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An adaptive collision resolution scheme for energy efficient communication in IEEE 802.15.4 networks

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ABSTRACT

IEEE 802.15.4 provides a widely accepted solution for low-cost and low-power wireless communications, and it is known to be applicable to many types of WSN application scenarios. To enhance energy efficiency and throughput of sensor nodes, many CSMA/CA schemes based on IEEE 802.15.4 have been proposed. However, they still suffer from unnecessary waste of energy and bandwidth due to inefficient backoff management. In order to overcome these problems, we propose an enhancement to existing schemes, called *adaptive collision resolution* (ACR). ACR appropriately adapts *backoff exponent* (BE) to the current network contention level based on physical and link-layer measurements. In addition, it adjusts *backoff periods* (BP) to avoid meaningless backoffs and additional *clear channel assessments* (CCAs) by using the estimated time remaining until the channel becomes idle. To verify the feasibility and applicability of our scheme, we studied mathematical analysis and tested it on the Matlab and USRP/GNU Radio testbed. We also performed simulation study using OPNET, and our simulation results indicate that ACR shows improved energy efficiency and throughput performance over existing schemes.

1. Introduction

IEEE 802.15.4 is a standard designed for low rate wireless personal area networks (LR-WPANs), and it is considered a promising solution for low power and low cost communication while achieving high networking flexibility [1]. For these reasons, the scope of its applicability and functionality goes beyond what traditional applications, such as habitat and healthcare monitoring, target tracking, military surveillance, smart grid, and home automation, have to offer [2–5].

One of the most challenging issues in IEEE 802.15.4 networks is the question of how to reduce power consumption in order to extend network lifetime. Therefore, unlike most wireless communication standards which primarily focus on achieving high throughput performance, the IEEE 802.15.4 standard aims at facilitating low cost and low power wireless communication. For efficient communication, it includes the collision resolution mechanism called *carrier sense multiple access with collision avoidance* (CSMA/CA), which allows sensor devices to avoid power-consuming packet collisions caused by multiple simultaneous transmissions.

However, the traditional IEEE 802.15.4 CSMA/CA has two main problems. First, aggressive binary exponential backoff may hamper the efficient communication of sensors. Whenever a *clear channel assessment* (CCA) reports that the channel medium is not clear, sensors simply increment the *binary exponent* (BE) at a time up to the maximum value (maxBE). This mechanism can waste idle slots and eventually result in throughput degradation since it may impetuously increase the BE even under a transient channel busy condition. Moreover, BE is simply reset to the

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initial value (minBE) upon a successful transmission or a packet drop. As a result, sensors may frequently suffer from meaningless backoffs and additional CCAs due to the initialized BE that is insufficient to resolve the current network contention level. Second, the sporadic CCA operation decreases not only energy efficiency, but also throughput. Unlike the IEEE 802.11 distributed coordination function (DCF), the CCA of IEEE 802.15.4 is not continuously conducted. Instead, sensors perform CCA only when they have finished the backoff process. In other words, sensors do not know whether or not there is an ongoing transmission while they are counting down *backoff periods* (BP) that are randomly chosen within $2^{BE}-1$. This may also result in waste of energy and bandwidth, since they should perform a meaningless CCA and succeeding backoff if the backoff timer expires under busy channel conditions.

There are two main approaches for enhancing CSMA/CA over IEEE 802.15.4 networks: backoff exponent adaptation and backoff period adaptation. In the backoff exponent adaptation approach, each sensor adjusts BE depending on physical and link-layer measurements [6,7]. On the other hand, in the backoff period adaptation approach, sensors shift the range of random BP to avoid redundant backoff and CCA operations [8]. Nevertheless, existing schemes are still limited in terms of energy efficiency and throughput since they do not effectively adjust the BE and BP.

In this paper, we propose a new collision resolution scheme, called *adaptive collision resolution* (ACR), which improves energy efficiency and throughput over IEEE 802.15.4 networks. In ACR, sensors carefully adjust BE by using consecutive success/failure transmissions and CCA results. To avoid impetuous changes, BE is decremented to reduce idle slots of backoff only when consecutive data transmissions succeed more than a certain threshold, or incremented to resolve high network contention only when consecutive CCAs sense the channel busy state or transmissions have failed consecutively. Furthermore, sensors appropriately extend the length of the randomly chosen BP based on the CCA results and estimated time remaining until the channel medium becomes idle. In this process, ACR uses a *frame start detection* (FSD) that can robustly detect the start of a frame being transmitted using a special preamble; it enables sensors to estimate the remaining channel busy time more accurately.

The main contributions of our work are as follows. First, we propose an enhancement to existing collision resolution schemes that improves IEEE 802.15.4 CSMA/CA performance. In the proposed scheme, BE is effectively adjusted based on physical and link-layer measurements. Second, we present a robust frame start detection (FSD) process that senses the start of a frame transmission and enables the range of the randomly chosen BP to be appropriately shifted to avoid the backoff timer expiration when the channel is in busy condition. Third, ACR is backward compatible with legacy IEEE 802.15.4 such that 802.15.4 sensors and ACR sensors can coexist smoothly, even though energy and throughput performance should be compromised in such situations. This is one of the key advantages of ACR since backward compatibility is one of important requirements.

The rest of this paper is organized as follows. In Section 2, we describe an overview of the IEEE 802.15.4 standard. In Section 3, we give a summary of related work and our motivation. Section 4 describes the proposed collision resolution scheme in detail. In Section 5, we present our experimental and simulation environments, and evaluation results. Finally, we conclude this paper in Section 6.

2. Background

2.1. Overview of IEEE 802.15.4 with beacon-enabled mode

The IEEE 802.15.4 standard specifies interoperable wireless physical and medium access control layers targeted to sensor nodes. It defines two operational modes, *non-beacon-enabled* mode and *beacon-enabled* mode. In non-beacon-enabled mode, a CCA is first performed in order for a sensor to carry out a transmission on the channel. If the CCA reports that the channel is busy, the sensor defers the transmission for a random period of time, and then tries again. However, due to the lack of periodic listen/sleep coordination via beacon-based synchronization, this mode let sensors consume a lot of energy [9]. In beacon-enabled mode, on the other hand, a coordinator manages a superframe structure that is bounded by periodic beacon frames. Each beacon frame is transmitted by the coordinator, and a time interval between two consecutive beacon frames consists of an active period and an inactive period that are mandatory and optional, respectively.

Fig. 1 shows the structure of a beacon interval in IEEE 802.15.4. As shown in the figure, the active period is divided into two periods, contention access period (CAP) and contention free period (CFP). In CAP, the slotted CSMA/CA mechanism is employed for channel access, where sensors contend with each other to perform transmissions. On the other hand, in CFP, the scheduled TDMA mechanism managed by a coordinator is used, where sensors can transmit without collisions during the designated slots since two or more sensors will not be allocated the same slot. Therefore, normal data traffic, control, and management frames are typically transmitted during CAP, and QoS-constrained traffic is delivered during CFP.

All sensors that are synchronized by periodic beacon frames of the coordinator remain awake during the active period, and enter a sleep state in the inactive period to reduce energy consumption. The length of the *beacon interval* (BI) and *superframe duration* (SD) are defined as follows:

$$\begin{cases} BI = aBaseSuperframeDuration \times 2^{BO} & 0 \leqslant BO \leqslant 14 \\ SD = aBaseSuperframeDuration \times 2^{SO} & 0 \leqslant SO \leqslant BO \leqslant 14 \end{cases}$$

where *aBaseSuperframeDuration* denotes the minimum length of the superframe and it is defined as the base slot duration (60 symbols) multiplied by the number of superframe slots (16 slots). The *beacon order* (BO) and *superframe order* (SO) parameters are determined by the coordinator and delivered to all sensors via the beacon frame.