Reservation Packet Medium Access Control for Wireless Sensor Networks
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Abstract - This paper introduces the Reservation Packet Medium Access Control (RP-MAC) protocol for Wireless Sensor Networks (WSNs). The protocol incorporates a periodic listen/sleep schedule to conserve energy and employs a novel channel reservation mechanism to enhance the rate at which packets can be transferred over multiple hops, thereby improving throughput and reducing end-to-end delay. To evaluate the performance of RP-MAC, it is compared with the established S-MAC protocol through simulation. Results show that RP-MAC can support much higher traffic loads as a direct result of its higher throughput capability along with reduced end-to-end delay for packet transmissions across a multi-hop link. These benefits come at the expense of higher energy consumption, but this is maintained at an acceptable level.

Index Terms—Wireless sensor network, medium access control, energy-efficiency, MAC, S-MAC, RP-MAC

I. INTRODUCTION

A Wireless Sensor Network (WSN) consists of a potentially large number of nodes deployed in an ad-hoc fashion, capable of monitoring environmental conditions and reporting them back to a central location. A wide range of applications is foreseen for WSNs, ranging from environmental monitoring and disaster prevention to military and tracking applications [1-2]. In many cases, sensor nodes will be deployed in remote or inaccessible places where they will be required to take periodic measurements or detect and report on events for a long period of time without external intervention and with no access to a fixed power source. To maximise network lifetime, energy-efficient operation is important, with traditional performance measures taking very much a secondary role. It is well understood that communication in a sensor network generally consumes more energy than computation, and so a lot of effort has been devoted to energy-efficient Medium Access Control (MAC) protocol design. MAC protocols determine the means by which nodes access the radio communications medium and transfer information through the network, and have a major impact on overall energy consumption.

It is worth remembering that the capacity of ad hoc networks is severely constrained and they have been shown not to scale well [3]. Developing more energy-efficient protocols at the expense of throughput and delay performance may not be the best approach. Improving the rate at which packets can be transferred through a network will alleviate capacity bottlenecks (such as those where traffic converges around a sink node) and enable the network to support a much higher rate of monitoring and/or event reporting. Associated reductions in end-to-end delay will permit delay sensitive applications to be supported.

This paper proposes the Reservation Packet Medium Access Control (RP-MAC) protocol, which incorporates a traditional listen/sleep schedule to improve energy efficiency. This is combined with a novel reservation mechanism to provide more efficient transfer of data over multiple hops, enabling it to support higher traffic loads and provide lower end-to-end delay compared with existing approaches. In the following section, some recently proposed and pertinent MAC protocols for WSNs are introduced. Then in section III, the RP-MAC protocol is described in detail, including the reservation mechanism. In section IV, the simulation scenario is presented, followed by a comparative performance evaluation of RP-MAC with S-MAC in section V. Finally, the advantages of RP-MAC are summarised in the conclusions in section VI.

II. RELATED WORK

A large number of MAC protocols have been proposed for sensor networks, with energy-efficiency the primary design criterion. Schedule-based Time Division Multiple Access (TDMA) and contention-based schemes are the most common, since they enable operation on a single frequency channel and provide flexible capacity assignment [4-5].

In schedule-based TDMA schemes, individual terminals are assigned particular time slots to transmit and receive data in a contention-free manner. As nodes only need to switch on their transceivers in their scheduled time slots, this can be a very energy-efficient approach, but scheduling is notoriously difficult to achieve in a distributed fashion. One example designed specifically for WSNs is the Traffic Adaptive Multiple Access (TRAMA) protocol [6], in which nodes announce their intended schedules and determine whether they have priority to transmit in each slot. Disadvantages of this approach include significant signaling overheads and complexity in determining transmission priorities. Tight synchronisation is also required.

Contention-based schemes are a natural solution for distributed networks because individual nodes decide how and when to access the radio medium, but they do suffer from a number of energy waste mechanisms. In addition to packet collisions (when more than one packet arrives at a receiver simultaneously), overhearing is a common problem which corresponds to nodes unnecessarily receiving packets destined to other nodes. Idle listening is another issue, which relates to energy consumed through idle sensing of the channel for possible packet reception.
A periodic listen/sleep schedule is often employed to reduce the energy expended through idle listening and overhearing, with nodes put into a low power sleep mode when they are not required to transmit or receive. S-MAC is a popular scheme based on this approach [7] and has been shown to provide energy-efficient communication in a wireless sensor network. A further extension of S-MAC is T-MAC, which employs an adaptive duty cycle mechanism. T-MAC can dynamically end the listen period to further reduce energy consumption [8].

The benefits of putting nodes to sleep to conserve energy comes at the cost of increased delay in transferring packets over multiple hops. S-MAC, for example, only supports one packet transmission process per listen/sleep cycle which means that nodes receiving packets in one listen period have to wait until the next before they can relay the packets to the next hop nodes, thereby incurring a delay on each hop greater than the sleep period. For large sensor networks, this shortcoming will inhibit its use for delay sensitive applications. It is worth noting that the rate at which packets can be transferred over multiple hops is inherently restricted, which limits the throughput capability of the network as a whole.

III. RESERVATION PACKET MEDIUM ACCESS CONTROL (RP-MAC) PROTOCOL DESIGN

There is a clear tradeoff between energy-efficiency and delay performance with MAC schemes employing a listen/sleep schedule. To reduce energy consumption, a longer sleep duration is called for, but this will serve to increase the delay associated with transferring packets over a multi-hop WSN. RP-MAC uses a listen/sleep schedule to maintain energy-efficiency, but introduces a reservation mechanism to reduce delay and increase throughput.

A. Listen and Sleep Schedule

RP-MAC incorporates a listen/sleep schedule similar to S-MAC, to conserve node energy. Both listen/sleep schedules are shown in figure 1.

In the listen period, both schemes initially incorporate a SYNC period, which is used by nodes to synchronise and maintain their listen/sleep schedules. SYNC packets contain a timestamp indicating the period of time from the end of SYNC packet reception to the beginning of the next listen period. When a node receives a SYNC packet, it either updates its neighbouring node schedule information if it has an established schedule, or it adopts the received schedule itself. A new node in the network must wait for at least one complete cycle to detect any existing schedules (through reception of SYNC packets) before choosing its own schedule. Contention-based access is employed for SYNC packet transmission. Nodes wishing to send SYNC packets select one of the minislots at random for transmission. If the channel remains free until the selected slot, the corresponding node will win the contention and transmit the SYNC packet. Otherwise, nodes will cancel their transmission and wait to receive SYNC packets from other nodes.

The S-MAC listen period also incorporates a DATA period, which is used to initiate data packet transfers. For a more detailed description of the operation of S-MAC, please see [9]. The RP-MAC listen period incorporates a Reservation Packet (RP) period, consisting of a number of equal sized transmission minislots for contention-based reservation packet transmission. The use of this period is described in detail in the following section. Guard times are present to handle differences in propagation delay and to overcome individual node time drifts.

The majority of nodes will enter a low power sleep mode during successive sleep periods. The only exception is when nodes need to be awake to transmit packets and receive packets destined to them. In S-MAC, the duration of the listen period is extended into the sleep period to accommodate one data packet transfer over a single hop, whereas in RP-MAC the sleep period is used to transfer data packets over multiple hops.

B. Reservation Packet Transmission

As outlined in section II, the listen/sleep schedule of S-MAC introduces significant delay, which aggregates over multiple hops and can limit the throughput and result in long delays in networks where the sink nodes are a long way away from the source nodes. Figure 2 shows the packet transmission processes within a single listen/sleep cycle for RP-MAC and S-MAC, based on transmission of packets from node A to node F along a chain. All nodes are assumed to be operating with the same listen/sleep schedule. In practice, as every node needs to monitor existing schedules before choosing a self-defined scheme, it is highly probable that nodes have the same schedule.

This figure shows that S-MAC only permits a packet to be transferred over one hop in a single listen/sleep cycle. In the DATA period, node A initially transmits an RTS (Request To
Send) packet to node B, which responds with a CTS (Clear To Send) packet to check the channel is clear for transmission. The data packet is then transmitted from node A to node B, followed by an acknowledgment (ACK) from node B. After this process, both nodes enter a low power sleep state and node B has to wait until the next listen period to initiate a transfer to node C.

In RP-MAC, reservation packets are transmitted in the RP period to inform nodes along a route that they need to wake up in the sleep period at an appropriate time for data packet transmission and reception, thereby reserving channel transmission time for efficient transfer over a number of hops within a single sleep period. A reservation packet contains the transmit node ID (IDtx), next hop node ID (IDnext), previous hop node ID (IDprev) and a sequence number (Nseq).

Nodes with data packets to send randomly select one of the RP minislots for transmission of a reservation packet. If the channel is sensed busy before the chosen slot, nodes cancel their scheduled RP transmissions to avoid collisions and retry in the next listen/sleep cycle. Considering the example shown, only node A has a packet to send, so it randomly selects an RP minislot and transmits a reservation packet to node B. The IDtx and IDnext fields are set to the IDs of node A and node B respectively. The IDprev is set to a default value (which represents no particular node address) and Nseq will be set to 1, to indicate that the data packet is due to be transferred over this hop in the first data slot of the sleep period.

On receiving the RP packet, node B will record the value of Nseq and use it to determine when it needs to wake up in the subsequent sleep period to receive the data packet (the first data slot in this case). If Nseq is smaller than the number of data slots in the sleep period, 5 in this example, a new reservation packet is immediately transmitted to reserve channel transmission time for transferring the data packet over another hop and node B will subsequently remain awake to transmit the packet following reception. The packet address fields are updated with the IDtx and IDnext fields set to the IDs of node B and node C respectively. The IDprev is now set to the ID of node A, since node A will overhear the packet and can be used as an acknowledgement for the previously received reservation packet. Nseq is incremented and set to 2 in this reservation packet, to indicate the appropriate time that node C should wake up to receive the data packet from node B (the second data slot). This process continues until node F receives a reservation packet from node E. The value of Nseq is now 5, which represents the maximum number of transfers that can take place in a single listen/sleep cycle. Node F transmits a reservation packet but only addresses the previous hop node to acknowledge the reservation packet it received.

By the end of the RP period, all nodes involved in communication will subsequently wake up at the appropriate times in the sleep period to take part in receiving the data packet and transmitting it to the next hop node. All other nodes will enter the low power sleep mode and remain asleep until the next listen period. This process enables data packets to be rapidly transferred over five hops in a single listen/sleep cycle. Data packets are acknowledged within the period of data packet exchange and a timeout is set for each reservation and data packet transmission. If acknowledgements are not received within the expected time frame, a node will consider itself to be the end of the transfer process within a particular cycle and will try and gain access to the channel in the next listen period.

IV. RP-MAC SIMULATION DETAILS

The performance of RP-MAC has been evaluated through simulation in OPNET modeler and compared with S-MAC. The 10-hop chain topology presented in figure 3 has been investigated, to evaluate the fundamental performance of both protocols for efficient data transfer over multiple hops.

A. Simulated Topology and Traffic Model

The topology consists of a single source node (node 0), a single sink node (node 10), with intermediate nodes addressing packets and relaying them in the direction of the sink node. A regular packet generation process has been employed in all simulations, to represent the common class of periodic monitoring applications. Individual packets are periodically generated at the source node based on a specified inter-arrival time. A wide range of source traffic loads are obtained by adjusting the packet inter-arrival time.

B. Main Simulation Parameters

The primary simulation parameters are presented in table I.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>RP-MAC</th>
<th>S-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control packet size (bits)</td>
<td>186</td>
<td>186</td>
</tr>
<tr>
<td>Data packet size (bits)</td>
<td>1640</td>
<td>1640</td>
</tr>
<tr>
<td>Reservation packet size (bits)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Sleep period (seconds)</td>
<td>0.5035</td>
<td>1.006</td>
</tr>
<tr>
<td>SYNC period (seconds)</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>RP period (seconds)</td>
<td>0.151</td>
<td>0.226</td>
</tr>
<tr>
<td>DATA period (seconds)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SYNC contention slot (seconds)</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>RP transmission slot (seconds)</td>
<td>0.015</td>
<td>0.015</td>
</tr>
<tr>
<td>Data rate (bps)</td>
<td>20000</td>
<td>20000</td>
</tr>
</tbody>
</table>

The simulated time of 1 hour for each run has been shown to provide statistically meaningful results. The S-MAC parameters correspond to those used in publicly available source code [10]. Variants RP-5 (or RP-10) indicate RP-MAC with a sleep period sufficiently long to contain 5 (or 10) data packet exchanges, enabling a packet to be transferred over 5 (or 10) hops. Control packet size relates to the SYNC, RTS, CTS and ACK packets in S-MAC and SYNC and ACK packets in RP-MAC. The RP-MAC control packets are smaller, as the SYNC packets do not require destination node information and ACK packets do not have channel busy duration information.

V. RP-MAC SIMULATION RESULTS

A. End to End Delay Performance
Figure 4 shows the average end-to-end delay experienced by packets as a function of the packet inter-arrival time. End-to-end delay represents the time that elapses from the instant a packet is generated until it is has been received by the sink node.

As the traffic load is increased, the end-to-end delay is observed to initially remain constant before rising sharply. These transition points represent the maximum rate at which packets can be transferred over the multi-hop chain, beyond which packets experience continual build up in the source node queue and the systems become unstable.

Interference between nearby nodes fundamentally limits the rate at which packets can be transferred across a multi-hop link, and the carrier sensing mechanism inhibits nodes from transmitting when other transmissions are detected in range. In these simulations the interference range is considered to be equal to the reception range (to illustrate the principles) and so a packet can only be transmitted by a node when the previous packet has been transferred at least three nodes away. For example a new transmission from node 0 can only take place when the previous packet has reached node 3, as a transmission from node 2 would interfere with a transmission from node 0 causing a collision at node 1. With S-MAC, it takes three listen/sleep cycles for a packet to be transferred a sufficient distance away, whereas RP-MAC only requires one cycle. As a result, RP-MAC can support much higher rates of periodic monitoring. It is worth noting that the throughput capability of S-MAC would be further limited in more realistic cases where the interfering range is greater than the reception range.

Focusing on the stable operating range, packets experience an average end-to-end delay of 15.1s with S-MAC compared with 0.73s with RP-5 and 0.9s with RP-10. This improvement is a direct result of the reservation mechanism. S-MAC requires at least 10 cycles to complete the transfer, whereas RP-10 and RP-5 require 1 and 2 cycles respectively. Despite RP-5 requiring an additional listen/sleep cycle to complete the transfer, packets experience shorter end-to-end delay, because the longer sleep period of RP-10 means that packets have to wait longer for initial transmission in the next listen period (on average). There is a trade-off between the initial delay prior to transmission (shorter listen/sleep cycle beneficial) and the transfer delay (longer listen/sleep cycle beneficial). The reduced end-to-end delay makes RP-MAC more suited to applications requiring timely delivery of packets to the sink node. The differences would be even more noticeable for a network with a greater number of hops from source to destination.

B. Number of Received Data Packets

To verify the greater throughput capability of RP-MAC, the number of packets received by the sink node over the entire simulation duration is presented in figure 5 as a function of packet inter-arrival time.

As expected, in the stable operating range, the number of packets received increases with decreasing packet inter-arrival time since a greater number of packets enter the system to be transferred to the sink. The number of received packets then reaches a peak value with each scheme, and remains constant with increasing traffic load. This reflects the throughput limitation of each scheme, with packets being transferred at the maximum possible rate and additional packets building up in the source node queue. The simulation results show that S-MAC can transfer 598 packets within a one hour, compared with 2888 for RP-10 and 5384 for RP-5. Both RP-5 and RP-10 transfer packets out of interfering range of the source node within a single cycle, enabling another packet to be transmitted in the next cycle. The longer cycle of RP-10 means that a longer period elapses before a new packet can enter the chain. Therefore, the throughput performance of RP-5 is superior. The ability of the RP-MAC to support much higher rates of periodic monitoring can be clearly seen.

C. Energy Consumption

It is important to examine the energy cost of improved throughput and delay performance. Energy consumption calculation is based on typical power consumption figures for different operational states and the time spent in each state. Figures of 14.4mW, 36mW and 15μW have been used for reception, transmission and sleep modes respectively, based on MICA2 devices [11-12].

Figure 6 shows the average amount of energy consumed per second as a function of packet inter-arrival time, over the stable operating range of each protocol. These figures are useful for estimating network lifetime. The energy consumption rate is seen to rise as a greater amount of traffic is introduced to the multi-hop chain, as expected. The RP-MAC protocol consumes more energy than S-MAC, but the difference is not particularly
significant given the observed gains in throughput capability and delay performance. Under stable operating conditions, the higher energy consumption figures of RP-MAC are primarily due to a higher duty cycle. According to the simulation parameters given in Table 1, the respective duty cycles are 10% for S-MAC, 24.6% for RP-5 and 19.2% for RP-10.

To highlight the true energy-efficiency of the schemes for transferring data, the average amount of energy consumed per packet is shown in Figure 7 as a function of packet inter-arrival time. It is interesting to note that the protocols become more efficient as the traffic load is increased, with a lower amount of energy consumed per data packet transferred. This is because the signaling overheads become less significant as a greater amount of information is transferred. RP-MAC requires more energy per packet transmission at low traffic loads but becomes more efficient than S-MAC when operating at loads beyond the stable operating range of S-MAC.

The lowest system energy consumption per packet S-MAC can achieve is about 0.183 J, which corresponds to a packet inter-arrival time of 4.2s. For RP-10, the lowest energy consumption value is 0.0748 J when the packet inter-arrival time is 1.2s. Since RP-5 offers the highest supportable traffic load, it achieves the lowest energy consumption figure of 0.0558 J, when the packet inter-arrival time as 0.7s.

VI. CONCLUSION

A wide range of MAC protocols have been proposed for wireless sensor networks, which aim to improve energy-efficiency, often by putting nodes into a low power sleep mode. Improvements in energy-efficiency generally come at the expense of increased delay and decreased throughput capability. Such schemes will not support delay sensitive applications or those requiring high rates of periodic monitoring. This paper introduces a new MAC protocol, RP-MAC, which incorporates a number of features to improve the rate at which packets can be transferred through a multi-hop network. A periodic listen/sleep schedule is employed to reduce energy consumption, and a novel packet reservation mechanism enables packets to be transferred over many hops within a single listen/sleep cycle.

The performance of RP-MAC has been evaluated for a 10-hop chain topology and compared with the S-MAC protocol. Simulation results show that RP-MAC can support higher traffic loads than S-MAC, with packets experiencing lower end-to-end delay. This makes RP-MAC more suitable for demanding applications and will help alleviate capacity bottlenecks, such as those observed where traffic converges around a sink. RP-MAC consumes more energy than S-MAC but the difference is relatively small compared with the benefits. For operation at high periodic monitoring rates, RP-MAC is more efficient than S-MAC within its own stable operating range, since a lower amount of energy is consumed on average to transfer a packet.

Future work will focus on evaluating the performance of RP-MAC for a range of network topologies, based on more realistic propagation models. The tradeoff in energy-efficiency and delay/throughput performance of RP-MAC variants will be explored as a function of the listen/sleep cycle duration.

REFERENCES