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DS-MAC: An energy efficient demand sleep MAC protocol with low latency for wireless sensor networks

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ABSTRACT

Duty cycling mechanism has been widely used to conserve energy that consumed by idle listening in wireless sensor networks, while fixed duty cycling introduces transmission latency in packet delivery. End to end latency is one of the most significant factors of packets loss in wireless sensor nodes, and many techniques have been proposed based on listening adaptively to reduce delay, which are mainly designed for light traffic loads. In this paper, we propose a novel asynchronous duty cycling MAC protocol, called demand sleep MAC (DS-MAC) that allows nodes to adjust their sleep time adaptively according to the amount of the received data packets in order to efficient and effective communication in the dynamic traffic load. DS-MAC protocol attempts to transmit a series of short token packets to wake up the receiver, which avoids the overhearing problem. Nodes in DS-MAC put the prediction field into ACK packets, which decreases the waiting delay of source node. Comprehensive simulation shows that when there are variable flows, such as broadcast traffic or transmissions from hidden nodes, DS-MAC significantly decreases waiting delay and energy consumption.

1. Introduction

Wireless sensor networks (WSNs) can be used to monitor the occurrence of many rare events, such as melting glacier, forest fire, and others. Wireless sensor nodes in environmental monitoring applications are often placed in hard-to-reach places of the valley and so on. Once the energy of a node exhausted, it is difficult to replace the battery, and the battery constrained energy limits the lifetime of the network. Idle listening is one of the most significant factors of energy consumption in wireless sensor nodes. Hence, many solutions for saving energy have been proposed utilizing the technique of duty cycling, just like B-MAC (Polastre et al., 2004) and S-MAC (Ye et al., 2002), when nodes have no data to transmit, it will turn their radio off to sleep for saving energy. Using duty cycling mechanism, each sensor node periodically switches between active state and sleep state. In the active state, a node is able to monitor the channel and transmits or receives data. In the sleep state, node turns off its radio to switch to a low power consumption mode. However, the wakeup–sleep mechanism brings about end-to-end transmission delay, especially when the traffic load is heavy. While the fixed duty cycling brings the end-to-end transmission latency, it also leads to the low bandwidth utilization ratio. As a part of the data link layer, the medium access control (MAC) layer controls the way that how the wireless sensor node to send or receive information, and the way to access the shared wireless medium. An efficient MAC protocol can reduce collisions, decrease end-to-end delay, increase network throughput and the lifetime of network. In order to reduce delay, save energy and improve the throughput, a variety of MAC protocols have been proposed.

Roughly speaking, MAC protocols with duty cycling technique for WSNs can be categorized into synchronized and asynchronous mechanisms, along with some other hybrid combinations. The purpose of these protocols is to reduce the idle listening and save energy. For rare event monitoring, idle listening is the main energy consumption state. Many synchronized protocols, such as S-MAC (Ye et al., 2002), T-MAC (Van Dam and Langendoen, 2003), R-MAC (Du et al., 2007), DW-MAC (Sun et al., 2008a), wake up nodes at the same time to communicate by synchronizing each sensor node. However, synchronous duty cycling MAC protocols require multi-hops time synchronization, which causes large network control overheads and poor network scalability. Especially when the change probability of traffic loads is high, the fixed duty

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cycling approach is inefficient in the performance of latency and bandwidth utilization.

While, nodes in the asynchronous approaches such as B-MAC (Polastre et al., 2004), WiseMAC (Amre and Jean-Dominique, 2004; Dutta et al., 2010; Niu et al., 2013; Tang et al., 2013) can sleep or wake up on its own duty cycle schedule without the constraint of synchronization mechanism. Nodes in Polastre et al. (2004), prior to data transmission, transmit a preamble which length is at least as long as the length of the receiver's sleep period. If a node finds that the packet is not expected for itself, it will go back to sleep state to save energy. When a sender has data to transmit, the sender utilizes low power listening (LPL) to connect the receiver. It is not necessary for explicit synchronizing between a sender and a receiver, the receiver just needs to wake up for a short time to sample the channel, which decreases the idle listening time and saves energy.

However, asynchronous MAC protocols also produce many questions. Firstly, too long preamble causes the overhearing problem of the non-target node. Secondly, asynchronous mechanism brings end-to-end waiting delay, since the communication nodes must be awake. Huang et al. (2013) reviewed the improvement and development, in the terms of preamble and delay, of asynchronous MAC protocols. Thirdly, a fixed duty cycling mechanism is not suitable for the changeable traffic load. Since too long sleep time will bring the packet queuing delay and too short sleep time will increase the idle listening time, which resulting in a waste of energy. Fourthly, when queuing packets are too many, it will cause packets' overflow.

In this paper, we propose a novel asynchronous duty cycle MAC protocol, called demand sleep MAC protocol (DS-MAC). DS-MAC introduces a novel mechanism, namely, demand sleep method, which adjusts the node's sleep time adaptively according to the amount of received data packets. When the amount exceeding a threshold, DS-MAC will shorten node's sleep time, since frequently switching between sleep state and active state will waste much energy. When the energy that a node saved in the sleep state is less than a node consumed when changing between sleep state and active state, for saving energy, the node will not turn into sleep state any more in the duty. When the amount of data packets node received is less than the threshold, nodes will increase its sleep time to save energy that wasted by idle listening. Similar to CMAC (Liu et al., 2009), DS-MAC is an asynchronous MAC protocol, which uses a sequence of token packets as preamble to wake up the destination node and also uses token packet as ACK packet. Different from CMAC, DS-MAC devises a prediction mechanism to estimate a node's wake-up time by putting the node's sleeping time of this duty into ACK and sending to its neighbors, therefore neighbors can know the node's wake-up time in next duty. To a certain extent, DS-MAC has the same effect with synchronous MAC protocol. Knowing the receiver's wake up time, the sender can decrease sending time of preamble, which shortens waiting latency. Concretely, the contributions of the paper are as follows.

1. We propose a novel asynchronous duty cycling MAC protocol, called DS-MAC, which adjusts node's sleep time adaptively according to the amount of received data packets. Whether in high or light traffic loads, nodes can receive or can send data timely, which reduces the waiting delay.

2. The overflow probability of queuing packages is decreased, since the waiting latency reduced, ultimately cutting down the loss of data packages.

3. DS-MAC adds the predicted sleep time into ACK package, which has the same effect with synchronous MAC protocol. With the prediction mechanism, a node only needs to wake up slightly before the receiver when it has data to transmit. Therefore, DS-MAC improves the energy efficiency and increases the lifetime of the network greatly.

4. Most of MAC protocols use such wireless sensor network model, which assuming that there is only single source sending data packets to sink node when an event happens. While DS-MAC does not restrict the number of source nodes that sending data packets, which enlarges the scope of application of DS-MAC.

The rest of this paper is organized as follows. In Section 2, we discuss related works in duty cycling MAC protocols for sensor networks about shortening transmission latency and decreasing overhearing problem, even about how to maintain the power efficiency. In Section 3, we present the system model of the protocol. In Section 4, we give a detailed design and analysis of DS-MAC protocol. Section 5 describes the impact of loss packet on the performance of DS-MAC. Section 6 compares DS-MAC with S-MAC and SW-MAC by simulation. The simulating scenarios include both constant bit rate (CBR) and variable bit rate (VBR) traffic patterns. We provide conclusions and discuss potential research work in Section 7.

2. Related works

The quality of MAC protocol is directly related to the performance of wireless sensor networks, since a MAC protocol can control the way that wireless sensor nodes accessing to the medium. A number of previous approaches have been proposed to adjust the duty cycling for saving energy or shortening the end-to-end latency in duty cycle MAC protocols. However, none of them like DS-MAC protocol can adjust the node's duty cycling adaptively according to the received data packets in changeable traffic loads, which significantly improves the network performance. In this section, we review the synchronous MAC protocols, and then the asynchronous MAC protocols.

2.1. Synchronous MAC protocols

Firstly, we describe the mechanism of synchronous protocols (Huang et al., 2013). Nodes in synchronous MAC protocol listen to the channel for a certain time. If a node does not hear any schedule from neighbor nodes, it decides its next wake up time and broadcasts its schedule to others, which makes the node become a synchronizer. If a node receives a schedule table from a neighbor before choosing its own schedule, it will follow the received schedule, which makes it a follower. Usually, these nodes are away from the cluster head node few hops. Nodes that all in one cluster are synchronized by a synchronizer that one hop or few hops away from them. If a node receives a different schedule table from neighbors after creating its own schedule, it will adopt two schedules, which allows it to become a bridge node between two clusters. Therefore, the node will wake up at the time of its own cluster header wakes up and adjacent cluster header wakes up.

S-MAC (Ye et al., 2002) is one of the most classical periodic synchronous MAC protocols. In S-MAC, the time of node is divided into some frames and then each is further divided into three periods, namely, SYNC, DATA and SLEEP. The wake up time and the sleep time of nodes in S-MAC are both fixied, not random. At the beginning of SYNC period nodes wake up to synchronize clocks with neighbors to ensure that the node and its neighbors wake up concurrently. Then, in the DATA period all nodes remain active. If a node has data packets to send, it exchanges Request-to-Send (RTS) and Clear-to-Send (CTS) frame with its destination node to contend for the channel. When source nodes receive the acknowledgement frame, they transmit packets to the destination node. For saving energy, if a node is not included in the communication or has no data to send, it will turn off its radio to sleep. It is evident that in every cycle, one packet can only be transmitted through one hop. Although later adaptive listening (Ye et al., 2004) was introduced to the S-MAC protocol to overcome these