i,j}^{s,d} + \sum_{(s,d)} \sum_j f_{j,i}^{s,d} \le B_i L_{\max} \quad \forall i \in V, \tag{21}$$

$$\sum_{(i,j)} f_{i,j}^{s,d} \le \lambda_{s,d}\delta_{s,d} \quad \forall (s,d), \tag{22}$$

$$f_{i,j}^{s,d} \ge 0, \quad L_{\max} \ge 0 \quad \forall i,j \in V, (s,d). \tag{23}$$

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

Function (19) is the objective, which is to minimize the maximal node bandwidth utilization. Constraint (21) states that a factor (i.e., $L_{\max}$) of B_i bandwidth is actually used by node i. Notice that $L_{\max}$, obtained from solving the formulation (19)–(23), can be greater than 1. When $L_{\max} > 1$, it means that the actual bandwidth usage of some nodes must have exceeded their capacities, which violates constraint (14). In this case, it indicates the given topology cannot accommodate the required traffic demands. In the following QoS topology control algorithm, we need to keep on adding more links into the topology until $L_{\max} \le 1$, which means the topology can support the required traffics (i.e., no node has the actual bandwidth usage exceeding its capacity).

The above formulation of the load-balancing QoS routing is a linear programming (LP) problem, which can be solved in time $O((|E|t)^{3.5})$ [22], where $|E|$ is the number of edges in graph G, and t is the number of node-pairs which have nonzero traffic.

Next, we integrate this QoS routing algorithm with the energy-efficient QoS topology control algorithm.

5.2.2. *Energy-efficient QoS topology control*

Let $R_{ij} = d^\alpha(i,j)/P_i$, the power utilization for node i to link node j. 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 are considered) in ascending order according to R_{ij}. Each time a node-pair (i,j) that has no link $(i \to j)$ and has the smallest R_{ij} is picked with the transmitting power of node i, p_i is increased until node j is reached. Then, the QoS routing algorithm runs on the network to see if the requested traffics can all be routed. This operation is repeated until the QoS topology is found, or all nodes reach their maximal power P_i (no topology can meet the QoS requirements in this case).

In the above algorithm, some links that make no contribution in carrying traffic are added into the topology because they have low weights of R_{ij}. These redundant links will cause maintenance overhead of the topology. The final step of the topology construction is to remove the links that have no traffic flowing through.

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

Output: power level p_i for any node i in V.

(a) Sort all node-pairs with $d_{i,j}^\alpha \le P_i$ in ascending order according to R_{ij}.
(b) Pick up the node-pair (i,j) that has the smallest R_{ij} but there is no link from i to j, and increase p_i to link j, making a new topology G.
(c) Run the QoS routing algorithm on G to obtain $L_{\max}$. If $L_{\max} \le 1$, then go to (d) (a solution is found); otherwise repeat (b) and (c).
(d) Remove redundant links from the obtained topology.

In step (b), the process stops if all nodes already reach their maximal power 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 maximal power utilization in the system is gradually increased until the required topology is formed. It is not difficult to see that the maximal power utilization needed to form the required topology is minimal. Furthermore, the topology found in steps (b) and (c) is minimal 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 (19)–(23)) is optimal in the sense that the maximal bandwidth utilization of the nodes in the topology is minimal. In other words, 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). Therefore, when traffic demands are splittable, our algorithm can find the optimal solution to the energy-efficient QoS topology control problem.

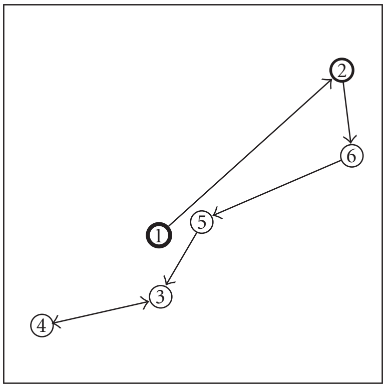


Figure 1: QoS topology for nonsplittable case.

Table 1: Requests and their routing for Figure 1.

s	d	$\lambda_{s,d}$	Route
1	2	29.9568	1 → 2
2	3	36.4634	2 → 6 → 5 → 3
2	5	34.2944	2 → 6 → 5
3	4	29.7357	3 → 4
4	3	35.9753	4 → 3
6	4	33.5743	6 → 5 → 3 → 4

Table 2: Requests and their routing for Figure 2.

s	d	$\lambda_{s,d}$	Splitted $\lambda_{s,d}$	Route
1	2	29.9568	16.4993	1 → 6 → 2
			13.4575	1 → 2
2	3	36.4634	14.3784	2 → 5 → 1 → 4 → 3
			11.8406	2 → 5 → 3
			10.2444	2 → 5 → 1 → 3
2	5	34.2944	34.2944	2 → 5
3	4	29.7357	15.6646	3 → 4
			14.0710	3 → 1 → 4
4	3	35.9753	35.9753	4 → 3
6	4	33.5743	31.0260	6 → 2 → 5 → 1 → 4
			2.5483	6 → 2 → 5 → 3 → 4

6. EXPERIMENTS

6.1. Simulation setup

The simulations are conducted in a 100 × 100 two-dimensional free-space region. The coordinates of the nodes are randomly and uniformly distributed inside the region. The value of α in the transmitting power function is set to 2, that is, $p_{ij} = d_{i,j}^{\alpha}$ for $\alpha = 2$. The nodes are classified into three classes according to their energy capacity: class A nodes with high-power capacity, class B nodes with medium-power capacity, and class C nodes with low-power capacity. The percentage of the nodes in the three classes is about 5%, 20%, and 75%, respectively. The total number of nodes of all three classes is set to 30. The energy capacity of class A nodes, P, is made enough to cover the whole region, the capacity of class B nodes is $P/4$, and the capacity of class C nodes is $P/8$. Corresponding to their energy capacities, the bandwidth capacities of class A, class B, and class C nodes are B, $B/4$, and $B/4$, respectively, where $B = 1000$ throughout the simulations.

The set of requests $R = \{(s, d, \lambda_{s,d}, \delta_{s,d})\}$ are generated by using the Poisson function (i.e., the requests originating from a node follow the Poisson distribution). $\delta_{s,d}$ for all node-pairs is uniformly set to 8 to avoid excessive "no-solution" cases. 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 demands for node-pairs follow a normal distribution. The mean value of traffic demands for all nodes is denoted by λ_m. The variance of a traffic demand originating from a node is $0.5 \times \lambda_m$.

We use the total bandwidth demands to measure the traffic load of the whole system. The total bandwidth, denoted by λ_{total}, is calculated as $k_{\text{total}} \times \lambda_m$, where k_{total} is the total number of requests in the system. During the simulations, for a specified value of λ_{total} (used as the x-axis in the following figures), we adjust the value of λ_m, after k_{total} is calculated, to make up the right amount of λ_{total}. Each data point in the following simulation charts is an average of 50 runs, in which the results are based on different node placement.

6.2. Simulation results and analysis

6.2.1. Topologies for nonsplittable traffic versus splittable traffic

The first experiment is to compare the topologies for the two cases of traffic nonsplittable and splittable. Figure 1 shows the topology for nonsplittable traffic of a network with 6 nodes and 6 requests, where node 1 is a high-power node, node 2 a medium-power node, and the rest are low-power nodes. The details of the requests and the routing computed by the *lp_solve* are given in Table 1. $\delta_{s,d}$ is set to 4 (consistent with the maximal hop-count for splittable case, which is 4. See Table 2). For comparison purposes, we compute the topology for the same node setting and requests for the *splittable traffic* case by using our proposed algorithm in Section 5. Figure 2 and Table 2 are the resulting topology and the routing of traffics, respectively. Notice that the redundant links are already removed in both Figures 1 and 2. $R_{\max}$ is 0.7517 for nonsplittable case (Figure 1), while it is 0.5965 for splittable case (Figure 2). It is obvious that the topology for the splittable case has a better balanced utilization of energy because it can split the traffics onto multiple routes and take the advantages of using short-distance links. From Figures 1 and 2, we can find that the long-distance link 6 → 5 in Figure 1 contributes to the high $R_{\max}$. Notice that nodes 3–6 are low-power nodes and it is very costly for them to reach nodes in long distance. While the topology in Figure 2 uses more short-distance edges to carry the splitted traffics through multiple paths, which results in a lower $R_{\max}$.

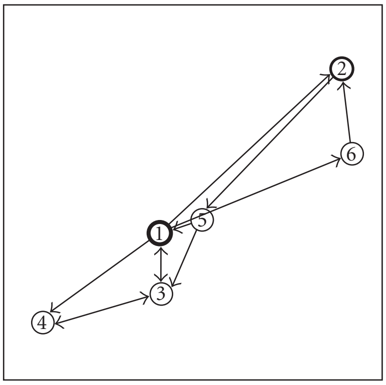
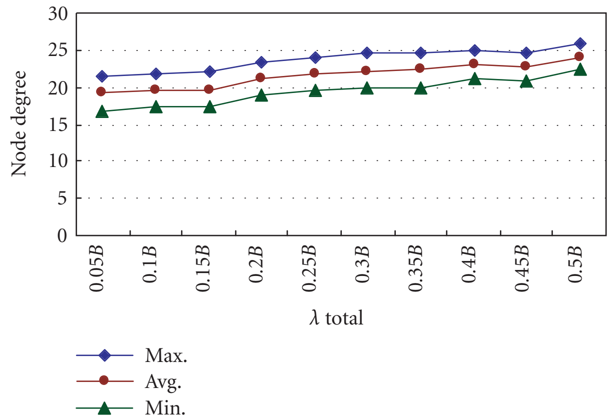
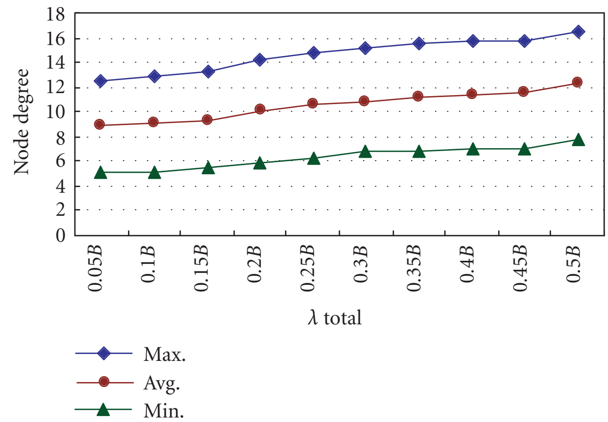


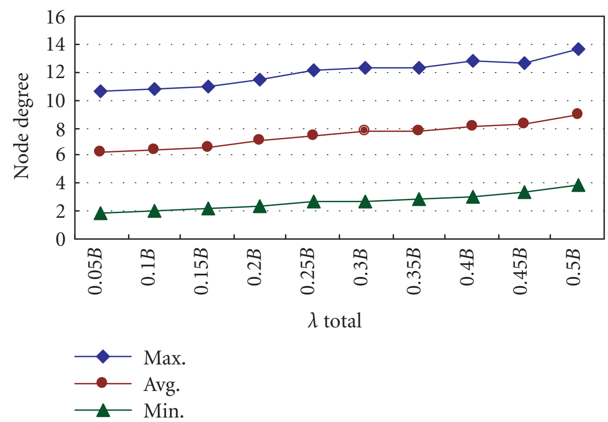
FIGURE 2: The QoS topology for splittable case.



(a) Class A nodes.



(b) Class B nodes.



(c) Class C nodes.

FIGURE 3: Average node-degrees versus λ_{total}.

6.2.2. *Topologies versus traffic load*

This experiment shows how the topology changes as traffic demands increase. Figure 3 shows average node-degrees versus λ_{total}. Notice that the topology graph is directed, the degree of a node is its incoming node-degree plus its outgoing node-degree. The following points have been observed from the simulation results.

(1) The topologies heavily rely on class C nodes to make interconnections. From Figure 3(c), we can see the average node-degrees of class C nodes are high relative to their energy and bandwidth capacities. During the simulations, it was observed that no-solution cases occur quite often when class C nodes have too small energy capacity, even though class A nodes have the ability to cover all nodes in the whole area. One reason is due to the asymmetric links among the nodes. A class C node must have outgoing links to reach destinations if it has outgoing traffics. Another reason is due to the bandwidth limit of class A nodes. Even though the transmitting power of class A nodes can reach any nodes, its bandwidth capacity prohibits it from relaying traffics for too many nodes.

(2) Node-degrees do not increase fast as the increase of λ_{total}. The main reason is because of our load-balancing routing algorithm which tries to accommodate more traffic as much as possible for a given topology. When the existing topology cannot support the required traffics, then it adds one link into the topology each time and hopes the new topology can accommodate the required traffics. By doing so, the density of the topology is always kept as low as possible. Another reason is that whether a topology can be found for the given traffic demands is restricted by the bandwidth capacities of some gateway nodes, rather than by the routing method. For some bad samples of traffic demands, no topology can be found to support them no matter how many more links are added in and these samples have to be discarded eventually.

(3) The bandwidth of class C nodes becomes the bottleneck for no-solution cases if all nodes have enough power to make the topology connected. Our initial bandwidth capacity for class C nodes was $B/8$, we often encountered the cases of no-solutions when λ_{total} gets close to 0.5 B, due to some class C nodes failure to relay required traffics. When we made the bandwidth capacity of class C nodes as $B/4$, this situation improved substantially. This result tells us that nodes still depend on their neighbors for relay traffics even if there are a few high power (and bandwidth) nodes in the system. Class C nodes must have a good bandwidth capacity for relaying traffics in order to make the ad hoc network function.

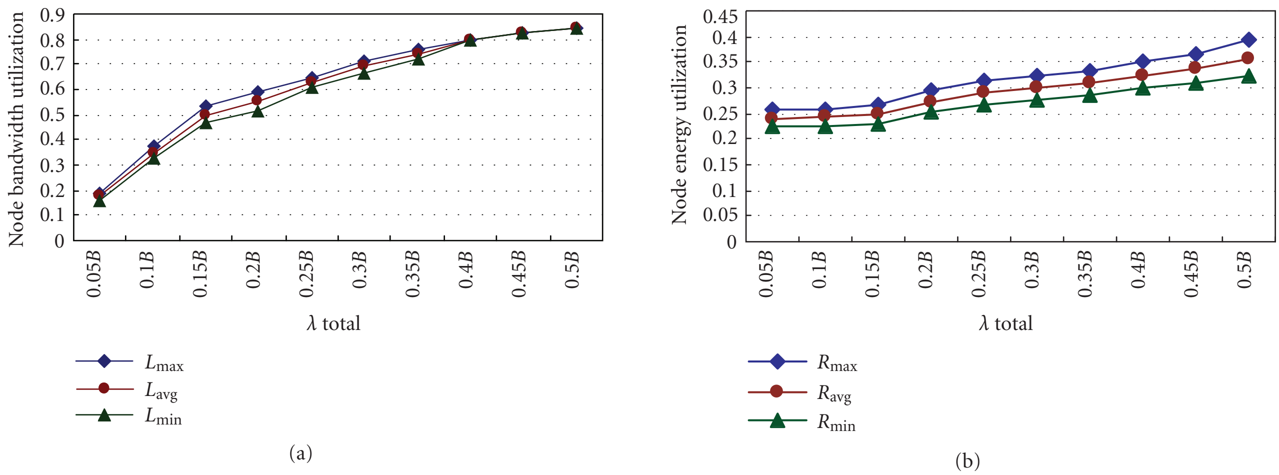


FIGURE 4: (a) Bandwidth utilization for class A nodes. (b) Energy utilization for class A nodes.

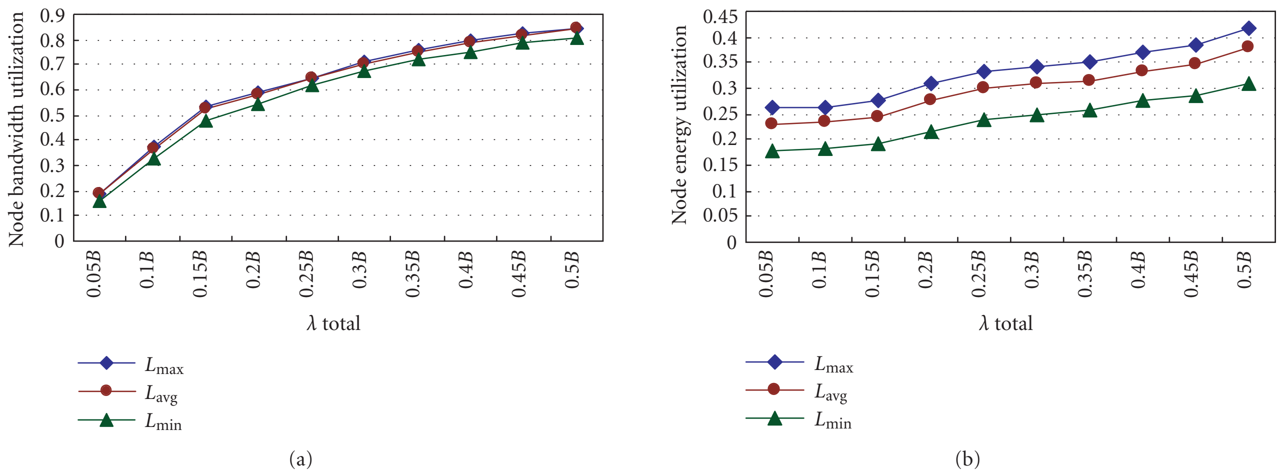


FIGURE 5: (a) Bandwidth utilization for class B nodes. (b) Energy utilization for class B nodes.

6.2.3. *Load-balancing and lifetime*

Figures 4–6 show the load-balancing of bandwidth and energy utilization of class A, class B, and class C nodes, respectively. The node bandwidth utilization was obtained from solving the LP formulations (19)–(23) by using Matlab 6.5. From the curves in Figures 4–6, we can see both the bandwidth and energy utilizations are well balanced among the nodes in the same class (the maximal, average, and minimal utilizations of nodes in the same class are very close, particularly for class A and class B nodes). For class C nodes (Figure 6), the minimal utilizations for both bandwidth and energy are substantially lower than the average values. This is because there are always some class C nodes at the edge of the topology (they do not relay traffic for other nodes). Nevertheless, we still see the maximal utilizations are very close to the mean values for class C nodes (this is desirable for load-balancing in this kind of nonhomogenous environment). From Figures 4–6, we can also see the energy utilization of nodes increase steadily with the increase of λ_{total}. This is an expected result, because with the increase of traffic load in the system, nodes have to use more energy to reach further neighbors to spread the traffic load out.

Another important observation from Figures 4–6 is the load-balancing among the nodes across different classes. The three curves for the maximal bandwidth utilizations of class A, class B, and class C almost overlap each other (the difference is less than 0.05%). The maximal energy utilizations for the three classes of nodes differ from each other within a margin of 3%. This shows that the system has a very balanced budget on the use of energy among all the nodes. The lifetime of the network will, therefore, be greatly increased (because no nodes will run out of energy substantially faster than others).

6.2.4. *Topologies for broadcast-dominated traffics*

We also conducted experiments on broadcast-dominated traffics. In many applications where class A nodes and class B nodes act as the first-level and second-level commanders, they originate much higher traffics than class C nodes. Figure 7 is an example of such a topology, where nodes 1

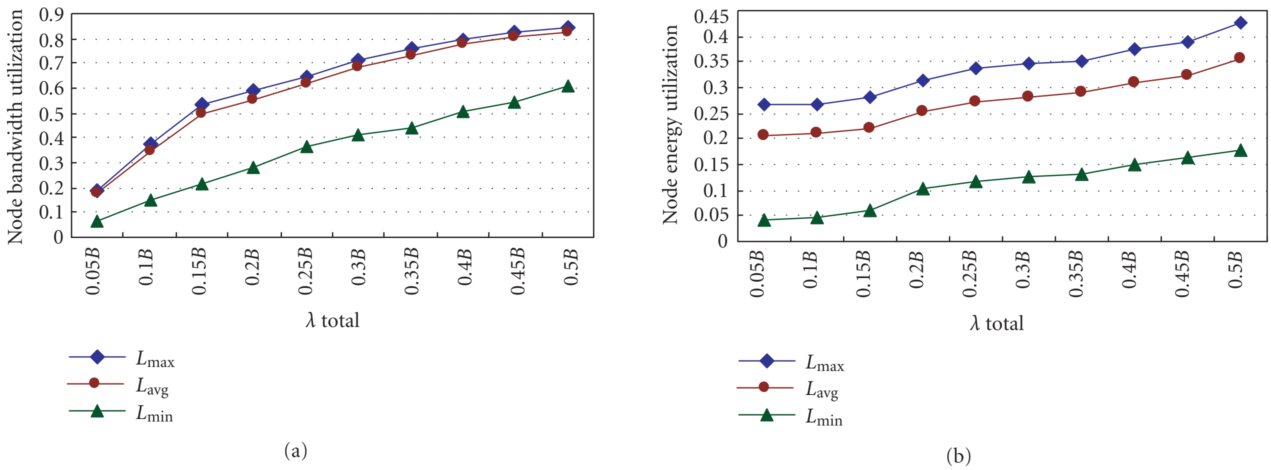


FIGURE 6: (a) Bandwidth utilization for class C nodes. (b) Energy utilization for class C nodes.

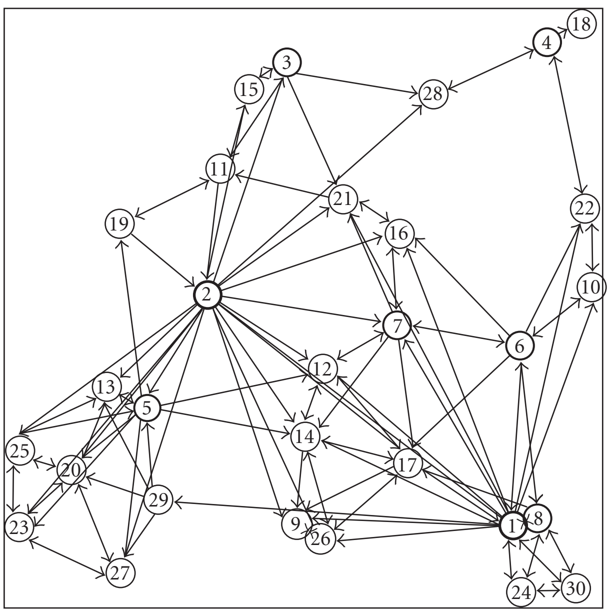


FIGURE 7: A topology for broadcast-dominated traffics.

and 2 are class A, nodes 3–8 are of class B, and the rest are of class C. We can see that most of class C nodes are still heavily involved in relaying traffics for others, even though they themselves are not traffic sources. This result proves again that traffic relay by low-power nodes plays an important role in balancing the power usage among all nodes. Table 3 shows the node-degrees of the nodes in Figure 7.

7. CONCLUSIONS

We have discussed the energy-efficient QoS topology control problem for nonhomogenous ad hoc networks. This is the first time in the literature that topology control is studied regarding QoS provisions. Both cases of nonsplittable and splittable traffics have been considered. For the former case, the problem has been formulated as an integer linear programming problem. For the latter case, 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.

TABLE 3: Node-degrees for broadcast-dominated traffics, λ_{total} = 0.3 B.

	Max.	Avg.	Min.	No. of nodes	No. of reqs.
Class A	21	18.5	16	2	9
Class B	10	6.5	3	6	11
Class C	9	4.73	1	22	0

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