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An adaptive CSMA/TDMA hybrid MAC for energy and throughput improvement of wireless sensor networks

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ABSTRACT

IEEE 802.15.4 as a standard for low rate wireless personal area networks (LR-WPAN) is an applicative choice for implementation of wireless sensor networks. Due to the advantages of this standard and its capabilities for more specification to wireless sensor networks, we were persuaded to resolve some of its proven weaknesses in such environments. The slotted CSMA/CA method utilized in beacon-enabled mode of 802.15.4 causes unacceptable level of energy consumption and throughput in conditions like high loads. To overcome these issues, we proposed an adaptable CSMA/TDMA hybrid channel access method by applying some modifications to the 802.15.4 standard. The energy and throughput improvement is achieved by dedicating a part of the contention access period to a time division medium access protocol (TDMA). To evaluate our proposed method in comparison with 802.15.4, we developed a simulation in OMNeT++. Analysis of the simulation results indicates general improvement of energy consumption and throughput. As a sensor network grows more populated or the load increases, the proposed method shows a better performance in comparison with IEEE 802.15.4 standard.

1. Introduction

Improvement of electronic devices and micro-electronic chips has suggested wireless sensor networks as a solution for network applications like video surveillance, traffic monitoring, object detection and tracking systems, etc. Such networks normally consist of a large number of distributed nodes that organize themselves into a multi-hop wireless network. Each node has one sensor, embedded processors and low-power radio and is normally battery operated [1].

Sensors have limited energy resources and their functionality continues until their energy is drained. Therefore, energy for sensor networks should be managed carefully to extend the lifetime of sensors [1]. Since the utilized medium access control (MAC) protocol takes control of a node's radio – as the most energy consuming part of a sensor node – MAC protocol has a very important role in wireless sensor network design.

Having a revision on suggested methods of wireless sensor data communication, MAC protocols can be divided into two main categories: contention based and TDMA-based protocols. In contention based protocols like S-MAC [2], B-MAC [3] and T-MAC [4] nodes can transmit without having any predetermined time assigned to them, therefore unwanted collisions may occur. These protocols provide mechanisms for avoiding and resolving collisions. TDMA-based protocols like TRAMA [5] and μ-MAC [6] are collision free because each node has a designated time slot in which only that particular node transmits. There are also hybrid CSMA/TDMA methods proposed. Z-MAC [7] is an example of such hybrid protocols which works adaptively, and goes toward a fully TDMA environment as the traffic increases.

In spite of the number of methods designed for wireless data communication, there is still no standard specified for

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wireless sensor networks. However, IEEE 802.15.4 Wireless Personal Area Network (WPAN) standard [8], as a standard for low rate and low power wireless communication between resource limited devices, is a candidate for such environments. Features like low duty cycle (up to 0.1%) and self-organization of 802.15.4 standard – which are specific characteristics of wireless sensor networks – make this protocol a more attractive choice.

According to [9], the collision avoidance mechanism is not efficient in case of a large-scale WSN. Also with high offered loads, the slotted CSMA/CA utilized in 802.15.4 causes lower network throughputs due to the collisions resulting from of multiple simultaneous transmissions, at the beginning of a new superframe. The weaknesses caused by the slotted CSMA/CA were our main motivation for designing a new hybrid MAC for WSN environments.

In this paper we propose a hybrid MAC protocol based on IEEE 802.15.4 standard to reduce energy consumption and improve data throughput in current IEEE 802.15.4 standard. In this method, the coordinator adaptively divides the contention access period (CAP) between slotted CSMA/CA and TDMA according to nodes' data queue state and level of collisions detected on the network. For acquiring the queue state information of the network nodes, data frame reserved bits have been used. Also modifications have been applied to the beacon frame GTS descriptor and reserved bits in order to assign TDMA slots to network nodes.

The rest of this paper is organized as follows. Section 2 presents an overview of the IEEE 802.15.4 standard. Section 3 reviews briefly some relevant previous works on wireless sensor network MAC protocols. The proposed CSMA/TDMA hybrid MAC protocol is presented in detail in Section 4. Simulation results are discussed in Section 5. Finally, the conclusions are given in Section 6.

2. Overview of 802.15.4 standard

This 802.15.4 supports both peer-to-peer and star topologies. In star topology the communications are established only between network devices and a coordinator which is a full-function device (FFD) capable of relaying messages [8]. In peer-to-peer topology a connection can be made between any two devices.

Two operational modes are defined in this standard, beacon-enabled and non-beacon mode. In non-beacon mode, like 802.11, channel access is only based on CSMA/CA. But in beacon-enabled mode the coordinator transmits a special-formatted frame named "beacon frame" in specified time intervals by which the devices synchronize themselves for accessing the channel [8].

The time interval between two beacon frames is called the beacon interval, and gets divided to an active and an optional inactive period. Devices are in sleep mode during the inactive period for energy saving purposes. The length of the active period is named as "superframe duration" and contains 16 equal time slots. The active period also consists of a Contention Access Period (CAP) and a Contention Free Period (CFP). The border between the CAP and the CFP is specified by the variable final CAP slot in the beacon frame. The CFP – which is managed by the coordinator – is used for applications demanding higher quality of service. Time slots in the CFP could be assigned to nodes only after they send a request to the coordinator. During the CAP, devices access the channel with a slotted CSMA/CA method [8].

For specifying the beacon interval (BI) and the superframe duration (SD), coordinator sets two beacon order (BO) and superframe order (SO) values in the beacon frame. These two parameters follow the $0 \leqslant SO \leqslant BO \leqslant 15$ constraint. The relation between BI and BO and between SI and SO are defined as below:

$$BI = aBaseSuperframeDuration \times 2^{BO}, \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO}, \quad (2)$$

where

$$aBaseSuperframeDuration(60\ symbols) = baseSlotDuration \times numberOfSuperframeSlots(= 16),$$

According to the above, the general form of beacon-enabled mode is as shown in Fig. 1.

3. Related work

Most protocols suggested for MAC layer of wireless sensor networks take advantage of either TDMA or CSMA/CA. Contention protocols like [2–4] provide advantages such as scalability, flexibility and self-organization. Besides, they have disadvantages such as idle listening and the overhead of using control packets like RTC/CTS for synchronization. TDMA-based protocols like [5,6] avoid collisions and idle listening by assigning pre-specified time slots to the network nodes. Though, these methods have difficulties in dynamically changing networks in which nodes enter and quit frequently (which is very common in wireless networks). Partitioning the space among network nodes and efficient management of time slots are important challenges in TDMA-based protocols.

Other protocols like Z-MAC [7] use hybrid models. Z-MAC utilizes an adaptive method of channel access which makes it work like CSMA in low contention, and similar to TDMA in high contention conditions. In [10] a local frame pre-schedule functionality is defined on hybrid CSMA/TDMA model in order to reduce energy consumption caused by unnecessary listening. In this model each node is aware of its own and its neighbors scheduling. Therefore if it is possible, the node intelligently goes to sleep and reduces energy consumption.

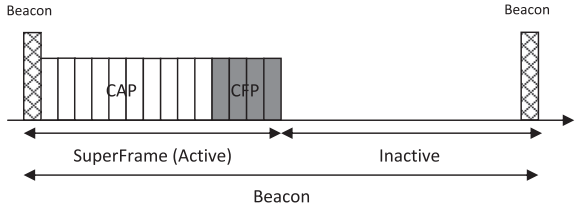

Fig. 1. Superframe structure in Beacon-enabled mode.