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Efficient construction of network topology to conserve energy in wireless ad hoc networks ☆

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Abstract

Wireless ad hoc networks are usually composed of battery constraint devices, which make energy conservation a vital concern of their design. Reducing energy consumption has been addressed through different aspects till now. Topology Control (TC) is a well-known approach which tries to assign transmission ranges of nodes to optimize their energy utilization while keeping some network properties like connectivity. However, in current TC schemes, the transmission range of each node is mostly accounted as the exclusive estimator for its energy consumption, while ignoring the amount of data it sends or relays. In this paper, we redefine the problem of Topology Control regarding both transmission range and traffic load parameters. After proving the NP-hardness of the new problem, we mathematically formulate it as a mixed integer linear programming problem to find optimal solutions. Then, we introduce polynomial-time heuristic algorithms to practically solve the problem. During construction of network topology, we deliberately take into account the impact of the employed routing method on load of individual nodes. Finally, we show the advantages of our proposals through simulations.

Keywords: Wireless ad hoc networks; Energy conservation; Topology control; Routing; Traffic load

1. Introduction

Wireless ad hoc networks are composed of several wireless devices that form a network without any special infrastructure. Energy conservation is perhaps the most important issue in such networks since battery charging is usually difficult. This fact becomes more vital in some special-purposed wireless networks such as sensor networks or networks deployed in military or critical environments.

Thus far, different techniques have been suggested to address energy conservation problem, ranging from efficient hardware design [1], to appropriate placing of communicating codes in the network [2]. One of the most well-known approaches to this problem, which is called Topology Control (TC), is based on constructing an efficient topology for the network such that the energy consumption becomes optimum while some essential properties like connectivity are preserved in the induced network graph. Minimizing the transmission ranges of ad hoc nodes such that the resulting topology remains connected is one of the main TC approaches [3]. In brief, the main intuition behind this approach is that the amount of communication's energy that each node consumes is highly related to its transmission range.

However, we believe that there is a shortcoming in the conventional definition of the TC problem that negatively affects all existing proposals. Factually, in the TC problem, the goal of optimization is solely based on minimizing the transmission ranges of wireless nodes. However, transmission range together with the load on a device will determine its actual energy consumption rate. For instance, a node with a very large range that forwards only a small fraction

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of network's traffic may consume much less energy than another node with a smaller transmission range that forwards much more packets per time.

In this paper, we try to consider the above deficiency. More precisely, we formulate a new problem, called *MinMax Load Sensitive Topology Control* (*MLSTC*), for multihop wireless ad hoc networks. We first provide a general description for this problem, and then discuss its tractability under two main constraints. Next, we mathematically formulate MLSTC as a Mixed Integer Linear Programming (MILP) problem to obtain optimal solutions. Particularly, we consider our problem separately under the presence of the shortest-path routing and multipath routing methods. We also introduce heuristics to effectively approximate the problem in polynomial time. At last, through experimental results, we show the superiority of the MLSTC approach over former TC schemes.

The remainder of this paper is organized as follows: In the next section, we survey the previous works on topology control in wireless ad hoc networks. In Section 3, we present the motivation and also the exact description of the MinMax Load Sensitive Topology Control (MLSTC) problem. Section 4 is devoted to the explanation of MILP approach, and Section 5 introduces the proposed heuristic methods. We demonstrate the simulation results in Section 6 and finally conclude the paper in Section 7.

2. Related work

Being one of the main sources of energy consumption, different techniques have been proposed to reduce the required energy of communications among wireless nodes. One of the most challenging problems is selecting transmission ranges of nodes so that the energy utilization becomes optimal while some important properties of the network, for example connectivity, are conserved. In [3], the authors provide a well formulation of this problem together with some efficient algorithms. In their graph-based model, topology control problem is represented by a triple ⟨M, P, O⟩ where M is the model of the graph, i.e., directed or undirected, P represents the network properties that are important for us to conserve, like connectivity, bi-connectivity, and strong connectivity, and O denotes the objective that should be optimized, like the maximum power consumption or total power consumption. Categorizing different versions of topology control problem according to this model, they presented valuable results including polynomial algorithms for some cases and proofs of NP-hardness for others.

In addition, many other works have been proposed as heuristic and optimal solutions for various forms of topology control problem [4–6]. As one of the initial papers, [4] has suggested two centralized algorithms along with two heuristic distributed methods. Later, Wattenhofer et al. [5] proposed an elegant distributed algorithm which works locally. The idea is to adjust the transmission range of every node so that it has at least one neighbor on each α angle. Surprisingly, they proved that global connectivity will be conserved if α is not bigger than $2\pi/3$. Another worth noting work is [6], where the authors have tried to find an equal and small range value for all nodes to obtain a strongly connected graph structure. Different from other proposals, they applied probabilistic methods rather than deterministic algorithms to attain such network property.

Other practical approaches are COMPOW [7] and CLUSTERPOW [8], implemented in the network layer. Both rely on the idea that if each node uses the smallest common power required to maintain connectivity, then the capacity of the entire network with respect to carrying traffic is maximized, the battery life is extended, and the MAC-level contention is mitigated. The major drawback of these approaches is their significant message overhead, since each node has to run multiple daemons, each of which has to exchange link-state information with their counterparts at other nodes.

In sensor networks, the problem of energy conservation can be stated in a different form that is how to build a broadcast/multicast tree that conserves energy well. This problem has been studied in [9], where the authors tried to adjust nodes' power, such that the total energy cost of a broadcast/multicast tree becomes optimized. Heuristics were proposed to address the issue, namely Broadcast Incremental Power (BIP), Multicast Incremental Power (MIP), Minimum Spanning Tree (MST), and Shortest Path Tree (SPT) algorithms. The proposed algorithms were evaluated through simulations. Later, Wan et al. [10] presented a quantitative analysis to evaluate the performance of these heuristics.

Working upon the topology constructed during topology control process, the method of routing can significantly influence the forwarding load and the energy utilization of nodes in the network. Numerous works have been suggested for energy efficient routing in wireless ad hoc and sensor networks; such as [11,12]. Five important metrics for energy efficient routing have been studied in [12], like minimizing energy consumed per packet, minimizing variance in node power levels, minimizing cost per packet, and so on.

One fundamental shortcoming which is appeared in all of these TC proposals is that they try to minimize energy utilization of nodes only through reducing their transmission ranges without taking into consideration the amount of data they send or forward. However, as we will show later, energy utilization in each wireless node is significantly affected by the volume of traffic it forwards. As an example, one common negative phenomenon in the process of data forwarding in multihop wireless networks is the appearance of highly-loaded and early-depleted areas in special geometric places like centric parts of the network [13,14]. This deficiency is caused since usually most of packets should pass over this small area to reach their destinations. In brief, the main contribution of this paper is to address this deficiency by constructing an efficient topology for the network.