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LPDQ: A self-scheduled TDMA MAC protocol for one-hop dynamic low-power wireless networks

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ABSTRACT

Current Medium Access Control (MAC) protocols for data collection scenarios with a large number of nodes that generate bursty traffic are based on Low-Power Listening (LPL) for network synchronization and Frame Slotted ALOHA (FSA) as the channel access mechanism. However, FSA has an efficiency bounded to 36.8% due to contention effects, which reduces packet throughput and increases energy consumption. In this paper, we target such scenarios by presenting Low-Power Distributed Queuing (LPDQ), a highly efficient and low-power MAC protocol. LPDQ is able to self-schedule data transmissions, acting as a FSA MAC under light traffic and seamlessly converging to a Time Division Multiple Access (TDMA) MAC under congestion. The paper presents the design principles and the implementation details of LPDQ using low-power commercial radio transceivers. Experiments demonstrate an efficiency close to 99% that is independent of the number of nodes and is fair in terms of resource allocation.

1. Introduction

The Internet of Things (IoT) [1] is a paradigm in which objects are augmented with sensors and actuators and integrated to the Internet through low-power wireless communications and standardized protocols [2] to enable interaction with humans and other machines in a Machine to Machine (M2M) context. Integrating objects with the Internet may be challenging due to available energy constraints and the need to have long-lasting network deployments [3]. It is widely known that the radio transceiver is the element that dominates energy consumption in wireless communication devices [4]. In particular, it is the Medium Access Control (MAC) layer that controls when the radio transceiver has to be powered on, either to transmit or receive, and thus determines the overall energy consumption. According to [5], the energy waste at the MAC layer comes from four sources: packet collisions, packet overhearing, idle listening, and protocol overhead. For that reason, it is key to design MAC protocols that are efficient in these terms.

Two aspects need to be tackled in the design of an efficient MAC protocol [6]: network synchronization and channel access. Regarding the former, MAC protocols can be classified into synchronous or asynchronous depending on whether nodes

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have a common notion of time that determines the action to take, e.g., receive or transmit. Regarding the latter, MAC protocols can be classified into reservation-based, random access and hybrid according to the availability of a network schedule that determines which node should transmit at each instant. The decision between the different alternatives depends on the application requirements and certain trade-offs exist between network performance and energy consumption. For networks with fixed nodes and periodic traffic it has been shown that a time-synchronized approach combined with schedule-based communications, e.g., IEEE 802.15.4e [7] based on Time Slotted Channel Hopping (TSCH), leads to high network efficiency and low energy consumption [8–10].

However, for networks with a large number of nodes, either fixed or mobile, that are collected on demand and generate bursty traffic patterns, such approach is suboptimal due to the energy required to create, distribute and maintain the network schedule. In these scenarios, which are common in the IoT domain, a better approach is to combine Low-Power Listening (LPL) for network synchronization [11] with a random channel access mechanism to enable data transmission [12]. However, current random channel access mechanisms, e.g., those based on Frame Slotted ALOHA (FSA), are suboptimal in terms of both network performance and energy consumption due to the effects of contention. Several authors have presented mechanisms to minimize collision probability in FSA-based protocols [13], which typically rely on discovering how many nodes are present in the network, either a priori (building a tree previous to data transmission) or a posteriori (inferring the number of collisions in the current frame), and adapting the number of slots per frame based on the feedback. Yet, when nodes generate bursty traffic patterns both approaches are not optimal because the discovery process either reduces network data throughput (due to time required to build the tree) or increases node energy consumption (due to data packet collisions in subsequent frames).

Due to the limitations of existing MAC protocols for such scenarios, in this paper we focus on the design, implementation and evaluation of Low-Power Distributed Queuing (LPDQ). LPDQ is based on LPL for network synchronization and DQ for channel access, and includes Channel Hopping (CH) to add robustness against multi-path propagation and external interference. The paper also presents the implementation of LPDQ using off-the-shelf hardware and a custom software stack, and discusses its main challenges and the solutions that have been adopted. Finally, an experimental evaluation is also presented, demonstrating LPDQ performance and comparing it to FSA in terms of packet throughput. The main benefits of the LPDQ compared to FSA are: (a) No collisions during data packet transmission, (b) Performance is independent on the number of nodes, and (c) Resources are evenly distributed among nodes. To the best of our knowledge, this is the first paper that presents and evaluates the performance of a MAC protocol based on the principles described above for the IoT. Moreover, as far as we know, none of the current research includes experimental evaluation showing the feasibility of the MAC protocol when implemented using low-power commercial radio transceivers.

The remainder of the paper is organized as follows. Section 2 presents the research related to improving the performance of FSA, as well as the research related to DQ. Section 3 presents the design principles and operational details of LPDQ. Section 4 discusses the implementation of LPDQ using off-the-shelf hardware and a custom software stack. Section 5 evaluates the performance of LPDQ and compares it to FSA. Finally, Section 6 concludes the paper.

2. Related work

This section presents the work related to our research and is divided into two subsections. The first subsection presents the research related to improving the performance of FSA, whereas the second subsection introduces DQ and presents the existing research. As introduced earlier, MAC protocols can be classified into reservation based, random access and hybrid. In that sense, FSA can be classified as random access, whereas DQ can be classified as hybrid. Other examples of hybrid channel access protocols are ZMAC and Crankshaft, which are extensively reviewed in Bachir et al. [6] together with other reservation based and random access MAC protocols.

2.1. Frame Slotted ALOHA

FSA is the channel access mechanism used by standards that need to support data collection scenarios where nodes generate bursty traffic, e.g., ISO 18000 [14]. ISO 18000 is a family of standards targeted at Radio-Frequency IDentification (RFID), e.g., item identification and management applications. The ISO 18000-1 standard defines the generic system architecture, whereas the remaining parts of the standard, e.g., ISO 18000-2 to ISO 18000-7, define the physical layer and data-link layer parameters to operate at different frequency bands, e.g., 135 kHz, 13.56 MHz, 2.45 GHz, 868–915 MHz, and 433 MHz. In particular, the data-link layer of ISO 18000-7 [15], which is targeted at active RFID operating in the 433 MHz band, uses LPL to wake-up nodes and FSA to enable data transmission. However, due to the effects of contention, e.g., two nodes transmitting in the same slot, the maximum performance of FSA is 36.8% only when the number of slots per frame is equal to the number of contending nodes [13].

To improve the performance of FSA, several authors have proposed various methods based on two principles. First, using a tree splitting algorithm to detect the number of nodes present in the network a priori, e.g., previous to data transmission. Second, determining the optimal number of slots per frame a posteriori, e.g., based on the information extracted from collisions in the current slot. The different proposals that are available in the literature are summarized next.

Yoon et al. [16] propose two mechanisms to improve the tag anti-collision protocol. The first is based on a dynamic approach to enable the reader select the optimal slot size. The second is based on a broadcast command that enables to