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MCAS-MAC: A multichannel asynchronous scheduled MAC protocol for wireless sensor networks

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ABSTRACT

Due to their energy efficiency, many duty cycling-based MAC protocols have been proposed in WSNs. Although these protocols considerably reduce energy consumption by minimizing idle listening and overhearing, the energy efficiency comes at the cost of decreased packet delivery ratio and increased delay. In this paper, we present a multichannel asynchronous scheduled MAC protocol, called MCAS-MAC, which inherits the basic asynchronous scheduling operation from AS-MAC and adds back-to-back packet transmissions and multichannel support for high traffic dense WSN. Using RaPTEX, we evaluate the performance of MCAS-MAC by comparing it with existing duty cycling MAC protocols including BMAC, SMAC and AS-MAC.

1. Introduction

Energy efficiency has been considered one of the most important requirements in designing a WSN, because the sensor nodes are often battery-powered and deployed in harsh environments, where the nodes have to operate for long periods of time unattended. Due to their energy efficiency, duty-cycling mechanisms are widely used in MAC protocols to reduce energy consumption in WSNs. With duty cycling, nodes periodically turn radio on for short periods of time and then put the radio in a sleep state to reduce idle listening and overhearing, which are recognized as the largest source of energy waste [30,36,37].

Many duty cycling-based MAC protocols [8,17,30,10,36,37] have been proposed, and are classified into two groups: synchronous and asynchronous. In synchronous MAC protocols [10,36,37], all nodes in a neighborhood share the same sleep and wakeup schedule and exchange packets only in common active periods. In asynchronous MAC protocols [8,30], a receiver periodically wakes up and performs low power listening (LPL) to detect the presence of any incoming packet and a sender transmits a long preamble prior to the data transmission to allow the receiver to detect the transmission. We previously proposed an asynchronous scheduled MAC protocol, called AS-MAC [17], in which neighboring nodes are asynchronously scheduled (neighboring nodes are scheduled to wake up at different times), learn and predict neighbor's future wakeup schedules based on periodic Hello messages, and turn radio on and transmit a packet in the intended receiver's next wakeup time. All these protocols significantly increase the energy efficiency and all of them have advantages and disadvantages in different scenarios.

However, all these protocols are optimized to reduce energy consumption at the cost of latency and packet delivery ratio in sporadic and infrequent traffic because most prior WSN effort focused on applications that require low-power, low-bandwidth, and low traffic with soft delay constraints. Advances in microprocessors and radio technology, however, have enabled a wide range of data-intensive application such as structural health monitoring, image and video processing, and emergency response [26]. These applications require high load and bursty traffic. As performance requirements and traffic patterns vary depending on applications, an ideal sensor MAC protocol should operate well under a wide range of traffic loads in terms of delay and packet delivery ratio without compromising energy efficiency.

In this paper, we propose a new duty cycling MAC protocol, called MCAS-MAC (multichannel asynchronous scheduled MAC), which is designed and implemented based on AS-MAC [17], yet exploits the multiple orthogonal channels available in many sensor

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nodes[1]. Like AS-MAC, MCAS-MAC asynchronously schedules the wakeup time of neighboring nodes, but each node wakes up on its own home channel, which is decided during the initialization phase. Using Hello packets, each node learns neighbors' schedules and home channels. For data packet transmissions, a sender predicts when and on what channel the intended receiver wakes up. After switching to the intended receiver's home channel immediately before the receiver's wakeup time, the sender performs a backoff and attempts to transmit data packets in the queue. In addition to extending the operation of AS-MAC to multiple channels, we further allow a node to send multiple queued packets at a wakeup time in case of high traffic load by introducing an additional dwell time after each data packet reception. With the use of multiple orthogonal channels and additional dwell time, MCAS-MAC allows for nearly collision free back to back packet transmission, resulting in improved packet delivery ratio and delivery latency without an increase in energy consumption.

We implement MCAS-MAC in TinyOS on the Mica2 platform and evaluate its performance in terms of energy consumption, delay, and packet delivery ratio by comparing it with SMAC, BMAC, and AS-MAC, which are representative protocols categorized as synchronous, asynchronous, and asynchronous scheduled sensor MAC protocols, respectively. We use RaPTEX as a performance evaluation environment, and our evaluation covers two single-hop scenarios and small (10 nodes) and large (100 nodes) scale multihop networks. In comparison with AS-MAC, MCAS-MAC significantly improves packet delivery ratio without performance degradation in delay and energy consumption, especially at high traffic loads. We show that MCAS-MAC obtains 400% better packet delivery ratio than AS-MAC in the dense single hop scenario and 200% more capacity in the 10 hop chain network.

The remainder of this paper is organized as follows. We provide a summary of the related work and their limitations in Section 2. In Section 3, the design and implementation of MCAS-MAC are described in detail. In Section 4, we evaluate the performance of MCAS-MAC via emulation, and we compare it with other energy efficient WSN MAC protocols. Section 5 concludes this paper.

2. Related work

In WSNs, many energy efficient MAC protocols have been proposed; they are usually classified into synchronous, asynchronous, and hybrid approaches.

In synchronous MAC protocols [10,36,37], nodes exchange their active or sleeping schedule with neighboring nodes and wake up and go to sleep at the same time. Nodes send and receive data and control packets only during the common active periods. Since all neighboring nodes are fully operational during the common active period, these protocols are well suited for broadcast-based communication. However, synchronous MAC protocols require synchronization, which adds energy cost and complexity. At low traffic with a small duty cycle, these protocols unnecessarily consume energy in idle listening during the common active period, resulting in poor energy efficiency. By performing LPL at every scheduled wakeup time, SCP-MAC [37] minimizes not only the length of a preamble but also idle listening. However, since every sender has to contend to acquire the channel at each common wakeup time, SCP-MAC results in increased contention and packet overhearing.

In asynchronous MAC protocols [8,30], a receiver periodically wakes up and performs LPL to check if there is an incoming packet. If the receiver does not detect any incoming packet, it goes back to sleep immediately. If it detects a packet, the node stays awake to complete the packet reception and goes back to sleep. In order to make sure that the receiver detects the existence of an incoming packet, the sender uses a long preamble corresponding to the sleep interval of the receiver. Generally, these protocols do not require nodes to synchronize their wakeup schedules, therefore the implementation is simple and provides high energy efficiency. However, in our previous study [25], we show that transmitting long preambles is not suitable in high traffic situations in terms of energy efficiency, delay, and packet delivery ratio because the long preamble causes high contentions and slow reactions to the packet collisions. Although X-MAC [8] significantly reduces the preamble size by using a strobed preamble, transmitting a preamble prior to data transmission unnecessarily occupies the wireless medium, which prevents neighbor nodes with pending packets from transmitting them, resulting in performance degradation, especially when there is high traffic demand in dense networks. By using receiver-initiated transmissions, RI-MAC [31] removes the need of transmitting a long preamble in asynchronous MAC protocols. However, RI-MAC require a sender to stay awake whenever it has a data packet, and it can switch back to sleep only after the data packet is transmitted, which causes large energy consumption at the sender side in case of high traffic load. PW-MAC [24] uses a receiver-initiated transmission like in RI-MAC; however it introduces use of the pseudo-random wakeup interval, which allows senders to predict the time when a receiver will wake up. Thus, it remove the long idle listening time of senders, unavoidable in RI-MAC. That is, RI-MAC reduces the duty cycle only for receivers, but PW-MAC reduces it both for receivers and for senders. However, each node has to transmit a beacon message whenever it wakes up and the sender receives the beacon whenever it transmits a data packet, which incurs large overheads.

By asynchronously coordinating wakeup schedules of neighboring nodes, AS-MAC [17,18] reduces overhearing, contention, and delay unavoidable in synchronous scheduled MAC protocols. By knowing the neighbor's wakeup time and turning the radio on only immediately before the wakeup time of the intended receiver, AS-MAC removes the need for a long preamble, as well as the extra sender side active period in RI-MAC. AS-MAC also separates the Hello interval from the wakeup interval; therefore each node sends the Hello packet at a larger periodic wakeup time based on its Hello interval, while each node sends a beacon packet at every wakeup time in receiver-initiated MAC protocols (e.g. [31,24]). Although AS-MAC requires the extra complexity and memory space for the schedule sharing and management, it considerably decreases energy consumption, delay, and packet loss in unicast scenarios. Although all these aforementioned protocols significantly increase energy efficiency while providing good delay and packet delivery ratio, the performances of the network is limited to the capacity of a single channel and performance may be radically reduced at high traffic loads, especially when the network operates at a low duty cycle. In order to overcome the limitations of single-channel-based protocols, many multichannel MAC protocols have recently been proposed in WSNs.

WiseMAC [32,4,12,29] presents asynchronously scheduled MAC protocols similar to AS-MAC. Ref. [4] provides MAC protocol for single hop networks relying on an access point. Ref. [12] presents MAC protocol for multi-hop WSNs. Ref. [29] argues that WiseMAC is energy efficient but presents a very limited maximum throughput. It also proposes an extension of WiseMAC improving the traffic adaptivity of WiseMAC. TrawMAC [34] presents asynchronously scheduled MAC protocol similar to AS-MAC and Wise-MAC, but it uses the consequent small preamble scheme and the preamble

[1] Although the specifications of CC1000 state a channel separation of 150 kHz is sufficient to prevent cross-channel interference, 800 kHz is recommended as a safer value to achieve effective orthogonality, resulting in 32 orthogonal channels on Mica2 [35].