SCP-MAC: Reaching Ultra-Low Duty Cycles

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Energy consumption is a critical factor in sensor networks. Since radio costs remain a large part of the energy costs in sensor network hardware, there has been much focus on minimizing energy consumption in radio medium access control (MAC) protocols. Scheduled protocols such as S-MAC [6], T-MAC [4], and TRAMA reduce energy consumption by coordinating nodes into periodic sleep/wakeup schedules. Their premise is that the cost of coordination is minimal compared to the savings in coordinated access. Recently a class of low-power listening (LPL) protocols, such as WiseMAC [1] and B-MAC [3], reduce listen overhead by replacing polling in contention periods with very low power "channel active" probes, replacing explicit coordination with per-message coordination via long pre-message preambles. However, both of scheduled and LPL-based MAC protocols are limited to duty cycles of 1–2%: scheduled protocols are limited by the delay one can tolerate between schedules, and LPL-based protocols are limited by the increasing transmit costs due to longer preambles.

We explore a new approach that can achieve *ultra-low* duty cycles of 0.01–0.1%, potentially reducing energy consumption by a factor of 10–100. This poster describes two novel results. First, we examine the the fundamental question of the relative benefits of coordinated network access compared to unsynchronized polling. We argue that the use of LPL-like channel probing is necessary, but it must be combined with scheduled access in order to operate in ultra-low duty cycles. Second, we propose a new MAC protocol based on scheduled channel polling (SCP-MAC). The novelty of SCP-MAC is the combination of scheduling and polling; we also describe novel additions including split contention windows and piggybacked synchronization with zero overhead.

We use theoretical analysis to find the best possible operating points for LPL and SCP. We demonstrate that SCP-MAC can operate for 2–3 times longer than to LPL-based MACs for the same energy budget when each is tuned for a completely periodic workload. Scheduled polling as a better match for *unpredictable* traffic when tuned for low-duty cycle operation. LPL suffers when mismatched to changing traffic loads because of preamble length. By contrast, SCP only pays penalty in latency, not in energy, and even the latency penalty can be eliminated with algorithms such as adaptive listen. We show in testbed experiments that LPL consumes 8 times more energy than SCP when presented with short-term bursty traffic.

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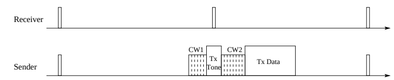

Fig. 1. Data transmission with synchronized channel polling.

I. Design of Scheduled Channel Polling

The basic scheme of SCP-MAC combines the strengths of channel polling and scheduling. Similar to low power listening (LPL), SCP puts nodes into periodic sleep state when there is no traffic, and they perform channel polling periodically. Unlike LPL, we synchronize the polling time of all neighboring nodes. The major advantage of synchronized polling is that a very short wake-up tone can be sent to wake up a node. The short wakeup tone largely reduces the overhead of transmitting long preambles in LPL.

Using short wakeup tone also makes SCP-MAC more robust to varying traffic load. The performance of LPL is sensitive to the channel polling period. Its optimal value requires knowledge of network size and completely periodic traffic. However, a large set of applications mix periodic and bursty traffic or consist of unpredictable traffic mixes. A worst case is a monitoring application where there is no traffic to send most of the time, but bursts of activity when a target is detected. Such a network does not have a single good operating point, since it employs a low duty cycle to match long idle periods, but then is penalized with long preambles during busy cycles.

Figure 1 illustrates the wakeup and data transmission scheme we propose for SCP-MAC. When a node has a packet to send, it waits in sleep state until the receiver's time to poll the channel. It will send a short *wake-up tone* to activate the receiver. Before sending the tone, it performs carrier sense within the first contention window (denoted as CW1 in the figure). As with typical CSMA protocols, nodes randomly select a slot in a fixed-length contention window to reduce chances of collision. If the node detects idle channel it will send the wakeup tone. Otherwise, it goes back to sleep and will perform regular channel polling. After a sender wakes up a receiver, it enters the second contention window (CW2 in Figure 1). If the node still detects channel idle in the second contention phase, it starts sending data.

Splitting contention phases achieves lower collision probability with shorter overall contention time. The collision probability is about inversely proportional to the contention window size. Since the two phases are independent, they have better performance than the single-phased one with the same overall slots. Alternatively, we can use fewer contention slots (to save energy) to achieve the same collision performance. The reason that we can split the contention with fewer overall slots is that SCP tolerates the collisions on tone transmissions Thus, we can use a small contention window for phase one. Then only surviving nodes enter the second phase, further reducing the collision probability.

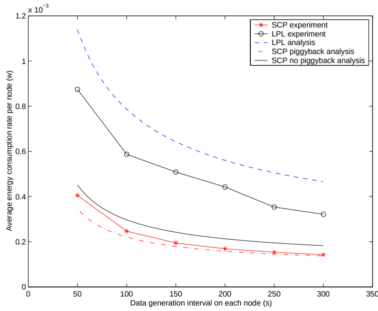

Fig. 2. Mean rate of energy consumption rate (W, or J/s) for each node as traffic send rate varies. (Assumes optimal LPL and SCP configurations, completely periodic traffic, and a 10-node network.)

On top of this basic wakeup and contention mechanism, SCP-MAC includes several optimization algorithms, including optional RTS-CTS, overhearing avoidance that works both with and without RTS messages, adaptive listen [6], an potentially fast-path schedule allocation [2].

II. Experimental Evaluation

We have implemented SCP-MAC in TinyOS on Mica2 motes. In this section we focus explicitly on evaluating relative benefits of scheduled and asynchronous channel polling. To focus on this core question we have disabled advanced SCP-MAC features, including overhearing avoidance and adaptive listen.

A. Optimal Setup with Periodic Traffic

We first compare the energy performance of SCP and LPL under optimal configuration with completely periodic, known traffic. While such traffic is somewhat artificial, it models environmental monitoring applications where sensors are periodically sampled. With static traffic loads we can optimize each for maximum energy conservation. While known, periodic traffic is somewhat artificial, this configuration models a environmental monitoring applications where sensors are periodically sampled.

In this test we place 10 nodes in a a single hop network. Each node periodically generates a 40B data message and broadcasts it to the network We vary the data rate to study how MAC performance varies. For this test we consider light traffic loads from long-lived monitoring applications, varying each node's time between messages from 50–300s.

For each static traffic load, we find out the optimal polling period of LPL and SCP through analysis [5]. Each experiment considers 5 message periods, so 50 total messages over each experiment.

Figure 2 shows the mean energy consumption *rate* (Joules per second or Watts) on each node. We expect slower traffic rates correspond to lower rates of energy consumption. For LPL, the optimal polling interval is longer for slower traffic rates, therefore the optimal preamble length is longer and so the cost of each message is longer. For SCP, the optimal sync period grows, and the optimal wake-up tone length grows slightly, but the rate of growth is lower than for LPL. In addition, the cost of SCP is much lower than LPL: we can see that LPL requires 2–2.5 times more energy than SCP to send the same amount of data. This savings is because scheduling allows much shorter wakeup tone on each data message.

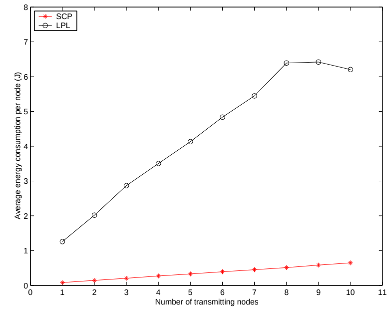

Fig. 3. Energy consumptions on heavy traffic load with very low duty cycle configurations.

To compare experiments with our analytical results, we also put the calculated energy consumption rate obtained from our analysis. We can see that both SCP and LPL experimental results closely match the trends of their analytical results with some fixed differences. The results validate the correctness of our analysis.

B. Energy Use Under Unanticipated Traffic Loads

In the prior section we consider optimal conditions for LPL and SCP with a completely known, periodic load. In many applications the traffic load is less predictable, and it is difficult to find a single best operating point of the MAC. To evaluate these scenarios we next consider MAC performance when operating outside its optimal regime. We tune LPL and SCP for a 0.4% duty cycle, polling every second. Since the polling interval is the same for both MACs, energy draw without traffic is almost identical. (SCP-MAC requires slightly more for schedules synchronization.)

To simulate a sensor detection, we trigger all nodes to enter "busy" mode at the same time. When busy, each node generates 20 100B-long messages as rapidly as possible. This burst of traffic forces the network into a suboptimal operating point.

To vary the degree of offered load, we vary the number of nodes in the network from 1 to 10. This traffic causes severe contention as the number of transmitting nodes increases. Figure 3 shows the mean energy consumption of each node as the number of nodes increases. We can see that at this heavy traffic, LPL consumes about 8 times more energy than SCP to transmit an equal amount of data.

An expanded version of this work can be found in a separate technical report [5].

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