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Energy-efficient neighbor discovery protocol for mobile wireless sensor networks

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Abstract

Low energy consumption is a critical design requirement for most wireless sensor network (WSN) applications. Due to minimal transmission power levels, time-varying environmental factors and mobility of nodes, network neighborhood changes frequently. In these conditions, the most critical issue for energy is to minimize the transactions and time consumed for neighbor discovery operations. In this paper, we present an energy-efficient neighbor discovery protocol targeted at synchronized low duty-cycle medium access control (MAC) schemes such as IEEE 802.15.4 and S-MAC. The protocol effectively reduces the need for costly network scans by proactively distributing node schedule information in MAC protocol beacons and by using this information for establishing new communication links. Energy consumption is further reduced by optimizing the beacon transmission rate. The protocol is validated by performance analysis and experimental measurements with physical WSN prototypes. Experimental results show that the protocol can reduce node energy consumption up to 80% at 1–3 m/s node mobility.
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1. Introduction

Wireless sensor network (WSN) is the most potential technology for very low power ubiquitous networks. Foreseen applications fields include monitoring of remote or hostile geographical regions, tracking of animals and objects, and monitoring in smart building and industries [1,2]. WSN may consist of even thousands of small and fully autonomous nodes, which gather sensor information, perform data processing, and communicate with each other. Nodes route data by multiple low-energy hops to sink nodes, which may act as gateways to other networks. Network management is fully decentralized eliminating the need for a fixed controller and infrastructure, which prevents a single point of failure.

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In most of these envisioned applications, nodes must operate with a scarce energy budget. They may have to scavenge supply energy solely from their operation environment, or operate up to several years with small batteries [3]. Hence, the energy consumption is one of the key performance metrics for WSN realizations.

To reach the energy budget, WSN nodes operate with constrained communication and computation resources. Thus, a typical node performs data processing using a MicroController Unit (MCU) having a couple of million instructions per second (MIPS) processing speed and tens of kbytes program and data memories [4,5].

Although the advances in radio frequency (RF) circuits have been significant, a radio transceiver is still the most power-consuming component in a WSN node. The power consumption of current radios is nearly the same in transmission and reception modes, and energy is saved only in a sleep mode, in which the radio circuitry is completely switched off. The nodes should come out of the sleep mode only to transmit or receive packets that are vital for node operation, thus avoiding idle listening of unnecessary traffic [6]. Therefore, a desired pair of nodes should be active simultaneously. As a global synchronization is very difficult to reach in large networks using low power and low cost components [7], nodes may reduce idle listening and energy consumption by forming locally synchronized communication links with their neighbors.

WSNs are often considered stationary in a way that the established communication links are unaltered for entire network lifetime. In practice, even an immobile network has a dynamic behavior [8,9] due to random node failures and dynamic operating environment caused by opened and closed doors, moving objects, changing weather conditions, and interferences from other networks, which all affect RF propagation. In addition, numerous envisioned WSN applications, such as access control, assets tracking, and interactive games necessitate the mobility of nodes causing dynamics for network topology [6,10]. Thus, WSN nodes should be able to recognize topology changes and update communication links rapidly, energy-efficiently, and with minimum interruptions on application data routing. In current WSN proposals, new neighbors are typically discovered by listening on available RF channels for their transmissions (network scan), lasting up to tens of seconds [11–13]. As calculated in [14], each second of a network scan consumes the energy equaling to 2800 frame transmissions using a typical low power transceiver. In dynamic networks, scans may increase node energy consumption one order of magnitude [14]. Thus, we need an energy-efficient neighbor discovery to substitute for network scans.

In this paper, we present a new energy-efficient neighbor discovery protocol (ENDP) for synchronized low duty-cycle medium access control (MAC) schemes. The presented protocol reduces the need for network scans by distributing synchronization information from nodes in two-hop neighborhood. This information is carried in the beacon payloads of underlying MAC protocol and utilized for establishing new communication links. In addition, ENDP introduces an efficient network beacon signaling scheme to make network scans more energy-efficient. To the best of our knowledge, ENDP is the first protocol that can effectively minimize network energy consumption in dynamic WSNs. The energy efficiency and operation fidelity are verified by analytical performance models and experimental measurements using real WSN prototypes.

This paper is organized as follows. Section 2 presents design approaches for low duty-cycle MAC protocols and discusses how neighbor discovery is currently performed. The design of ENDP is presented in Section 3. For obtaining realistic results, we introduce a WSN prototype platform and determine its radio energy models in Section 4. According to the energy models, the performance of ENDP is determined analytically and optimized in Section 5. Section 6 presents experimental measurements by the prototypes. The paper is concluded in Section 7.

2. Related research

2.1. Low duty-cycle MACs

The MAC sublayer operating on top of a physical layer (PHY) manages radio transmissions and receptions on the shared wireless medium, and hence has a major effect on network performance and energy consumption. The design objectives of WSN MAC differ completely from traditional wireless voice and data networks, which pursue to maximize wireless medium utilization. In WSNs, MAC is pursuing to provide energy-efficient, adaptive and error tolerant operation, and adequate scalability for large and dense networks having only few kbit/s network throughput requirement [15].

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