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L-MAC: A wake-up time self-learning MAC protocol for wireless sensor networks

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This paper analyzes the trade-off issue between energy efficiency and packet delivery latency among existing duty-cycling MAC protocols in wireless sensor networks for low data-rate periodic-reporting applications. We then propose a novel and practical wake-up time self-learning MAC (L-MAC) protocol in which the key idea is to reuse beacon messages of receiver-initiated MAC protocols to enable nodes to coordinate their wakeup time with their parent nodes without incurring extra communication overhead. Based on the self-learning mechanism we propose, L-MAC builds an on-demand staggered scheduler to allow any node to forward packets continuously to the sink node. We present an analytical model, and conduct extensive simulations and experiments on Telosb sensors to show that L-MAC achieves significant higher energy efficiency compared to state-of-the-art asynchronous MAC protocols and a similar result of latency compared to synchronous MAC protocols. In particular, under QoS requirements with an upper bound value for one-hop packet delivery latency within 1 s and a lower bound value for packet delivery ratio within 95%, results show that the duty cycle of L-MAC is improved by more than 3.8 times and the end-to-end packet delivery latency of L-MAC is reduced by more than 7 times compared to those of AS-MAC and other state-of-the-art MAC protocols, respectively, in case of the packet generation interval of 1 min. L-MAC hence achieves high performance in both energy efficiency and packet delivery latency.

1. Introduction

To support data transmission in Wireless Sensor Networks (WSNs), a Medium Access Control (MAC) protocol [1] which controls radio communication for each sensor node is carefully designed to achieve high energy efficiency and low packet delivery latency. Over the past few years, duty cycling has been greatly explored in designing energy-efficient MAC protocols. In duty cycling approaches, nodes wake up periodically to sense the communication channel for incoming data. If there are no packets received or to send, a node will go to sleep to save energy. However, despite much work having been done in the literature [1–10], there is still a lack of a practical solution to resolve the trade-off between energy efficiency and packet delivery latency in duty cycling MAC protocols, especially when they are applied to low data rate applications.

Duty cycled MAC protocols for sensor networks can generally be divided into two categories: synchronous [2,3,11,12] and asynchronous [4–8,13–15].

In the synchronous approach, the active periods of nodes are synchronized to overlap with that of their neighbor nodes [2,3] so that a communication link between a sender and its one-hop receiver can be established immediately during their wakeup period. As a result, synchronous protocols normally achieve low packet delivery latency. For example, D-MAC [3] achieves very low packet delivery latency by adopting a staggered wakeup pattern. However, synchronous MAC protocols require nodes to be fully synchronized, which is very expensive and even difficult to achieve in certain circumstances due to its complexity [1]. Efficient synchronization is still a challenging topic in duty-cycled WSNs because duty-cycled WSNs are normally partitioned, limited power, constrained computational capacity, and long delay (i.e., nodes may sleep most of the time). Especially, in low data rate applications, when the number of data packets is relatively small, the synchronization overhead O_{sync} can be dominant compared to that of data communication O_{data}. While a node may send/receive only one data packet to its parent in a cycle, it may need to receive/send multiple

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timing packets from neighbor nodes for synchronization purpose. This results in a high ratio (i.e., $\partial = O_{sync}/O_{data}$), which is obviously not efficient.

Asynchronous protocols [4,16,17] have been proposed to address the above limitation, and they decouple the duty cycle schedules of different nodes and thus eliminate the overhead for synchronization to achieve higher energy efficiency compared to synchronous protocols. However, the major limitation of these protocols is that they typically have high end-to-end delay for packet delivery due to the sleep latency problem [1]. We conducted analysis over existing asynchronous MAC protocols, and discovered that their performance (i.e., delivery latency and energy efficiency) is negatively impacted when the length of wakeup interval is increased. Therefore, a node has to wake up frequently, even in the case of low data rate applications, to achieve a reasonable trade-off between the energy efficiency and the packet delivery latency. For example, in B-MAC [4], the optimal wakeup interval for both applications with a periodic reporting interval of 5 min and applications with a lower reporting interval of 20 min is lower than 500 ms; a larger interval leads to higher energy consumption and higher packet delivery latency. In both of the aforementioned applications, a node has to wake up frequently for listening (i.e., every 500 ms) even when only one packet is generated in either case (i.e., every 5 min or 20 min). It is obvious that most of these wakeups are unnecessary because no data packet is transmitted.

This paper focuses on the trade-off problem between energy efficiency and packet delivery latency of MAC protocols in low data rate and periodic reporting applications which are popular used in industrial automation. To better trade off packet delivery latency and energy efficiency in low data rate WSNs, we propose a novel and practical wakeup time self-learning receiver-initiated MAC protocol (L-MAC). L-MAC is designed for low data rate periodic reporting applications where a data collection tree is normally used to gather data from sensors. A child node in L-MAC learns to adapt its sleep period based on the relative wakeup time with its parent in a way so that it can maintain its wakeup time to be closely earlier than that of its parent. Importantly, the node measures the relative wakeup time by itself through reusing beacon messages which are typically used for probing purposes in the receiver-initiated MAC approach. L-MAC does not require synchronization or schedule information exchanging, and incurs no extra transmission overhead compared to other receiver-initiated MAC protocols. As a result of the wakeup time self-learning, not only the idle listening of the sender but also that of the receiver (i.e., parent node) are reduced significantly as their wakeup time are designed to be close to each other. Whenever a child node wakes up and has packets to send, it can send the packets quickly, thus improving the energy efficiency and one-hop packet delivery latency.

We also design L-MAC's staggered wakeup scheduler based on the above self-learning mechanism, allowing a node to forward packets continuously to the sink without strictly depending on length of the wakeup interval, thus further shortening end-to-end delivery latency and transmission overhead. Moreover, built on the staggered scheduler, L-MAC seeks to expand wakeup interval in proportion to data rate. The purpose is to allow nodes in low data rate applications sleep longer compared to those in higher data rate applications, without a significant negative effect on network performance such as latency and delivery ratio. With the same amount of active time in a wakeup interval, the larger the interval length is, the lower the duty cycle of a node achieves, hence further improving energy efficiency. As a result, L-MAC is able to achieve both low latency and high energy efficiency at the same time. Through our comprehensive analysis, extensive simulations and experiments on Telosb sensors using TinyOS, we show that L-MAC outperforms state-of-the-art protocols. In particular, under a context of setting an upper bound value for one-hop packet delivery latency within 1 s and a lower bound value for packet delivery ratio within 95%, results show that the duty cycle of L-MAC is improved by more than 3.8 times and the end-to-end packet delivery latency of L-MAC is reduced by more than 7 times compared to those of AS-MAC and other MAC protocols, respectively, in case of the packet generation interval of 1 minute. L-MAC hence achieves high performance in both energy efficiency and packet delivery latency.

In summary, this paper makes the following contributions.

- We analyze the trade-off issue between energy efficiency and latency in existing MAC protocols, and discover their limitations when applied to low data rate applications.
- We propose a novel self-learning mechanism which enables a node to coordinate its wakeup with its parent without requiring synchronization or exchanging schedule information. We also design a staggered wakeup scheduler to allow a node to forward packets continuously to the sink. The design of L-MAC is very simple and easy to implement in real scenarios.
- We provide a detailed theoretical framework to quickly analyze and evaluate performance of current MAC protocols. Through our comprehensive analysis, we show that L-MAC achieves significantly higher energy efficiency compared to other asynchronous MAC protocols and a similar result of latency compared to synchronous MAC protocols. We conduct extensive simulations and experiments with Telosb motes, and show that L-MAC allows nodes in low data rate applications to sleep longer compared to those in higher data rate applications by setting a larger wakeup interval, without a significant negative effect on latency. As a result, L-MAC achieves high performance in both energy efficiency and packet delivery latency.

The rest of this paper is organized as follows. Section 2 discusses related works. Section 3 gives the overview and the detailed design of L-MAC. The analytical model and analysis of the trade-off problem in existing MAC protocol as well as L-MAC are presented in Section 4. Section 5 describes our validation and evaluation. Finally, Section 6 concludes the paper.

2. Related works

In this section, we discuss the state-of-the-art in the literature, focusing on energy efficiency and packet delivery latency. Energy efficiency is a critical issue in both traditional WSNs [1,16] and energy harvesting WSNs [18–21], as well as in general machine-to-machine communication [22]. Therefore, duty cycling [16] has been greatly explored in designing energy-efficient MAC protocols.

Duty cycled MAC protocols for sensor networks can generally be categorized into synchronous and asynchronous schemes. In synchronous approach, MAC protocols are designed under an assumption of time synchronization among neighbor nodes. Sensor nodes are required to synchronize their active time together, as a natural solution to establish communication between two nodes. In this way, synchronous MAC protocols are normally designed to achieve a low packet delivery delay. D-MAC [3] is a notable synchronous protocol which achieves low packet delivery delay. Some MAC protocols use global synchronization [23,24], others exploit local synchronization [3,11,12,25,26]. In both approaches, a node is required to exchange timing information packets periodically with multiple neighbor nodes for synchronization purpose. Efficient and precise synchronization is a challenging topic in duty-cycled WSNs. The reason is that such a network is normally partitioned, long delay, limited power, and limited computational capacity, and nodes may sleep most of the time. Beside the cost of time synchronization, synchronous MAC protocols also require nodes exchanging their