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An energy-efficient, transport-controlled MAC protocol for wireless sensor networks

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ABSTRACT

In wireless sensor networks (WSNs), one major cause of wasted energy is that the wireless network interface is always on to accept possible traffic. Many medium access control (MAC) protocols therefore adopted a periodic listen-and-sleep scheme to save energy, at sacrifice of end-to-end latency and throughput. Another cause is packet dropping due to network congestion, necessitating a lightweight transport protocol for WSNs. In this paper, we suggest a transport-controlled MAC protocol (TC-MAC) that combines the transport protocol into the MAC protocol with the aims of achieving high performance as well as energy efficiency in multi-hop forwarding. Although TC-MAC also works through a periodic listen-and-sleep scheme, it lowers end-to-end latency by reserving data forwarding schedules across multi-hop nodes during the listen period and by forwarding data during the sleep period, all while increasing throughput by piggybacking the subsequent data forwarding schedule on current data transmissions and forwarding data consecutively. In addition, TC-MAC gives a fairness-aware lightweight transport control mechanism based on benefits of using the MAC-layer information. The results show that TC-MAC performs as well as an 802.11-like MAC in end-to-end latency and throughput, and is more efficient than S-MAC in energy consumption, with the additional advantage of supporting fairness-aware congestion control.

1. Introduction

Advances in the hardware technologies of microprocessors, memory, and wireless communication have made the wireless sensor network (WSN) [1] more popular. The WSN enables a wide range of emerging applications such as environmental monitoring, mobile target tracking, smart space, and ubiquitous computing. However, the most noteworthy limitation of the WSN is that every sensor node is operated by a built-in battery, which is hard to recharge or replace. Reducing unnecessary energy consumption is therefore a very important challenge that has been addressed at each layer of the protocol stack. Our specific focus is the medium access control (MAC) because MAC can control the on and off states of the wireless interface to enhance energy efficiency.

In typical WSN applications, the detection of events occurs sporadically. Hence, each sensor node spends most of its time in an idle listening state to receive possible event packets that are not actually sent. Since this idle listening state consumes as much energy as the receiving state [2,20], the idle listening accounts for most of the wasted energy in a wireless interface. Traditional MACs such as sensor-MAC (S-MAC) [3,8] and Timeout-MAC (T-MAC) [4] reduce idle listening considerably by adopting a periodic listen-and-sleep scheme. However, the periodic listen-and-sleep scheme causes a long latency problem when coupled with multi-hop forwarding, as shown in Fig. 1. Node A forwards data to node B during the first listen period but node B cannot forward data to node C because the listen

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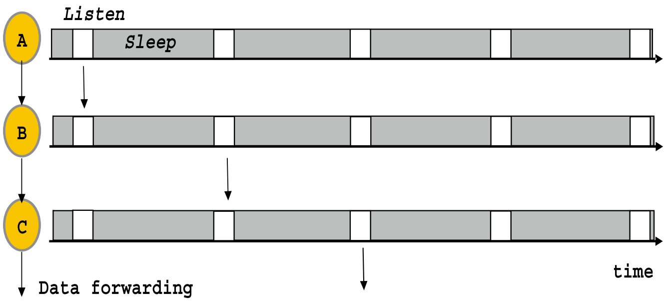

Fig. 1. A long latency problem with a periodic listen-and-sleep scheme.

period is over; hence, node B must wait for the next listen period. This type of delay accumulates at each hop in the forwarding path and causes a very long latency as the forwarding hop count increases. The listen period could be extended as a naive approach to relieve this problem, but that would increase energy consumption of every node. Hence, there is a trade-off between latency and energy savings, and traditional MACs for WSNs have concentrated more on energy savings. The increased latency resulting from this trade-off has the potential to produce a major problem in some applications if an important event fails to arrive at a sink or a base station in time. There are many emerging WSN applications requiring fast response, such as smart hospitals, military surveillance, intrusion detection, disaster monitoring, and real-time control.

To solve the long latency problem without sacrificing energy efficiency, we have suggested a Look-Ahead Scheduling MAC (LAS-MAC) [5]. LAS-MAC separates the channel reservation process and data transmission process of the Carrier Sense Multiple Access (CSMA) protocol, then it makes data transmission schedules across the multi-hop nodes during the listen period and transmits data by following the schedules during the sleep period; the nodes with no schedule go to sleep. LAS-MAC can thus forward data much faster.

Another problem caused by the periodic listen-and-sleep scheme is a decrease in throughput. Although WSNs generally assume very light traffic, the amount of traffic increases when events in densely deployed nodes are generated, when the number of event sources increase their reporting rate, and when events are gathered near the base station. However, a reduced listen period limits the time for data transmission, causing network congestion with queue overflows. Network congestion leads to the waste of communication resources and energy, affecting event detection reliability at the sink. Therefore, the throughput of MAC protocols must also be enhanced without sacrificing energy efficiency.

To mitigate network congestion, in addition, the sources of traffic must help by reducing their data transmission rates, so transport protocols are used. However, the traditional transport protocols used in general computer networks, such as the Transmission Control Protocol (TCP), are inadequate for WSNs. TCP is too heavy for WSNs because it provides the mechanisms such as connection establishment, end-to-end congestion control, and end-to-end error recovery. In general WSNs, a connection establishment mechanism is unnecessary for most event-driven data collection, and the end-to-end congestion control takes such a long time that it leads to high packet dropping in a small-sized buffer. Further, many WSN applications such as environment, habitat, and disaster monitoring do not require strict reliability in each data packet transmission due to data redundancy within a region, but rather require fairness among flows for reliable event detection, so an end-to-end packet error recovery mechanism is also unnecessary. The need for lightweight transport control mechanisms for WSNs therefore seems clear.

In this paper, we present a design for a transport-controlled MAC (TC-MAC) protocol targeted to provide a low end-to-end latency, high throughput, and light-weight congestion control, without sacrificing the energy efficiency earned from the periodic listen-and-sleep scheme. The periodic listen-and-sleep scheme remains one of the best ways to eliminate idle listening, and TC-MAC is also based on it. However, TC-MAC uses the listen period more efficiently by supporting multi-hop channel reservations; it then uses the sleep period for data transmission according to the prior reservations. To utilize the sleep period more efficiently, TC-MAC allows data packets to contain schedule information for subsequent data so that further data can be transmitted. TC-MAC can therefore forward a greater amount of data through more hops as compared to previous MACs using the periodic listen and sleep scheme. In addition, TC-MAC supports the congestion control mechanism in a MAC-layer with a light overhead. The MAC-layer can trace how a shared channel is used by each flow, so TC-MAC traces the channel usage information through a traffic monitor, and then regulates the transmission rate of traffic flow sources in a way that achieves fairness among traffic flows. To mitigate network congestion, TC-MAC uses backpressure for neighbor regulation and an explicit congestion notification for traffic flow source regulation as the COngestion Detection and Avoidance (CODA) [6] protocol does.

The rest of this paper is structured as follows. In Section 2, we survey several related works. In Section 3, we describe our basic design and the operations of TC-MAC. In Section 4, we show a simple queuing analysis of TC-MAC in a multi-hop chain topology. In Section 5, we discuss the scalability of TC-MAC. In Section 6 we present the performance results of TC-MAC and compare them with those of other MAC protocols. Finally, in Section 7 we present our conclusions.