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Wireless Sensor Network Energy-Adaptive MAC Protocol

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Abstract

Wireless Sensor Networks (WSNs) provide a valuable capability to autonomously monitor remote activities. Their limited resources challenge WSN medium access control (MAC) layer designers to adequately support network services while conserving limited battery power. This paper presents an energy-adaptive WSN MAC protocol, Gateway MAC (G-MAC), which implements a new cluster-centric paradigm to effectively distribute cluster energy resources and extend network lifetime. G-MAC's centralized cluster management function offers significant energy savings by leveraging the advantages of both contention and contention-free protocols. A centralized gateway node collects all transmission requirements during a contention period and then schedules their distributions during a reservation-based, contention-free period. With minimal overhead, the gateway duties are efficiently rotated based upon available resources to distribute the increased network management energy requirements among all of the nodes.

1. Introduction

Sensor networks monitor phenomena as diverse as moisture, temperature, speed, and location using a wide variety of detectors. Since wireless sensor networks (WSNs) operate in a broadcast medium, these networks require a medium access control (MAC) layer to resolve contention in a random, multi-access environment. In efforts to make inexpensive sensors ubiquitous, these sensor platforms tend to have limited processor capability, memory capacity, and battery life. In dynamic ad hoc network environments, WSNs have the additional challenge of self-adapting to changes in topology, traffic loads, and existing battery conditions.

This paper describes an energy-adaptive MAC protocol, Gateway MAC (G-MAC), which implements a new cluster-centric paradigm to effectively distribute cluster energy resources and extend network lifetime. The G-MAC protocol's innovative architecture is motivated by the necessity for resource-challenged WSN mote sensor platforms to minimize the time radios spend in both the idle and the receive modes. Research shows that wireless platform transceivers expend a significant amount of energy receiving on an idle channel [1], and many of the WSN mote platform radios expend more energy in receive than in transmit mode [2]. G-MAC provides effective network control mechanisms to maximize sleep durations, minimize idle listening, and limit the amount of cluster control traffic overhead. G-MAC dynamically rotates point coordination duties among all the nodes to distribute the management energy costs, to allow other nodes to sleep longer, and to extend the network's lifetime.

2. WSN sources of energy loss

WSN MAC protocols extend network lifetimes by reducing the activity of the highest energy-demanding component of the sensor platform – the radio. Trading off network throughput and latency (delay), energy-efficient MAC protocols synchronize network communication to create opportunities for radios to sleep with active duty cycles as low as 2.5% under minimal traffic conditions [3]. Typical sources of energy loss in WSNs include idle listening, frame collisions, protocol overhead, and message overhearing.

Idle listening: Idle listening occurs when a device listens to an inactive medium. Contention-based WSN MAC protocols attempt to synchronize network traffic so that transmissions begin only in predetermined time slots. Once all network transmissions are complete for a particular cycle or time *frame*, the protocols allow nodes to return to sleep until the next transmission period. Contention-free WSN MAC protocols reduce idle listening by scheduling transmission slots and allowing nodes not actively exchanging messages to sleep.

Frame collisions: A frame collision occurs when a node sends a message which collides or overlaps in

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time with another message. Single-channel radios cannot simultaneously receive while in transmit mode. Therefore, the message sender's only indication of a collision is the failure of the receiver to return an acknowledgement (ACK) for the message. Protocol designers reduce frame collisions by employing contention-free scheduling protocols or contention-based backoff algorithms to minimize the probability of collisions.

Message overhearing: Receiving and discarding messages intended for other nodes, or *message overhearing*, is commonly employed in non-energy constrained networks to increase throughput and decrease latency. Message overhearing is costly in WSNs since all of the nodes expend energy receiving a message intended for just one node. Early rejection and network allocation vector (NAV) sleep are energy-efficient methods which reduce message overhearing. Early rejection allows a sensor node to turn off its radio once it has read a different destination field for an incoming message. NAV sleep allows nodes to schedule a sleep period during the overheard request-to send / clear-to send (RTS-CTS) handshake sequence by noting the message duration field and scheduling a NAV table interrupt [2][4][5].

3. Related work

Most existing contention-based WSN MAC protocols reduce idle listening, but they fail to prevent the nodes from actively monitoring channel contention periods and reservation protocol (RTS-CTS) packets before transitioning to sleep [4][6][7]. Sensor MAC (S-MAC) [4] and Timeout MAC (T-MAC) [6] are contention-based protocols focused on reducing idle radio listening by concentrating the network's data transmissions into a smaller active period and then transitioning to sleep for the remainder of the cycle. S-MAC establishes a fixed active cycle (i.e. 10% active), and T-MAC allows the traffic to adjust the duration of the active period dynamically by transitioning nodes to sleep only after listening to an idle channel for a timeout period equivalent to a transmitting node's worst-case contention backoff. Concentrating the transmissions into a smaller active period reduces idle listening, but it also increases the probability of collisions, thus wasting precious bandwidth and energy. Berkeley-MAC (B-MAC) [7] is another contention-based protocol that saves energy by having radios periodically wake up to sample the medium. Transmitting nodes extend the duration of message preambles to cover the entire range of the wakeup period to ensure all nodes receive the preamble and remain awake to accept the message. This protocol loses efficiency as network traffic increases because all nodes remain awake throughout the entire packet transmission and a portion of the extended preamble. However, B-MAC is an efficient protocol in low network traffic conditions since nodes will spend most of the time sleeping.

Time division multiple access (TDMA) reservation-based protocols establish fixed time periods for nodes to communicate to eliminate the channel contention and idle listening energy costs [8][9][10]. To use the bandwidth efficiently, many of these protocols expend significant energy in exchanging control packets to reallocate unused time slots or require complex algorithms to allocate time slots based upon previous traffic requirements. Traffic-Adaptive MAC (TRAMA) is a schedule-based, MAC layer protocol that optimizes power savings during inactive periods [8]. TRAMA employs a complex algorithm to schedule message recipients for a contention-free period and release unused timeslots. The protocol requires all nodes to monitor a contention period to learn neighboring nodes' traffic needs. G-MAC similarly gathers traffic demands during a contention period, but saves additional energy since only transmitting nodes wake up to send their traffic requirements for consolidation by a centralized gateway.

Centralized cluster management techniques offer the ability for a single node to coordinate traffic exchanges. The Low-Energy Adaptive Clustering Hierarchy (LEACH) [9] and Power-Aware Clustered TDMA (PACT) [10] protocols use an "off-line" self-election technique similar to G-MAC to establish a cluster head node. LEACH is a self-organizing, cluster-based protocol which uses a passive, "off-line" probability-based algorithm to randomly select a cluster head node. The LEACH algorithm assumes that all nodes were deployed simultaneously with the same energy levels and does not take the current energy level of the node into consideration. The protocol simply ensures that all nodes serve as cluster head an equal number of times. PACT extends the LEACH algorithm by appending a two-bit status field to every message and basing the election eligibility on the node's battery energy level. G-MAC's resource adaptive voluntary election (RAVE) scheme does not require the transfer of any resource information and successfully chooses a gateway from the most resource-eligible nodes.

4. Gateway MAC protocol design

G-MAC improves on existing WSN MAC protocols by establishing a traffic rhythm which extends the sleep duration to amortize power mode transition costs and efficiently rotating point coordination function (PCF) responsibilities among all eligible nodes.

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4.1 G-MAC communication scheme

While other WSN protocols strive to reduce idle listening, G-MAC *eliminates* cluster-wide idle listening to obtain significant energy savings. Figure 1 illustrates a traffic collection and distribution rhythm which enables nodes to sleep for extended durations, facilitates bi-directional traffic within the cluster, promotes fair data exchange, and utilizes the bandwidth efficiently. The dynamic allocation of the contention-free exchange slots offers the same network scalability as contention-based schemes, but the contention-free period offers better network stability under heavy loads due to the scheduled nature. Since nodes compete equally during the contention period using Future-Request-To-Send (FRTS) control messages, the random exponential backoff promotes fair competition for schedule slots. Starting the frame cycle in the collection period, the cluster coordinator, called the gateway, collects two types of network traffic requests: intra-network (local) and inter-network (non-local) traffic. Intra-network traffic represents messages exchanged between nodes in the same cluster for data fusion. The sender transmits a FRTS message to the gateway to reserve a delivery slot in the contention-free distribution period. Inter-network traffic represents messages which originate in the cluster to be forwarded by the gateway to the outside network, messages which originate outside the network to be delivered to a cluster node, or tandem messages traveling through the network. The inter-network sender and gateway exchange an RTS-CTS-data-ACK message sequence for immediate collection. The gateway must limit the amount of inter-network messages it stores due to limited memory capacity. After all transactions are complete, the gateway attempts to forward all traffic out of the cluster and then transitions to sleep. The distribution period begins with all nodes waking up and receiving the gateway traffic indication message (GTIM). In this synchronization message, the gateway declares the current time, the next collection period, the next distribution period, and the schedule of message transactions between cluster nodes. The GTIM describes the traffic exchange slots by source, destination, and relative offset time. If a node is scheduled to transmit or receive a message during the distribution period, the node sleeps until the indicated exchange time, wakes up to exchange the message, and then returns to sleep. If a node is not scheduled to exchange a message, the node transitions to sleep throughout the distribution period. At the end of the schedule, the gateway will wake up and use the remaining distribution period to exchange inter-network traffic with other gateways. When the contention/collection period begins again, only nodes with traffic to send wake up and request a scheduled exchange slot for the subsequent contention-free distribution period.

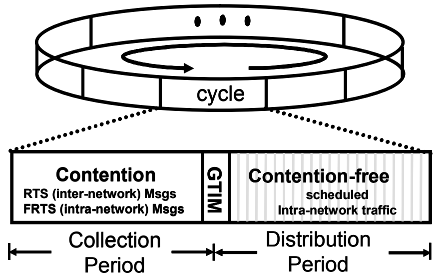

Figure 1. G-MAC Frame Architecture

The significant energy savings provided by the G-MAC traffic pattern are a result of the reduction in the amount of time all nodes must monitor the network. Receiving the GTIM is the only time that all nodes will be awake unless the GTIM schedule contains a broadcast message. Unlike the other WSN MAC protocols, G-MAC eliminates cluster-wide idle listening and extends the length of time inactive nodes can sleep.

4.2 Resource adaptive voluntary election

G-MAC periodically elects a new gateway node to equally distribute the energy requirements among all of the nodes using the resource adaptive voluntary election (RAVE) scheme. RAVE is a passive cluster coordinator election scheme similar to LEACH [9], but the RAVE algorithm allows for a self-election based on each node's available battery and memory resources, not a strict probability-based calculation. PACT [10], another passive election scheme, addresses battery resource as a discriminator for cluster head eligibility, but the election is still based on probability. G-MAC's multi-tiered resource levels shown in Table 1 facilitate the rotation of the gateway duties among the nodes with the most available resources. These duty rotations provide graceful network degradation until all node's energy levels are exhausted. A similar G-MAC table categorizes memory levels to distribute gateway duties away from nodes which have queued forwarding network messages and are in a reduced memory capacity. The critical resource level algorithm assigns a node's resource level (RL) according to the most critical resource. Although this model only shows four distinct resource levels, the model can easily be extended for better resource resolution.

Critical Resource Level Algorithm

if Pwr=Min or Memory=Min then Resource Level = 3
elseif Pwr=Low or Memory=Low then Resource Level = 2
elseif Pwr=Med or Memory=Med then Resource Level = 1
else Resource Level = 0

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Table 1. Battery Resource Level

Battery Pwr Level	Power Level Nomenclature	Voltage Range (volts)
00	High	$2.6 < Pwr \leq (3.0\text{-}3.6)$
01	Med	$2.4 < Pwr \leq 2.6$
10	Low	$2.1 < Pwr \leq 2.4$
11	Min	$Pwr \leq 2.1$

Table 2. RAVE Election Contention Backoff

Resource Level (RL)	Election Contention Backoff **Random (2^7) + (RL * 128)**
0 High	0 to 127 slots (0ms to 2ms)
1 Med	128 to 255 slots (2ms to 4ms)
2 Low	256 to 383 slots (4ms to 6ms)
3 Min	384 to 511 slots (6ms to 8ms)

In addition to a default gateway changeover frequency for self-recovery, every GTIM contains an election flag bit to indicate the initiation of an immediate gateway election. To reduce the overhead of exchanging available resource updates, G-MAC uses a passive method of determining the next gateway by calculating an election contention backoff period based upon a node's available resources. RAVE's election contention backoff algorithm chooses a gateway from the most energy or memory eligible group of nodes using the equation:

$$ElectionBackoff = Random\,(2^7) + (RL * 128)$$

where ***ElectionBackoff*** is the number of contention slots a node will backoff before sending a self-election packet, ***Random (2^7)*** generates a random number from 0 to 127, and **RL*128** offsets the random number into an eligibility band based upon available resource levels (RL). Table 2 illustrates the election eligibility contention backoff windows and eligibility groups.

A gateway node will signal for a new election whenever it transitions to a lower energy state, reaches critical memory levels, or approaches a default changeover. Nodes immediately calculate an election contention backoff when they encounter a periodic or signaled election. The new gateway is the *volunteer* node which successfully transmits a self-election message after the start of the GTIM period. The departing gateway node confirms the new gateway, distributes the upcoming GTIM distribution schedule, and changes to a regular node status. In the event of a gateway node failure, after waiting for three consecutive missed GTIMs, the nodes will automatically conduct an election with a peer confirmation mechanism. RAVE also uses this timeout driven peer-election method to initially self-configure the cluster.

5. Analysis of protocols

The Sensor MAC [4], Timeout MAC [6], Berkeley MAC [7], and Gateway MAC WSN MAC protocols were modeled in MATLAB using similar configurations to provide a fair comparison. The IEEE 802.11 standard MAC protocol [11] establishes a baseline for a network lifetime without any power-saving mechanisms. The S-MAC model has a 500ms frame time with a fixed sleep period of 450ms, translating to a 10% duty cycle. The S-MAC implementation includes RTS-CTS exchanges for message overhearing avoidance. The T-MAC model also has a frame time of 500ms with the adaptive sleep timeout set to 10.2ms and a fixed contention period of 5ms for every packet. The B-MAC model senses the channel for 0.35ms during every 14ms check interval. The low power listening mechanism for B-MAC consumes the same power as the receive mode in all other models. The G-MAC protocol also uses a 500ms frame time containing a collection period, a GTIM broadcast, and a distribution period. The size of the GTIM is 33 bytes + (3 bytes * number of packets/frame). The system models forty nodes in a single-hop neighborhood and operates at 62.6kbps. The network lifetime is based solely on the CC2420 radio energy to receive (19.7mA), transmit (17.4mA), and power down sleep (0.02mA) [12].

The results in Table 3 indicate that G-MAC performs significantly better than the other protocols in every traffic situation. The empty network case shows the protocol overhead and idle listening effects determined by the effective duty cycle. IEEE 802.11 performs poorly with a 100% duty cycle. B-MAC establishes a 2.5% effective duty cycle, and S-MAC uses a 10% fixed duty cycle. With adaptive listening, all T-MAC nodes must monitor the network for a complete timeout period of 10.2ms at the beginning of every 500ms slot for a 2.1% duty cycle. G-MAC's equivalent 0.95% duty cycle is the weighted average of the duty cycle of the gateway node and the other nodes. The gateway node monitors the network for a complete timeout and sends the empty GTIM. All other nodes wake up only to receive the GTIM and return to sleep.

Regular unicast and broadcast traffic are modeled using four 32-byte messages per second. By only having the transmitting nodes awake during the contention period, G-MAC outperforms all of the other protocols in terms of network lifetime. T-MAC performs better than S-MAC due to its ability to curtail the active period after completing all transmissions. Interestingly, S-MAC uses less network energy with traffic than in the empty traffic scenario. The ability for the passive nodes to transition to sleep after receiving the RTS or CTS messages allows them to save message overhearing energy costs. The performance of B-MAC significantly decreases with traffic because each passive node has to wake up and

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Table 3. MAC Protocol Performance Results

MAC Protocol	Network Lifetime (days) Empty Network (no traffic)	Unicast Traffic	Broadcast Traffic
802.11	6	6	6
S-MAC	63	88	63
B-MAC	244	87	87
T-MAC	295	130	108
G-MAC	480	455	203

receive every message. Additional tests show that B-MAC works well in ultra-low traffic networks.

Figure 2 shows that G-MAC does not require a densely populated cluster to distribute the additional gateway energy consumption costs and save energy. A network size of 25 nodes closely achieves the same network lifetime as 100. The other protocols are unable to leverage increased network energy capacity to gain network lifetime with increasing cluster size. G-MAC's ability to schedule traffic and eliminate network-wide idle listening provides an immediate advantage for all cluster sizes.

6. Future Work and Conclusions

The WSN link layer MAC protocol introduced in this paper, Gateway MAC, establishes a robust, centralized coordination function which eliminates cluster-wide idle listening and significantly reduces energy consumption. G-MAC dynamically apportions TDMA slots according to the network traffic demands without imposing any cluster-wide message overhearing or idle listening overhead and increases the network lifetime by 250% for unicast traffic. As shown in the simulation results, G-MAC achieves significant energy savings in both heavy- and light-density traffic environments by performing all required traffic scheduling operations while most of the nodes are sleeping. Future work in WSN protocols includes creating a message priority quality of service (QOS) system and optimizing the schedule by placing receivers or transmitters with multiple messages into adjacent schedule slots. Providing solutions for these resource-constrained networks requires delicate tradeoffs in energy, latency, and throughput.

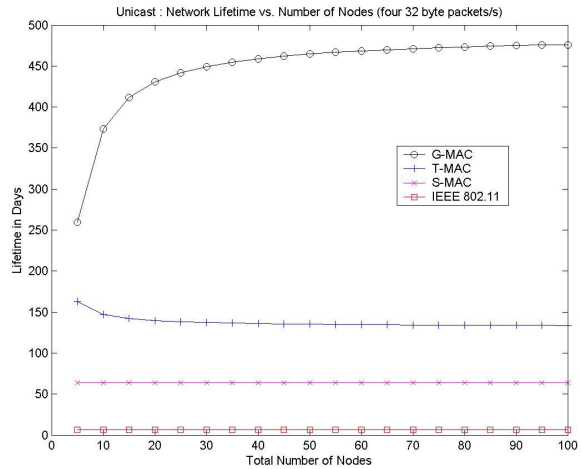

Figure 2. Network Lifetime vs. Number of Nodes

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