ELSEVIER
CrossMark
Available online at www.sciencedirect.com
ScienceDirect
Procedia Computer Science 56 (2015) 309 – 316
Procedia Computer Science

The 10th International Conference on Future Networks and Communications (FNC 2015)

Energy-Aware Topology Control And Qos Routing In Ad-Hoc Networks

Fadoua Yakine[a,*],Abdellah Idrissi[a]

[a]*Computer Science Laboratory (LRI)*
Department of Computer Science, Faculty of Sciences
University Mohammed V - Agdal, Rabat 10000,Morocco
yakine.fadoua@gmail.com,idriab@gmail.com

Abstract

In order to reduce energy consumption in wireless ad hoc and sensor networks, the Topology Control (TC) remains one of the most important technique used. TC is able to construct network topologies, which have desired characteristics. It has also a dynamic ability to change the node transmitting range in a way to meet graph global property such as connectivity, while reducing energy consumption and radio interference. In this paper, we explore the energy-aware Topology Control in wireless ad hoc networks by formulating and solving the corresponding optimization problem. We propose an ILP formulation that minimizes the total transmission power needed by nodes to construct a topology that can meet Quality of Service (QoS) requirements between source and destination node pairs with less computational effort. The simulation results show that our algorithm has a better performance for data traffic in ad hoc networks. To evaluate the efficiency of our proposed algorithm, we compare its performance by simulation with another QoS model, using power efficiency measures.

Peer-review under responsibility of the Conference Program Chairs

Keywords: Ad-hoc Networks; Wireless; Energy efficiency; QOS; Topology Control.

* Corresponding author. Tel.: +212-675-369-462.
E-mail address: yakine.fadoua@gmail.com

Peer-review under responsibility of the Conference Program Chairs
doi:10.1016/j.procs.2015.07.213

1. Introduction

An ad hoc wireless network is a network composed of untethered units communicating with each other via radio transceivers. The communication between two nodes that are not direct neighbors requires the relay of messages by intermediate nodes in a multi-hop fashion. Each unit in a network of this kind can serve as a router, as well as a communication end-point.

Nowadays many modern network applications such as transmission of multimedia data, real-time collaborative work, and interactive distributed applications require ad hoc networks to provide QoS provisions and it has gained so much attention[1].

QoS routing deals not only with finding a route from a source to a destination, but also a route that satisfies QoS requirements, often given in terms of bandwidth, delay or loss probability[1].

The main goal of QoS provisioning is to achieve a more deterministic network behavior so that information carried by the network at a higher quality level and the use of network resources can be better utilized[2].

The provision of QoS in mobile ad hoc networks is much more challenging than in wired networks due to the unreliable wireless nature of channel, node mobility, multi-hop communications, contention for channel access, a lack of central coordination and limited device resources[3].

Our paper provides a technique for Topology Control based on an optimization formulation, where the objective is to minimize the overall energy consumed by all the nodes in the wireless ad hoc network with the respect of quality of service requirements. Inspired by the formulations related to the minimum power broadcast trees for Wireless Networks[4], we adapt them to provide QoS connected topologies.

Many works[5,14,15] , presented in related works section adopted the same modeling approach. Similar to Jia's et al. study[14], the present formulation has the same goal of finding a network topology that can meet the QoS requirements except that we are minimizing the node total transmission power not its maximal power. To evaluate the efficiency of our proposed algorithm, we describe, re-implement and compare their algorithm with ours. We also provide a computational study, where the execution times for both are compared.

Our algorithm is designed specifically for multi-hop wireless ad hoc networks deployed on a 2-dimensional surface.

2. Related Works

Topology control (TC) is a technique commonly used in wireless ad hoc networks and sensor networks for saving energy. It aims to control the topology of the graph representing the communication links between network nodes with the purpose of maintaining some global graph property (e.g., connectivity), while reducing energy consumption and/or interference that are strictly related to the nodes' transmitting range[2].

Several works have studied the topology control in wireless ad hoc network. Chen and Huang[6] first studied the strongly connected topology control problem, which aims to determine a connected topology while minimizing the total energy consumption. They proved that this problem is NP-complete.

Since Energy efficiency is a key design issue in wireless network protocols, providing an efficient wireless network that consumes the minimum energy while ensuring the necessary topological connectivity is highly desired[7].There are several researches that have already discussed energy-efficient topology control in ad hoc wireless networks. Most of the works have been focused on the construction and maintenance of a network topology with the required connectivity by using minimal power consumption.

Lloyd et al.[8] studied the topology control problem under many optimization objectives including both minimizing the maximum energy consumption and minimizing the total energy consumption but the problem is still NP-complete. Ramanathan and Rosales-Hain[9] considered the problem of topology control by adjusting the transmit power for each node. They formulated it with the consideration of connectivity and bi-connectivity constraints and the objective of the minimization of the maximal transmitting power. Additionally, they proposed two neighbor-based heuristics, such as local information no topology (LINT) and local information link state topology (LILT), to deal with topological changes. The authors in[10] focused their research on the network connectivity with minimal power consumption and proposed a minimum spanning tree based topology control algorithm. Li et al.[11] introduced a distributed topology control protocol called CBTC. Each node increases its transmitting power until it finds a neighbor node in every cone of degree α. The basic idea of the algorithm is that a node u tries to find the minimum power $P_{u,\alpha}$ that ensures that there is a node in every cone of angel α. Huang and al. in[12] had extended the CBTC protocol to the case of directional antennas. Marsan et al. in[13] addressed the problem of determining an optimal Bluetooth topology, which minimizes the maximum traffic load of nodes (thus minimizing the maximum power consumption of nodes).

Jia et al. in[14] first discussed the construction of network topology that can meet input QoS requirements in terms of end-to-end delay and bandwidth with the minimization of the maximum power consumption per node. Liu et al. in[5] considered two cases of the QoS topology control problem: the traffic demands are not splittable as well as the traffic demands are splittable, which are formulated as the integer linear programming problem and the mixed integer linear programming problem respectively. They proved that the ratio of the second algorithm is at most n, where n is the number of nodes in networks. In[15], Li et al. formulated the QoS topology control problem in heterogeneous ad hoc networks in form of an integer linear programming problem or a mixed integer linear programming problem. This study produced a network topology that meets QoS requirements and minimizes the maximum energy utilization of nodes. Cheng et al.[16] considered the power assignment of nodes in a wireless ad hoc network such that the induced topology is strongly connected and it consumes minimum total energy. They revealed the relation between the energy consumption of an optimal solution and spanning tree-based solutions, and proposed an optimization algorithm to improve the result of any spanning tree-based topology.

The cooperative communication techniques can also be used in topology control. Cardei et al.[17] discussed the topology control with cooperative communication (TCC), which aims to provide a strongly-connected topology with minimum total energy consumption. Cabrera et al.[18] presented the first control-theoretic investigation of topology control in MANET. They proposed LINT a simple representative fully distributed local information topology control algorithm and showed its instability under certain conditions. Then, they formulated it in a control theoretic-context, and derived a new mechanism, which is shown to be stable for a wide range of parameter variations.

Wieselthier et al. defined in[19] a topology control algorithm based on minimum-power spanning tree. They proposed three greedy heuristics namely Broadcasting Incremental Power (BIP), Minimum Spanning Tree (MST) and the Shortest-Path Tree (SPT). Wan et al.[20] proposed a quantitative analysis to measure the performance of these heuristics.

Many mathematical programming approaches have been introduced in several works for the design of energy-efficient Broadcast/Multicast routing protocols for wireless ad hoc networks. Three linear integer-programming models, where a source node has to broadcast a message to all the other nodes, are presented in[4] without any experimental implementation. Bauer et al.[21] presented a model for numerically evaluating the BIP heuristic in large networks based on multi-commodity flow and a Lagrangean relaxation.

3. System Model

In this section, we introduce the system model and define the research problem.

An ad-hoc network can be represented by a graph G (V, E), where V is the set of N nodes in the network and E is the set of links in two-dimensional plane.

In this paper, we make the following assumptions in the problem formulation.

We consider that the network supports multi-hopping where a message could travel over multiple hops to reach its destination. Only the nodes that transmit messages consume energy.

A cost P_{ij} is associated with each link (i,j).it corresponds to the transmitting power required to establish a link from node i to j.

The power required for a transmission originated at node i to be received at node j is defined by :

We adopt the widely used transmitting power model for radio networks:

$$P_{ij} = (r_{ij})^{\alpha} \tag{1}$$

where:

P_{ij} = the transmitting power used by the node i to reach destination j.

r_{ij} = the distance between nodes i and j.

α = a parameter which is not less than two depending on the characteristics of the communication medium.

We assume that any node i ∈V can choose its power level p_i, but not to exceed a maximum value P_{max}: $0 \le p_i \le P_{max}$. There is a link between i and j. a link if $p_i \ge (d_{ij})^{\alpha}$.

P_{total} denotes the total energy cost consumed by all nodes in the network. The P_{total} formula is: $P_{total} = \sum_{i=1}^{N} p_i$

Let $B_{s,d}$ and $D_{s,d}$ denote the bandwidth and delay constraints of the node pair (s,d).

Our QoS topology control problem is the following : Given a set of nodes V with their corresponding coordinates, $B_{s,d}$ and $D_{s,d}$ of node pair (s, d), where s,d∈V, we need to determine the transmission power p_i for each node i($0 \le i \le N$) and minimize P_{total} while meeting the end-to-end QoS constraints namely delay and bandwidth.

4. Problem Formulation

In this section, we present the ILP formulation for the routing problem denoted by Routing-IP.

In order to formulate the problem, we define a set of optimization variables in Table I.

TABLE I. . NOTATION OF ILP FORMULATION

Variable	Description
X_{ij}	Boolean decision variable which is equal to one if there is a link from node i to node j, and zero otherwise;
p_i	The transmitting power consumed by node i.
$x_{i,j}^{s,d}$	Boolean decision variable that we have introduced in the model to ensure flow constraint. $x_{i,j}^{s,d} = 1$ if there is a route from s to d going through link (i, j), else $x_{i,j}^{s,d} = 0$.

Our Model is the following:

$$\textbf{min :} \sum_{i=1}^{N} p_i \tag{2}$$

s.t.

$$X_{ij} = X_{ji} 1; \forall i, j \in V \tag{3}$$

$$P_{max} \ge p_i - \sum_{j=1}^{N} P_{ij} X_{ij} \ge 0; \forall i \in V, i \ne j \tag{4}$$

$$\sum_{j=1}^{N} X_{ij} \ge 1; i = s, i \ne j \tag{5}$$

$$\sum_{j=1}^{N} X_{ij} = 1; \forall j \in \{V - s\}, i \ne j \tag{6}$$

$$\sum_{j=1}^{N} X_{ij} \le (N-1) \sum_{j=1}^{N} X_{ji}; \forall (i,j) \in \{V - s\}, i \ne j \tag{7}$$

$$\sum_{j} x_{i,j}^{s,d} - \sum_{j} x_{j,i}^{s,d} = \begin{cases} 1 & \text{if } s = i \\ -1 & \text{if } d = i \forall i \in v \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$x_{i,j}^{s,d} \le X_{ij}; \forall i, j \in V \tag{9}$$

$$\sum_{(i,j)} x_{i,j}^{s,d} \le D_{s,d}; \forall s \in V, \forall d \in V \tag{10}$$

$$\sum_{(s,d)} \sum_{i} x_{i,j}^{s,d} \lambda_{s,d} + \sum_{(s,d)} \sum_{i} x_{j,i}^{s,d} \lambda_{s,d} \le B_{s,d}; \forall i, j \in V \tag{11}$$

Fig. 1. Routing-IP Model

Formula (2) is the objective function, which aims to minimize the sum of energy consumed by all nodes in the network.

Constraint (3) ensures that each edge is symmetric. It corresponds to two directed links.

Constraint (4) defines the relations between the transmitting power p_i and the binary variables X_{ij}.

The constraint (5) expresses the condition that the source node s of the request should transmit at least once.

The node reachability constraints (6) express that any number of transmissions can be made out of a node i.

In order to avoid any loops in the final tree, constraints (7) are added .they stipulate that a node (except the source s) can transmit only if it receives a transmission from some other node to prevent any loops in the final solution.

Constraint (8) ensures that all links on (s,d) should meet the flows conservation.

Constraint (9) ensures that the route between each node-pair is valid. It states that traffic is circulating from node i to node j only when the link (i,j) exists.

Formula (10) gives the delay Constraints.

Formula (11) requires that the nodes passed by most flows should meet the bandwidth constraints.

5. Quality Measures

Different approaches to topology control will produce different results. For a collection of nodes V, let G denotes the graph on V for which there is an edge from node u to node v only if u can directly reach v. let T denotes the topology returned by the topology control algorithm. It is desirable to judge the quality of topology T and compare it with results from other algorithms. In order to do this, several criteria and measures are required, which include connectivity, energy efficiency, throughput and robustness to mobility[22].

Our focus in this paper is on energy-efficiency. To measure energy-efficiency of any topology, we used its energy stretch factor and hop stretch factor. The following definitions are proposed in[22].

- The energy stretch factor is the worst increase in energy used to deliver a packet between any pair of nodes u and v along a minimum energy path between the original graph G and the topology controlled graph T.

$$\text{Energy stretch factor} = \max_{u,v \in V} \frac{E_T(u,v)}{E_G(u,v)} \tag{12}$$

where:

(u, v) , $E_T(u, v)$ = the energy consumed along the most energy-efficient path in graph G and T respectively.

- The hop stretch is similar except that the focus is on path length as opposed to energy consumption.

$$\text{Hop stretch factor} = \max_{u,v \in V} \frac{|(u,v)_T|}{|(u,v)_G|} \tag{13}$$

where:

$(u,v)_G$ is the shortest path in graph G and $|(u,v)_G|$ is its length.

6. Experimental results

In this section, we conduct simulation experiments to evaluate the performance of two algorithms. The first one we provide in section 4, the second one is Jia's et al.[14].

We present and discuss the results obtained by performing our model and the QoS Topology control model of Jia's et al. in the case of non-splittable traffics. Both of those models are been formulated as an integer linear programming problem (ILP) .To solve ILP problems, we used the solver software CPLEX (12.5.0.0)[23] based on the branch-and-bound method in the same network topologies and report the results given from both of them. As hardware platform a personal computer with 4 GB RAM and 2.4 GHz, Core2 Duo Intel processor was used.

Network nodes are arbitrarily placed in a two dimension simulation areas. Initially the available bandwidth B of all nodes is set to 500.The set of requests is a quadruplet $R = \{(s, d, B_{s,d}, D_{s,d})\}$. To generate the set R, we developed a script that selects randomly a pair (s,d). The bandwidth constraint $B_{s,d}$ is assigned by a random function of a normal distribution with variance equal to 0.5 μ_m , where μ_m is the mean value of the normal distribution function. i.e., μ_m is the average bandwidth demand per request. The delay constraint is set to (2N/3). The parameter α in the power model is set to 2 and 4.

The first experiment is to compare the resulting topologies for the two models. We use the input topology shown in Figure 2 of six nodes and six requests to illustrate the above. We consider the same simulation setting as in[14].The Simulations are conducted in a 100m×100m two dimensional free space region. The number of nodes is set to be 6 (N=6). The coordinates of the nodes are randomly distributed. All nodes share the same bandwidth B = 500. The delay constraint $D_{s,d}$ for the node pair (s,d) is set to 4. The average traffic amount per request is 0.06B.

The details of the 6 requests and the routing information for each model are reported in table II.

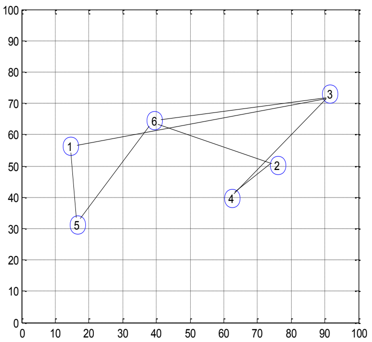

Fig. 2. The QoS topology for non-splittable case

TABLE II. REQUESTS AND THEIR ROUTING FOR FIGURE 2.

s	d	$\lambda_{s,d}$	Routes: Routing-IP model	Routes: Jia's et al. model
2	4	148.6403	2→4	2→4
3	4	142.2603	3→4	3→4
5	1	152.0183	5→1	5→1
5	3	137.897	5→6→3	5→6→2→4→3
1	3	155.6549	1→5→6→3	1→5→6→3
6	2	163.5291	6→2	6→2

One interesting point to note is that while the routes are pretty the same in the both optimal model obtained solutions; the value of the objective function P_{total} and X_{ij} variables are different in the two solutions. This is due to how power costs of nodes i are calculated in the two formulations. In our formulation, a node is limited to one transmission only; the power cost is the corresponding element from the power matrix (Formula 4). In Jia's et al. formulation, however, the optimal solution obtained could involve implicit transmissions. The power cost is the maximum of the individual costs of the transmissions out of that node.

In the next experiments, N nodes are randomly distributed within 1000m×1000m region to form an ad hoc network. The simulation parameters are summarized in Table III.

TABLE III. PARAMETER VALUES FOR SIMULATION

Parameter	Values
N size	10,20,30,40,50,60,70,80,90,100
$B_{s,d}$	500
Ds,d	2N/3
α	2 and 4
μ_m	0.02B

The second experiment is to analyze the generated topologies. Figure 3 plots the total energy consumption with the size of network changing when α is 2 and 4.

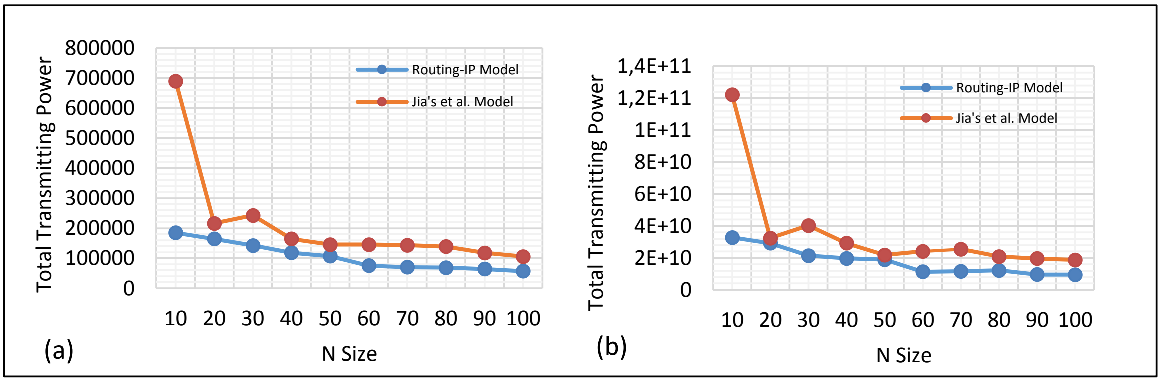

Fig. 3. (a) Total Energy Consumption versus N (α=2); (b) Total Energy Consumption versus N (α=4)

As it is shown in figure 3, the energy consumption of both algorithms decreases with the increase of the node number. This is due to the fact that the nodes density increases correspondingly and each node can reduce its transmission power to reach other nodes. Furthermore, the performance of our algorithm is the better than Jia's et al.

.Ours picks routes with minimum transmitting power to reach nodes. We can also notice that the total energy consumption increases fast, when N is small. The reason why that is the high node density provides more choices for traffic flows and therefore reduces the energy consumption when finding a QoS route.

To better evaluate the performance of two algorithms in term of energy efficiency, we used the two metrics described in section 5.The energy metrics are shown in figure 4.

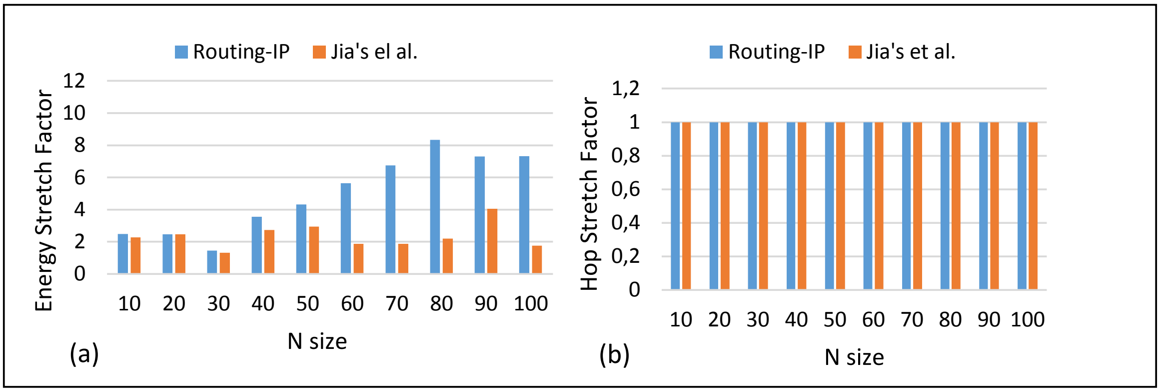

Fig. 4. (a) Energy stretch factor; (b) Hop stretch factor

The hop stretch factor is equal to 1 for Routing-IP and Jia's et al.model.

In table V, we present the computation times necessary to solve the two formulations with different N sizes (10≤N≤100). Random ten requests are generated and solved for each of these values and average results are reported.

TABLE V. COMPUTATION TIMES OF THE TWO MODELS (SECONDS)

N size	Jia's et al. Model	Routing-IP Model
10	0,13333	0,06167
20	1,00167	0,14167
30	4,83833	0,23167
40	23,465	0,43833
50	83,9586	0,65429
60	300,987	0,95714
70	958,41	1,55714
80	2758,35	2,02714
90	2823,66	2,55286
100	7219,76	3,53000

For all the tests, the computation times for the two models increase with the networks size N.

Our algorithm has shown that it has a very satisfactory performance. The execution time of the algorithm on network size varying from N = 10 to 100 nodes increases from 0,06167 sec to 3,530000 sec by an increase ratio of 5624.015%

The running time of the 2nd algorithm on the same networks passes from 0,13333s to 7219,76 s = 2 h by an increase percentage of 5 414 855,37%. This too huge. This is the running time of our algorithm× 875 times.

Our algorithm is faster than Jia's et al..It gives better results is less time. Moreover, we showed that the space dimension has a negligible impact on the computation time for our Algorithm contrary to the Jia's et al.

7. Conclusion

We have discussed QoS topology control problem with energy efficiency in ad hoc networks. In this work, we focused on Integer Linear Programming (ILP), an exact solution technique, to optimize QoS routing in wireless ad hoc networks. Our proposed algorithm reduces the energy consumption while meeting the QoS requirements in terms of end-to-end delay and bandwidth. To capture the quality of the generated topologies, we compare our formulation with the formulation of Jia's et al. for the case of non- splittable traffics using energy efficiency factors. Experimental simulations showed that ours could effectively reduce the total energy consumption of the network and achieve the best computational performance in much less time.

We intend to study the complexity of finding the optimal topology for larger networks and the scalability of the technique we used.

References

1. Badis, Hakim, Gawędzki, Ignacy, and Al Agha, Khaldoun. QoS routing in ad hoc networks using QOLSR with no need of explicit reservation. In : Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th. IEEE, 2004. p. 2654-2658.
2. Santhi, G. and Nachiappan, Alamelu. A survey of QoS routing protocols for mobile ad hoc networks. International journal of computer science & information Technology (IJCSIT) Vol, 2010, vol. 2.
3. Hanzo, Lajos and Tafazolli, Rahim. A survey of QoS routing solutions for mobile ad hoc networks. Communications Surveys & Tutorials, IEEE, 2007, vol. 9, no 2, p. 50-70.
4. Das, Amal K., Marks, Robert J., El-Sharkawi, Mohamed, and al. Minimum power broadcast trees for wireless networks: integer programming formulations. In : INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications. IEEE Societies. IEEE, 2003. p. 1001-1010.
5. Liu, Hai, Li, Deying, and Jia, Xiaohua. QoS topology control with minimal total energy cost in Ad hoc wireless networks. In: Mobile Ad-hoc and Sensor Networks. Springer Berlin Heidelberg, 2006. p. 622-637.
6. Chen, Wen-Tsuen and Huang, Nen-Fu. The strongly connecting problem on multihop packet radio networks. Communications, IEEE Transactions on, 1989, vol. 37, no 3, p. 293-295.
7. Cheng, Xiaochun, Cardei, Mihaela, Sun, Jianhua, et al. Topology control of ad hoc wireless networks for energy efficiency. Computers, IEEE Transactions on, 2004, vol. 53, no 12, p. 1629-1635.
8. Lloyd, Errol L., Liu, Rui, Marathe, Madhav V., et al. Algorithmic aspects of topology control problems for ad hoc networks. Mobile Networks and applications, 2005, vol. 10, no 1-2, p. 19-34.
9. Ramanathan, Ram Et Rosales-Hain, Regina. Topology control of multihop wireless networks using transmit power adjustment. In: INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. IEEE, 2000. p. 404-413.
10. Li, Ning, Hou, Jennifer C., and Sha, Lui. Design and analysis of an MST-based topology control algorithm. Wireless Communications, IEEE Transactions on, 2005, vol. 4, no 3, p. 1195-1206.
11. Li, Li, Halpern, Joseph Y., Bahl, Paramvir, et al. Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks. In: Proceedings of the twentieth annual ACM symposium on Principles of distributed computing. ACM, 2001. p. 264-273.
12. Huang, Zhuochuan, Shen, Chien-Chung, Srisathapornphat, Chavalit, et al. Topology control for ad hoc networks with directional antennas. In: Computer Communications and Networks, 2002. Proceedings. Eleventh International Conference on. IEEE, 2002. p. 16-21.
13. Marsan, Marco Ajmone, Chiasserini, Carla F., Nucci, Antonio, et al. Optimizing the topology of Bluetooth wireless personal area networks. In: INFOCOM 2002. Twenty-first annual joint conference of the IEEE computer and communications societies. Proceedings. IEEE. IEEE, 2002. p. 572-579.
14. Jia, Xiaohua, Li, Deying, and Du, Dingzhu. QoS topology control in ad hoc wireless networks. In: INFOCOM 2004. Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies. IEEE, 2004. p. 1264-1272.
15. Li, Deying, Jia, Xiaohua, and Du, Hongwei. QoS topology control for nonhomogenous ad hoc wireless networks. EURASIP Journal on Wireless Communications and Networking, 2006, vol. 2006, no 2, p. 43-43.
16. Cheng, Xiaochun, Cardei, Mihaela, Sun, Jianhua, et al. Topology control of ad hoc wireless networks for energy efficiency. Computers, IEEE Transactions on, 2004, vol. 53, no 12, p. 1629-1635.
17. Cardei, Mihaela, Wu, Jie, and Yang, Shuhui. Topology control in ad hoc wireless networks using cooperative communication. Mobile Computing, IEEE Transactions on, 2006, vol. 5, no 6, p. 711-724.
18. Joao Cabrera, Ram Ramanathan, and Carlos Gutierrez. Stable Topology Control for Mobile Ad-Hoc Networks. Communications Letters on, 2007, vol. 11, no. 7, p. 574 - 576.
19. Wieselthier, Jeffrey E., Nguyen, Gam D., and Ephremides, Anthony. On the construction of energy-efficient broadcast and multicast trees in wireless networks. In: INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE. IEEE, 2000. p. 585-594.
20. Wan, P.-J., Călinescu, G., Li, X.-Y., et al. Minimum-energy broadcasting in static ad hoc wireless networks. Wireless Networks, 2002, vol. 8, no 6, p. 607-617.
21. Bauer, Joanna, Haugland, Dag, and Yuan, Di. Analysis and computational study of several integer programming formulations for minimum-energy multicasting in wireless ad hoc networks. Networks, 2008, vol. 52, no 2, p. 57-68.
22. Rajaraman, Rajmohan. Topology control and routing in ad hoc networks: A survey. ACM SIGACT News, 2002, vol. 33, no 2, p. 60-73.
23. IBM ILOG CPLEX V12.1, 2009. User's Manual. IBM ILOG CPLEX V12.1.