Computer Networks 55 (2011) 3256–3274

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Energy-aware routing algorithms for wireless ad hoc networks with heterogeneous power supplies

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ARTICLE INFO

Article history:
Received 2 November 2010
Received in revised form 9 March 2011
Accepted 14 June 2011
Available online 26 June 2011

Keywords:
Energy-aware routing
Heterogeneous power supplies
Energy consumption model
Wireless ad hoc networks

ABSTRACT

Although many energy-aware routing schemes have been proposed for wireless ad hoc networks, they are not optimized for networks with heterogeneous power supplies, where nodes may run on battery or be connected to the mains (grid network). In this paper, we propose several energy-aware routing algorithms for such ad hoc networks. The proposed algorithms feature directing the traffic load dynamically towards mains-powered devices keeping the hop count of selected routes minimal. We unify these algorithms into a framework in which the route selection is formulated as a bi-criteria decision making problem. Minimizing the energy cost for end-to-end packet transfer and minimizing the hop count are the two criteria in this framework. Various algorithms that we propose differ in the way they define the energy cost for end-to-end packet traversal or the way they solve the bi-criteria decision making problem. Some of them consider the energy consumed to transmit and receive packets, while others also consider the residual battery energy of battery-enabled nodes. The proposed algorithms use either the weighted sum approach or the lexicographic method to solve the bi-criteria decision making problem. We evaluate the performance of our algorithms in static and mobile ad hoc networks, and in networks with and without transmission power control. Through extensive simulations we show that our algorithms can significantly enhance the lifetime of battery-powered nodes while the hop count is kept close to its optimal value. We also discuss the scenarios and conditions in which each algorithm could be suitably deployed.

1. Introduction

Energy-aware routing is an effective scheme to prolong the lifetime of energy-constrained nodes in wireless ad hoc networks [1–13]. Routes are discovered considering the energy cost to transmit packets from source nodes to destination nodes, or considering the remaining battery energy of nodes. This could result in finding routes in which nodes consume less amount of energy for packet forwarding, or routes in which nodes are likely to have more remaining battery energy.

The existing energy-aware routing schemes, however, are not optimized for networks with heterogeneous power supplies. In some applications of ad hoc networking, there might be devices in the network which are connected to the mains (grid network). A simple example is a meeting scenario, where laptops of participants form an ad hoc network to exchange information during the meeting. Some laptops might be connected to the mains, while others use their batteries (see Fig. 1). Another scenario is home networking, where devices at home form an ad hoc network to exchange context [14]. In a home network, most devices are connected to the mains (e.g., appliances), while some handheld devices may run on a battery (e.g., a smart phone). In these scenarios and other similar scenarios of ad hoc networking, energy-aware routing schemes could be

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1389-1286/$ - see front matter
doi:10.1016/j.comnet.2011.06.015

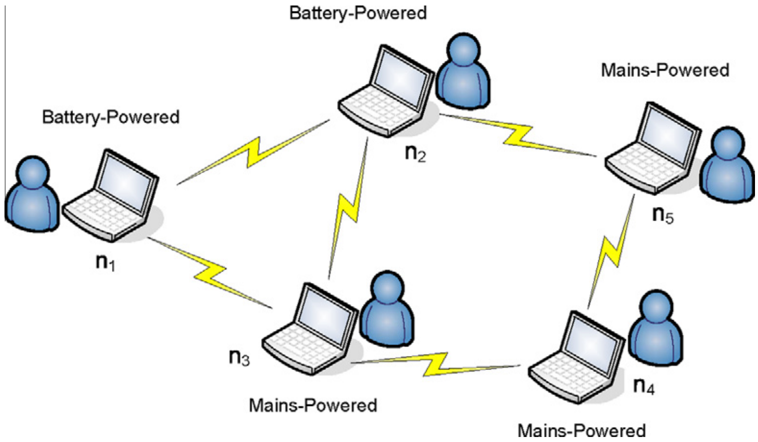

Fig. 1. Schematic of a wireless ad hoc network comprised of mains and battery powered devices.

devised considering the heterogeneity of power supply of nodes to avoid relaying over battery-powered (BP) devices. We can benefit from the advantage of having mains-powered (MP) nodes in the network to reduce the energy consumption of BP nodes for packet forwarding. This can extend the lifetime of BP nodes in such networks.

Although we can deploy the existing energy-aware routing schemes in networks with MP nodes, for instance, by considering no energy cost for packet forwarding by such nodes, such solutions may not be optimal. One problem is the increased hop count. Considering no energy cost for MP nodes may increase the number of hops of the selected routes, because longer routes consisting of MP nodes will be preferred to shorter routes consisting of BP nodes. Apart from this, the existing schemes are not designed on the basis of a realistic energy consumption model for packet exchange over wireless links. Many energy-aware routing schemes such as those proposed in [15,16,1,11,12,17,18] do not consider the energy consumed by processing elements of transceivers during packet transmission and reception. Measurements presented in [19] show that these sources of energy consumption might be in the same order as the transmission power of nodes which is considered in the design of energy-aware routing schemes in [15,16,1,11,12,17,18].

The novelty in this paper is the proposal of novel energy-aware routing algorithms for ad hoc networks which consist of both MP and BP nodes. To this end, we use a realistic energy consumption model for packet transmission and reception over wireless links, where the energy consumed by processing elements of nodes are also taken into account. We provide a detailed explanation for energy consumption of nodes by bringing into the picture the effect of transmission power control [20,21] on the consumed energy. The energy consumption model that we present can also provide a substrate for further investigations on energy-aware routing in multi-rate wireless ad hoc networks. Nevertheless, in this paper, we only consider single-rate networks, and leave multi-rate networks for future studies.

On the basis of the developed energy consumption model, we propose Least Battery-powered Nodes Routing (LBNR) and Minimum battery cost with Least battery-powered Nodes Routing (MLNR) algorithms. LBNR and MLNR algorithms minimize the energy cost of end-to-end packet traversal in ad hoc networks keeping the hop count of the selected routes minimal. They differ with each other in the way they define the energy cost of packet forwarding. LBNR considers the power supply of nodes and their consumed energy for packet transmission and reception, while MLNR considers the residual battery power of BP nodes as well.

We unify LBNR and MLNR algorithms into a generic framework for energy-aware routing in ad hoc networks. The route selection in this framework is formulated as a bi-criteria decision making problem. Minimizing the energy cost of end-to-end packet traversal and minimizing the hop count of selected routes are the two criteria that we consider in this paper. Nevertheless, other criteria such as maximizing end-to-end reliability of routes could also be easily added to the proposed framework. By using different methods to solve the bi-criteria decision making problem, we then propose LBNR–LM and MLNR–LM algorithms, which use the lexicographic method [22], and LBNR–WSA and MLNR–WSA, which use the weighted sum approach [22]. We use extensive simulations to evaluate the performance of the proposed algorithms in static and mobile ad hoc networks and in networks with and without transmission power control.

An important characteristic of our proposed algorithms is that (as we will show in the paper) they can generalize some of the well-known energy-aware routing algorithms such as MBCR (minimum battery cost routing) and MTPR (minimum total transmission power routing) [1,2]. Furthermore, while the proposed algorithms in this paper have been designed for ad hoc networks with both MP and BP nodes, they can also be deployed in networks with only BP nodes. This makes, our proposed algorithms generalized schemes which are applicable not only to the networks with only BP nodes but also to the networks