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Hierarchical power management in disruption tolerant networks using traffic-aware optimization

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ABSTRACT

Recent efforts in Disruption Tolerant Networks (DTNs) have shown that mobility can be a powerful means for delivering messages in highly-challenged environments. DTNs are wireless mobile networks that are particularly useful in sparse environments where the density of nodes is insufficient to support direct end-to-end communication. Unfortunately, many mobility scenarios depend on untethered devices with limited energy supplies. Without careful management, depleted energy supplies will degrade network connectivity and counteract the robustness gained by mobility. A primary concern is the energy consumed by wireless communication, and in particular the energy consumed in searching for other nodes to communicate with. In this paper we examine a hierarchical radio architecture in which nodes are equipped with two complementary radios: a long-range, high-power radio and a short-range, low-power radio. In this architecture energy can be conserved by using the low-power radio to discover communication opportunities with other nodes and waking the high-power radio to undertake data transmission. We develop a generalized power management framework for controlling the wake-up intervals of the two radios. In addition, we show how to incorporate knowledge of the traffic load, and we devise approximation algorithms to control the sleep/wake-up cycling to provide maximum energy conservation while discovering enough communication opportunities to handle that load. We evaluate our schemes through simulation under various mobility scenarios. Our results show that our generalized power management scheme can tune wake-up intervals of the two radios to balance energy efficiency and delivery performance. Also, when traffic load can be predicted, our approximation algorithms reduce energy consumption from 60% to 99% compared to no power management.

1. Introduction

Network designers often think of mobility as a detriment to building robust networks. However, recent efforts in Disruption Tolerant Networks (DTNs) have shown that mobility can be a powerful means for delivering messages in highly-challenged environments [1–7]. DTNs are wireless mobile networks that are particularly useful in sparse environments where the density of nodes is insufficient to support direct end-to-end communication. When mobile nodes encounter each other, opportunistically or intentionally, they pass messages to route them toward their final destinations. Unfortunately, many mobility scenarios depend on untethered devices with limited energy supplies. Such scenarios include stationary sensor networks utilizing mobile access points to collect sensed data or vehicle-aided communication networks for handhelds or laptops, in which some nodes have limited energy while the others may have abundant energy [6,3,5,8]. Without careful management depleted energy supplies will degrade network connectivity and counteract the robustness gained through mobility.

However, mobile devices exhibit a tension between saving energy and providing connectivity through opportunistic encounters. In order to pass messages, the device must discover *contacts* with other nodes [2] – typically the discovery is done using the same wireless interface used for message transfer. At the same time, energy conservation requires "sleeping," i.e., turning off or disabling the wireless interface – the wireless interface is one of the largest energy consumers in mobile devices [9] whether they are actively communicating or just listening [10,11]. If the wireless interface is asleep, the node cannot discover other nodes for communication and vice versa. Thus, power management in DTNs must balance discovery of other nodes while aggressively sleeping the radio during the remaining periods. However, as we show in this paper, using naive schemes nodes may devote up to 95% of their energy to searching for other nodes – this energy is purely overhead for discovery.

In this paper, we examine the possibility of using a hierarchical radio architecture in mobile DTNs, in which nodes are equipped

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with two complementary radios: a long-range, high-power radio and a short-range, low-power radio. In this architecture, energy can be conserved by using the low-power radio to discover contacts with other nodes and then waking up the high-power radio to undertake data transmission. Most previous studies using this hierarchical radio architecture have considered only densely deployed networks, in which the short range of the low-power radio is sufficient for discovery [12–15]. However, DTNs are generally applicable to sparser networks, where the low-power radio may reach a subset of other nodes that could be reached by the high-power radio, even when the nodes are mobile. Therefore, if a node relies only on the low-power radio to discover contacts, it may miss them due to the shorter range. To avoid missing contacts, we propose a generalized power management scheme that uses *both* radios to participate in contact discovery. This generalized scheme controls the *wake-up interval* of each radio, which it uses to trade between energy savings and the performance of message delivery. To guide the trade-off, we also incorporate knowledge of the traffic load in the network and devise approximation algorithms to determine the optimal wake-up intervals which minimize the overall energy consumption, while discovering enough contacts to handle the expected traffic load. In addition, we devise an adaptive sleeping algorithm that decides *how* to sleep (i.e., turn off, disable, or stay on) based on the expected overhead for a given wake-up interval.

We compare our generalized scheme with two alternative schemes: one that only uses the high-power radio for discovery, and one that only uses the low-power radio. First, our evaluation results without traffic information show that the scheme relying only on the low-power radio achieves the best energy efficiency in discovering contacts, while it may miss some contacts due to the shorter range. On the other hand, the generalized two-radio scheme can tune wake-up intervals of both radios to balance between energy efficiency and delivery performance. However, these gains depend heavily on what the wake-up interval of the radio is set to. Second, we show that by using the traffic load information to determine the wake-up intervals our approximation algorithms reduce energy consumption by 60–99% compared to the case without power management. Finally, by evaluating power management schemes in three different mobility scenarios, we show that the relative energy efficiency of using the additional low-power radio increases as the sparseness of the network increases.

This paper represents follow-on work to our previous work DTN power management [16]. Here we consider a more realistic setting and present the details of the analysis and additional results including results based on real mobility trace. Based on this more realistic and extensive evaluation we are able to reach more definitive conclusions regarding the energy-savings potential of the two-radio architecture.

The remainder of this paper is organized as follows. In Section 2, we describe our system model. In Section 3, we present our power management framework. Section 4 contains an evaluation of our two-radio scheme under various wake-up intervals. In Section 5, we propose wake-up interval estimation for our power management according to the expected traffic load. Section 6 presents an evaluation of our traffic-aware power management schemes. We discuss related work in Section 7 and conclude in Section 8.

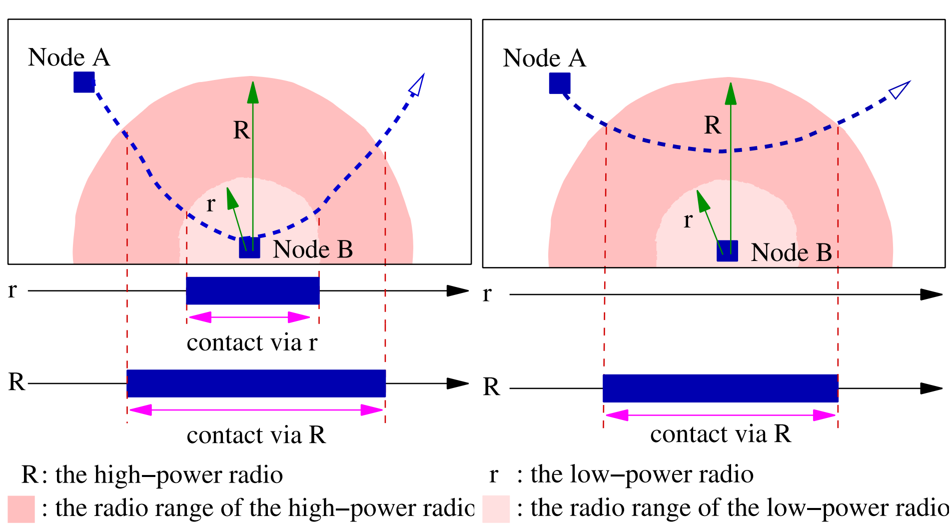
2. System model

This section describes the radio model and routing protocols we use in this paper.

2.1. Radio model

In a mobile DTN, two nodes communicate with one another during *contacts* [2] that occur when the two nodes, either mobile or stationary, are within the radio range of each other. Even if the devices are equipped with multiple radios, the nodes may or may not discover a particular contact opportunity depending on the range of the radios, which radios are active, and the movement trajectory of the two nodes. Fig. 1 shows two possible contact scenarios using a two-radio system. In Fig. 1(a), node A moves along the trajectory shown and node B stays in one location. Node A first enters within B's high-power radio range and then within B's low-power radio range. As a result, the nodes have a long contact via their high-power radios and a short contact via their low-power radios. In contrast, Fig. 1(b) shows that when node A passes node B using a different trajectory, it only enters the range of the high-power radio of node B.

While using a low-power radio alone may discover less contact opportunities than a high-power radio it does so at substantially reduced energy costs [10,14]. Table 1 shows the power usage of two sample radios, one high-power radio: 802.11, and one low-



(a) Contacts via both radios (b) A contact only via the high-power radio

Fig. 1. Contacts discovered by the high-power and low-power radios, where *R* and *r* are the high-power and low-power radios, respectively.