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Schedule-based multi-channel communication in wireless sensor networks: A complete design and performance evaluation

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ABSTRACT

Recently, wireless sensor networks (WSNs), enabling the connection between the physical world and the digital world, have become an important component of the Internet of Things (IoT). Several applications in the IoT require the efficient and timely collection of larger amounts of data. Due to the interference and contention over the wireless medium, the limited bandwidth of the radios, the limited resources of the battery-operated sensor nodes, this requirement becomes a challenging task. In this research, we exploit the multi-channel operation capability of the radios to provide the higher network throughput and propose an efficient scheduling algorithm to eliminate collision, idle-listening or over-hearing, which are consequences of non-coordinated transmissions. Our work focuses on scheduling the regular traffic that is periodically transmitted and on adapting the schedule to the additional traffic that can be requested at some point in time. To deploy the schedule-based multi-channel protocol on real applications, we design the complete communication procedure that is necessary for sensor nodes to communicate among them to form a network and to propagate the sensed data to the collection point. We also propose a low-overhead time synchronization scheme that is critical for a schedule-based protocol. The results of extensive simulation experiments show that the proposed scheduling algorithm can achieve collision-free parallel transmissions over different channels to provide high throughput and high delivery ratio while meeting the crucial energy efficiency requirements. Finally, we demonstrate the feasibility of the protocol and the time synchronization scheme on a laboratory-scaled test-bed of real motes.

1. Introduction

Recently, applications of Internet of Things (IoT), where physical sensors gather data readings from the field and deliver the traffic to the Internet, are emerging rapidly. The data are captured or created by the networks of smart objects or devices equipped with sensors and connected by

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wireless medium, wireless sensor networks (WSNs). The IoT approach is present in several application areas, such as smart cities, home automation, and industrial applications. Its impact on economies and societies around the world will potentially become enormous [1]. However, more stringent Quality of Service requirements (e.g. timely-delivery, larger bandwidth) of IoT applications and the traditional lifetime optimization requirement of WSNs, an enabler of IoT, should be addressed to fulfill the needs of new applications.

As the hardware costs are continuously decreasing, the number of WSN deployments is expected to grow drastically. Network density will increase greatly, resulting in high levels of inter-WSN interference. The challenge to be addressed is the increased bandwidth demand in the presence of higher levels of interference from both internal and external sources. This challenge stems from the fact that the amount of traffic is increasing while the bounded wireless channel capacity needs to be shared between devices within the same geographical area.

To deal with that, *multi-channel communication* is applied for using the 16 non-overlapping channels in the 2.4 GHz band or the 10 channels in the 915 MHz band and the ability of switching channels quickly in the standard IEEE 802.15.4-compliant hardware [2]. First, this helps to avoid the external interference when the rapidly increasing number of WSN application deployments is working on the same ISM bandwidth. Secondly, it allows multiple simultaneous transmissions on different channels to increase the network throughput. However, multi-channel communication has to cope with *channel coordination* since sensor nodes are equipped with half-duplex transceivers. To allow successful communication, the transmitter and the receiver must switch at the same moment to the same channel that has no nearby communication at that moment. Hence, the operation of a multi-channel communication protocol often requires sensor nodes in the network to have a common notion of time, or *time synchronization*. On the other hand, the protocols should fulfill the *energy-efficiency* requirement essential for WSNs.

A schedule-based approach in which each communication between a pair of nodes is assigned to a *timeslot – frequency* combination is most energy-efficient since a careful schedule can help nodes to avoid useless transmission or reception, the main causes of a node's energy waste [3]. However, it strictly requires network-wide time synchronization, which in turn might create overhead. Clearly, the energy saving property of a schedule-based approach should be considered in balance with the overhead resulting from the time synchronization scheme required. Existing related work is still lacking a complete solution and performance evaluation of schedule-based communication protocols.

Several proposals [4–6] have paid attention to the scheduling algorithm to obtain a contention-free, traffic-adaptive schedule. The algorithms in [4,6] are based on a centralized approach, while the proposal in [5] uses a distributed approach based on a Reinforcement Learning technique. On the other hand, the newly released IEEE 802.15.4e standard [7], an amendment to IEEE 802.15.4 to redesign the MAC layer, has proposed a framework for schedule-based communication without however any guidance on how to assign *timeslot – channel* combinations to each communication.

In this paper, we present a complete design of a contention-free multi-channel MAC protocol for data gathering WSNs, called RL-MMAC. RL-MMAC exploits the schedule-based approach to achieve the desired energy efficiency and the network throughput improvement and applies the multi-channel hopping mechanism to achieve reliability. The main contributions of the paper are summarized as follows:

- We analyze the requirements of multi-channel communication in wireless sensor networks and how a schedule-based approach and channel-hopping mechanism can help to improve network performance in terms of energy-efficiency, reliability and data throughput.
- We present the Reinforcement Learning (RL) based scheduling algorithm which produces the traffic-adaptive schedule for every node and the extension scheme for adapting the scheduled operation of nodes when additional traffic requests or new nodes joining require extra resource usage.
- We present the complete design for deploying RL-MMAC in real applications. It includes a detailed mechanism of data and control message exchange (such as routing metric information or timing information), a timeslot diagram and a time synchronization scheme specifically designed for a schedule-based channel-hopping MAC.
- We provide extensive simulation results on a large-scale network to show the traffic adaptation and the optimality of the RL-based scheduling algorithm. Furthermore, we demonstrate the feasibility of RL-MMAC by experimental tests performed on a lab-scale test-bed of Sentilla Jcreate motes. The deployment also shows the feasibility of tight time synchronization of the proposed schedule-based protocol without producing large communication overhead.

2. Background

The current trend in the proposed standards and recommendations for WSN data communication architectures shows a concern for the Quality of Service (QoS) for IoT applications. Several approaches focus on defining a new physical layer, in which new technology is applied, e.g. ultra-wide band technology to support higher data rates. Several examples are IEEE 802.15.3, the physical and MAC layer standard for low-cost, low-power consumption but high data rate WPAN [8] and Wibree (Bluetooth Smart), a wireless communication technology designed for low power consumption, short-range communication, and low cost devices that can operate till 1 Mbps [9]. Another direction is to propose an amendment to adapt the existing hardware standards to support higher data rates. The IEEE 802.15e Working Group redesigned the MAC layer in the existing IEEE 802.15.4-2006 standard toward a low-power multi-hop MAC, better suited for the emerging needs of embedded industrial applications, called IEEE 802.15.4e [7]. Both directions tend to integrate