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Maximum lifetime broadcast communications in cooperative multihop wireless ad hoc networks: Centralized and distributed approaches ☆

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ABSTRACT

We investigate the problem of broadcast routing in energy constrained stationary wireless ad hoc networks with an aim to maximizing the network lifetime measured as the number of successive broadcast sessions that can be supported. We propose an energy-aware spanning tree construction scheme supporting a broadcast request, considering three different signal transmission schemes in the physical layer: (a) point-to-point, (b) point-to-multipoint, and (c) multipoint-to-point. First we present a centralized algorithm that requires global topology information. Next, we extend this to design an approximate distributed algorithm, assuming the availability of k-hop neighborhood information at each node, with k as a parameter. We prove that the centralized scheme has time complexity polynomial in the number of nodes and the distributed scheme has a message complexity that is linear in the number of nodes. Results of numerical experiments demonstrate significant improvement in network lifetime following our centralized scheme compared to existing prominent non-cooperative broadcasting schemes proposed to solve the same lifetime maximization problem in wireless ad hoc networks. Due to lack of global topology information, the distributed solution does not produce as much advantage as the centralized solution. However, we demonstrate that with increasing value of k, the performance of the distributed scheme also improves significantly.

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1. Introduction

The first decade of 21st century has seen a phenomenal rise in research interest on the issue of energy conservation in the design and analysis of routing protocols for multihop wireless networks. Wireless ad hoc networks (WANETs) constitute an important subclass of multihop wireless networks, where nodes are often battery operated and recharging or replacing these batteries may not be feasible in certain applications. In other cases, where energy resources of nodes could be replenished, the rising global awareness for green communication demands their use in a frugal manner. WANETs have huge application potential for all traditional areas of mobile computing and also in disorganized or hostile environments.

☆ This is a substantially revised and extended version of the paper "Cooperative Broadcasting for Energy Constrained Static Wireless Ad Hoc Networks" published in 6th International Conference on Wireless Communication and Sensor Networks (WCSN, 2010). Theorem 1 of Section 3.1, and Sections 4 and 5 are completely new technical contributions in this paper.

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A survey of energy conservation routing solutions for WANETs reveals that the proposed solutions can be broadly classified into two categories, (1) to minimize the energy consumption and (2) to maximize the network lifetime [1]. Our subsequent discussion belongs to the second category in the light of a prominent and recent trend of cross-layer approach for designing better energy conserving communication protocols for WANETs.

The three different lines of studies, which are followed in the research for network lifetime maximization in WANETs, are as follows [2]:

(i) maximizing network lifetime of a single routing session under a static network topology,
(ii) maximizing network lifetime of a single routing session under dynamic network topology updates and
(iii) maximizing the lifetime for a sequence of routing requests with dynamic topology updates for each routing request.

Several polynomial-time optimal solutions were proposed for the first type problem [3–5]. For multicast routing, Floreen et al. [6] showed that the second type problem is NP-hard. The third category of the lifetime maximization problem, also referred as online routing problem, was shown to be NP-hard for unicast and multicast routing in [7] and [2] respectively. Although several strategies were proposed addressing the problem of maximizing network lifetime for a single routing session, to the best of our knowledge, very few solutions were proposed for solving the online routing problem in WANETs. The unicast, multicast and broadcast routing solutions of this problem were discussed in [7], [2] and [8] respectively.

However, most of these studies were based on a common assumption that wireless links in the network are reliable (i.e. free from packet loss), which is not at all realistic. Recently, Li et al. [9] studied the maximum lifetime broadcasting and multicasting problems (first type) in energy constrained ad hoc networks with unreliable links. They [9] proved that, the problem of network lifetime maximization for unreliable networks is NP-complete. They authors designed a heuristic algorithm focusing on link quality which achieves significant improvement in network lifetime compared to traditional algorithms for maximum lifetime broadcasting and multicasting.

In parallel to algorithmic and protocol research in energy-limited WANETs, in recent years, the use of *cooperative communication* [10] has spurred a great deal of interest among researchers. The key idea is to overcome deleterious effects of wireless fading channels through spatial diversity while avoiding the complexity of mounting multiple antennas on small nodes in wireless networks. *Cooperative transmission* [11] is basically a multipoint-to-point communication technique, where multiple nodes along a path coordinate together to transmit a message to the next hop as long as the combined signal at the receiver satisfies a threshold *signal to noise ratio* (SNR). Since the cooperating nodes, together, successfully emulate a virtual transmit-antenna array as observed in real *multiple input single output* (MISO) transmission, this transmission technique is also referred as *virtual multiple input single output* (vMISO) transmission [12]. Routing problem under cooperative radio transmission model is called cooperative path routing and its application for energy aware routing in multihop wireless networks has been discussed in [11–17].

Broadcast is considered to be an import communication mechanism in WANETs to disseminate information from a single source node to all other nodes in the network. Many routing protocols exploit this technique for maintenance of routes between nodes [18]. Hence, design of energy aware broadcast schemes for WANETs is of paramount importance.

1.1. Related work

In [19] and [20], the authors investigated the scope of cooperative communication for solving the first problem. In this paper, we study a particular model of category (iii) of lifetime maximization problem for broadcast routing (described in the previous subsection) in energy-constrained, static, WANETs. We consider the case where the network is required to support a sequence of broadcast sessions, $B = \{b_1, b_2, \ldots, b_n\}$, where each session $b_i, b_i \in B$, will be specified by a source node s_i and message length m_i. For simplicity, we consider $m_i = 1$, for all i. The broadcast requests, which are generated at different nodes in the network, arrive sequentially over time and the network has no information available about the arrival pattern of future requests. For a given broadcast sequence B, the *network lifetime* is defined as the number of broadcast requests that can be successfully supported without replenishment of the energy resources of the nodes during network operation. Our objective is to maximize this number for a given broadcast sequence, in a given wireless network. Park and Sahni [8] addressed the same problem by proposing a class of centralized algorithms that jointly optimizes the minimum residual energy level of the nodes after each broadcast session and the total transmission power for each broadcast session. Nonetheless, the analysis was carried out from a pure graph-theoretic perspective. The authors did not explore the impact of signal transmission techniques on the design of efficient routing strategies for the lifetime maximization problem. This is the primary motivation of our present study.

1.2. Contributions

Here, we address the problem by adopting a cross layer approach. We propose a centralized solution first. Next, we extend this design to a distributed solution, where knowledge of global topology information is not required. To the best of our knowledge, there is no published work on the hardness of online problem of optimal broadcast routing for maximizing network lifetime for energy-constrained WANETs. We show that like multicasting [2], the online optimal broadcast routing problem in WANETs is also NP-hard. Hence, we follow a heuristic approach. We propose a cooperation-based broadcast routing scheme, which combines energy saving potential of cooperative transmission in the physical layer with an energy-aware spanning tree algorithm in the network layer to maximize the network lifetime. In our proposed solution, three different sig-

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