Available online at www.sciencedirect.com

ScienceDirect

Ad Hoc Networks 5 (2007) 844–854

www.elsevier.com/locate/adhoc

Adaptive cross-layer MAC design for improved energy-efficiency in multi-channel wireless sensor networks ☆

Haythem Bany Salameh *, Tao Shu, Marwan Krunz

Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721, United States

Received 13 February 2007; accepted 15 February 2007
Available online 2 March 2007

Abstract

We present a novel cross-layer design for improving energy efficiency in a wireless sensor network that utilizes a multi-channel non-persistent CSMA MAC protocol with adaptive MQAM modulation at the physical layer. Cross-layer interactions are achieved through joint, traffic-dependent adaptation of the backoff probability at the MAC layer and the modulation order at the physical layer. The joint optimization of the backoff probability and the modulation order is conducted subject to a constraint on the packet retransmission delay. Such an optimization is shown to produce a significant improvement in the per-bit energy requirement for successful packet delivery. Our analytical findings are verified through numerical results and computer simulations.

Keywords: Cross-layer design; Backoff probability; Traffic load; CSMA; MQAM; WSN

1. Introduction

Wireless sensor networks (WSNs) have recently been used for numerous applications, including environmental monitoring, smart spaces, data collection, robotic exploration, etc. [1,18]. The sensing devices in these applications are characterized by a limited battery lifetime, making energy efficiency a critical factor in the design of communication protocols [5] for WSNs. Current channel access protocols for WSNs can be divided into scheduling-based and contention-based protocols. Scheduling-based protocols, which include TDMA-, FDMA-, and CDMA-based schemes, are collision free. Among these protocols, TDMA-based designs are considered the most appropriate for WSNs [13]. However, many factors limit the use of TDMA protocols in WSNs, including scalability and adaptivity to network dynamics [15,17]. For contention-based (random access) protocols, the most mature channel-access approach is the one that follows the carrier sense multiple access (CSMA) paradigm. CSMA is characterized by its simplicity, flexibility, robustness, and adaptivity to changes in the number of active nodes. No clock synchronization or global

☆ An abridged version of this paper was presented at the *IEEE GLOBECOM Conference*, San Francisco, November 2006. This work was supported in part by the National Science Foundation under Grants CNS-0627118 and CNS-0313234.

* Corresponding author. Tel.: +1 520901 0106; fax: +1 520 6269249.

E-mail addresses: haythem@ece.arizona.edu (H.B. Salameh), tshu@ece.arizona.edu (T. Shu), krunz@ece.arizona.edu (M. Krunz).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2007.02.011

topology information are needed. Essentially, there are two variants of CSMA: p-persistent and non-persistent. As shown in [3], the MAC protocol used in the IEEE 802.11 standard can be well modeled by a p-persistent CSMA scheme. In contrast, many other MAC schemes proposed for WSNs are variants of non-persistent CSMA. In non-persistent CSMA, a node senses the carrier only when it is about to transmit. This limits the time spent on monitoring the medium, and hence conserves energy [1,8]. Both variants of CSMA have been extensively studied over the past three decades. Stationary throughput and delay characteristics were derived for slotted and unslotted channels, under finite- and infinite-population models [8,16]. Analytical results related to the energy efficiency were reported for a slotted CSMA system with a finite population size [2,4,3]. In these works, the system consists of a small number of stations (usually less than 100), and each station is assumed to operate under heavy traffic, i.e., each station always has data packets to transmit. The finite-population and heavy-traffic assumptions best describe the situation in a WLAN, but do not adequately characterize that of a WSN. In contrast to a WLAN, a WSN may consist of a large number (thousands) of nodes. Each individual node contributes only a small amount of traffic to the network through sparse access to the channel (i.e., low duty cycle). Such a setup makes a model with an infinite-population and moderate traffic load more appropriate for analyzing random channel access in a WSN.

In this paper, we investigate the energy efficiency of a multi-channel non-persistent CSMA MAC protocol for a WSN with an infinitely large node population. To improve the energy efficiency, defined as the energy consumption for successfully transmitting a bit, we consider the joint optimization of the modulation scheme (physical layer) and packet retransmission probability (MAC layer). We assume that at the physical layer, a node is capable of adjusting its modulation order according to the instantaneous traffic load of the system. By using adaptive modulation, the system can control the transmission duration of each packet, leading to a controllable traffic load. The key advantage of using a multi-channel scheme is that the traffic load in the network can be distributed over different channels, which leads to fewer collisions and improved capacity. As we show later, this allows for more energy saving and higher network utilization. It should be noted that multi-channel CSMA protocols for wireless networks have been previously considered [12,11,10,14,7]. It was shown that such protocols are more efficient than their single-channel counterparts. However, these previous works have not considered the joint optimization of the physical layer and the MAC layer, and thus leave the room for further energy efficiency improvement.

The remainder of this paper is organized as follows. In Section 2, the system model is presented. An analytical expression for the transmission delay is derived in Section 3. In Section 4, the energy efficiency is optimized. Section 5 describes the proposed protocol. In Section 6, numerical and simulation results are presented. Conclusions are presented in Section 7.

2. System model

We consider the system in Fig. 1. The available bandwidth R (in symbols/s) is divided into $J+1$ non-overlapping additive white gaussian noise (AWGN) channels. One channel is used for control, while the remaining J channels are used for data. Each data channel has a transmission rate R_i symbols/second. The functional abstraction of a node contains three components: a packet generator, an M-ary quadrature amplitude modulation (MQAM)-based physical layer, and a multi-channel non-persistent CSMA-based MAC layer (described in section VI). Packets have the same size, say L bits. A node only contributes an infinitesimal amount of traffic to the channel. Nodes collectively

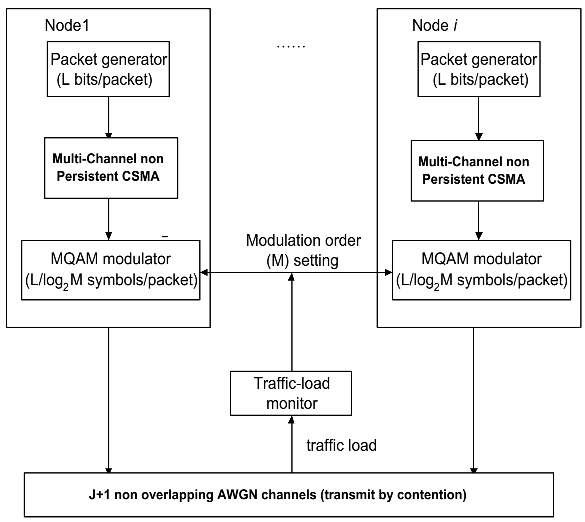

Fig. 1. System model of a node in a WSN.