

ENERGY-AWARE SENSOR MAC PROTOCOLS

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ABSTRACT

Sensor network applications typically require continuous monitoring of physical phenomena for extended periods of time under severe energy resource constraints. Accordingly, design considerations for sensor Media Access Control (MAC) protocols depart significantly from those of traditional wireless MAC protocols that largely ignore the energy factor. In this paper, we re-examine the design space of wireless sensor MAC protocols and modify IEEE 802.11 Distributed Coordination Function (DCF) to incorporate energy-adaptive contention mechanisms for prolonging sensor lifetime. Performance of the proposed schemes is evaluated with DCF as a baseline and results indicate the benefits of energy-aware mechanisms for sensor MAC protocols.

Keywords — MAC protocols, sensor networks, contention

I. INTRODUCTION

Sensor networks are an emerging technology that has many important applications ranging from environment protection and homeland security, to space exploration. A sensor net typically consists of many tiny nodes that collaborate in their sensing, processing and communicating activities to accomplish high-level application tasks (e.g., temperature sensing in a specified region). Energy is a major constraint in sensors, which signifies the importance of energy conserving schemes in protocol design. Also, certain nodes may drain energy faster than the others, and may even go out service prematurely disrupting network connectivity [1]. Wireless Media Access Control (MAC) protocols arbitrate among several sensors to provide the channel allocation function. Traditional MAC protocols, such as MACAW [2] and IEEE 802.11 Distributed Coordination Function (DCF) [3], largely ignore the energy factor and emphasize per-node fairness that are not as important in the context of sensor nets. One way of optimizing existing MAC protocols for sensor nets is to make the contention scheme energy-aware. In this paper we present schemes that accomplish this by providing preferential treatment to low-energy nodes as compared to high-energy nodes. This allows sensor networks to prolong lifetime by shifting the energy cost of contending for the channel from lower energy nodes to higher energy ones because the energy resources at the weakest nodes largely determine the lifespan of the

network.

In this paper, we introduce two energy-adaptive contention schemes for wireless sensor MAC protocols. The first mechanism, *Energy-Aware Back-off Window*, (based on MACAW backoff behavior) allows nodes with low energy levels to have smaller contention windows and shorter maximum queue lengths than those of high energy level nodes. Essentially, compared to higher energy nodes, lower energy nodes try to send packets more aggressively at the same time they give up more readily since fewer packets are allowed to be queued. Adopting this behavior, lower energy nodes suffer shorter overall contention time, and as a result reduce the energy consumption during the contention time. Note that the total energy consumption consists of that used for (A) transmitting data, (B) contending for the channel, and (C) idling. We cannot reduce (A), schemes such as low duty cycle sensor nets attempt to save (C). This paper deals with saving energy in case (B).

The second scheme, namely, *Adaptive Limited Contention* uses the same principle but employs an alternative realization: an adaptive tree walk protocol mechanism [4]. Specifically, nodes in the radio range form a virtual cluster. Initially, all nodes in the cluster are eligible to transmit. When a first collision occurs, only a subset of nodes with certain energy level (favoring weaker nodes) is eligible to transmit. When a second collision occurs, only a subset of the previous subset, which satisfies a more stringent energy level requirement, is eligible to transmit, etc., until the contention is resolved. Again, the weaker nodes have shorter maximum queue lengths.

The report is organized as follows: section II describes related research work, followed by a detailed description of the proposed mechanisms in section III. The performance of the protocols is evaluated in section IV. Finally, section V concludes the paper and lays out future work.

II. RELATED WORK

There are on-going efforts that introduce periodic sleeping behavior into sensor nets to conserve energy. In [6], three sources of energy wastage in the MAC layer have been identified, namely, collision, overhearing and idle listening. The paper describes a scheme that reduces all three by putting nodes to sleep when they are in the idle state. Nodes determine sleep schedules by periodically exchanging SYNC packets to maintain synchronization among neighboring nodes in an attempt to reduce latency. Complete synchronization is difficult to achieve, which may result in increased packet latency. Also, nodes bordering two neighborhoods experience reduced sleep and hence drain energy faster than other nodes in the network. The new IEEE 802.15.4 standard [5] is another example of a sensor MAC protocol that uses periodic sleep in the nodes to conserve energy. This scheme also requires synchronization among nodes to decide on suitable sleep schedules. Contention-free MAC protocols to reduce energy consumption in sensor networks have been discussed in [1]. There, energy-aware schemes that use energy criticality information to compute contention parameters have been proposed, where the criticality of a node is a function of its residual energy and the amount of traffic in its queue. The protocol mechanism favors critical nodes and dynamically allots more TDMA slots to such nodes.

However, protocols requiring channel reservation are not adaptive to network dynamics and may result in inefficient channel utilization.

Our work is orthogonal and complementary to these research efforts. We introduce energy-aware contention mechanisms that can save energy in addition to that saved by periodic sleeping. Our schemes operate in a contention environment much like DCF [3] and MACAW [2], modified along the above mentioned dimensions.

III. PROTOCOL DESCRIPTION

Our two proposed schemes are based on DCF and MACAW with modifications to include energy-aware mechanisms. The basic components common to both energy-aware mechanisms are as follows:

Energy Tables and sleep

In our proposed schemes, nodes exchange energy information by piggybacking their current energy levels in the RTS/CTS packet exchanges. An alternative is to use periodic exchange of special protocol packets, but we consider piggybacking for its low overhead. It is assumed that sensor nodes have access to their current energy level information. All nodes in the neighborhood hear and record energy level information. Each node maintains an energy table that lists neighbor IDs along with their residue energy levels and uses this local energy information to compute the parameters of our scheme, described in the following section.

During every RTS/CTS exchange, nodes' energy tables get updated and each node uses this up-to-date energy information to compute its contention window size. We retain the physical carrier sensing and virtual carrier sensing from DCF [3]. Nodes defer from transmitting when the channel is busy, and resume their back-off at the end of a transmission. Nodes not involved in the current transmission sleep for the duration of the transmission, known from the Network Allocation Vector (NAV [3]) field in RTS/CTS, to conserve energy. Hence the proposed mechanisms adopt sleep behavior only through the virtual carrier sensing process of DCF.

Energy metrics

The MAC layer energy-aware adaptations are based on three metrics:

(1) the relative energy level of the current node defined as:

$$REL = \frac{E_c - E_l}{E_h - E_l}$$

where E_l and E_h are the energy levels of the nodes in the neighborhood that have the lowest and highest residue energy respectively and E_c is the current node's energy level. The higher the node's current energy level as compared to its neighbors, the higher the REL value.

(2) The percentile of nodes with residue energy lower than or equal to the current node given as:

$$PR = \frac{f_b + \frac{1}{2}f_w}{N}$$

where f_b is number of nodes whose energy levels are lower than the current node, f_w is the number of nodes that have the same energy level as the current node, and N is the total number of nodes in the neighborhood. PR indicates the energy ranking of a node among its neighbors.

(3) A composite measure that combines the above two metrics:

$$a = b \text{ REL} + g \text{ PR}$$

where b, g are tunable parameters that satisfy the constraint: $b + g = 1$. All the three parameters a, b and g have a value in the range $[0, 1]$.

The energy metrics REL and PR each measure a different aspect of the current node's energy position among nodes in the neighborhood. The metric a carries the information of both REL and PR and therefore we mainly use a as the measure of residual energy level. The protocol details specific to each energy-aware mechanism are described below.

I. Energy-aware contention window sizing

Exponential back-off is used in traditional wireless MAC protocols to resolve contention, which has no consideration for node energy levels. Repeated unsuccessful retransmissions consume significant amount of energy, which nodes with low energy-levels can least afford. We modify the back-off window sizing on the base of MACAW [2]. In MACAW, contention window size increases by a factor of 1.5 upon collision and decreases by a factor of 0.5 upon a successful transmission. In our modified scheme, the increase factor becomes $1 + a$ and the decrease factor becomes a . Since the average of a is 0.5, an average node will behave the same as MACAW, but lower energy nodes with smaller a (reflecting energy criticality) will have less back off and earlier chance of successful transmission. In other words, the contention scheme is made energy-aware and generally favors lower energy nodes. However, increasing the transmission probability of lower energy nodes causes unfair throughput favoring lower energy nodes. To rectify this situation, we adjust the number of packets allowed to be queued, called maximum queue size (q), according to the following conservation relationship:

$$q_i p_i = q_j p_j$$

where, q_i, q_j and p_i, p_j refer to queue sizes and probabilities of transmission of node i and j , respectively. The intuition behind the conservation equation is that although packets have different transmission probabilities, the aggregate probability of generating traffic is roughly the same across all nodes in the neighborhood.

II. Adaptive limited contention

The aim of adaptive limited contention is to restrict the number of nodes contending for the channel to an optimum value in order to reduce collisions and yet not wasting transmission opportunities. Our energy-aware mechanism favors lower energy nodes by providing them with a higher probability of transmission at the expense of higher energy nodes. Initially, all interfering nodes, which form a virtual cluster, have the same probability of transmission in each slot. When collision occurs, the transmission probability is calculated based on past collision history and the node energy level. Again, lower energy nodes have higher transmission

probabilities. The differentiation of transmission probabilities is again balanced by different queue sizes according to the throughput conservation equation explained in the previous scheme.

If each station transmits during a contention slot with probability p , then P_s , the probability of successful channel acquisition on that slot is [4],

$$P_s = kp(1 - p)^{k-1}$$

where k is the average number of contending nodes. The optimal value of p is $1/k$, which maximizes P_s . Further, if M is the average number of collisions experienced by a node, then M converges to $1/P_s$, hence,

$$\frac{1}{M} = kp(1 - p)^{k-1}$$

In our implementation, a node estimates a value for k according to the above equation, using its transmission probability (p) at the previous round and the number of collisions suffered as M . The equation is solvable using approximate expansion assuming p is small. Energy awareness is introduced by a modulating factor, and the transmission probability for the next round is as follows:

$$p = \frac{1}{k(0.5 + a)}$$

The energy-aware modulating factor is chosen so that an average node ($a = 0.5$) behaves as if no energy-aware mechanism is present. The effect of transmission probability p is that the average number of contending nodes is pN , rather than N , assuming N nodes intend to transmit. Adapting p is equivalent to modulating the population of potential contenders for the channel, thus limiting the degree of contention.

IV. PERFORMANCE EVALUATION

We simulated the performance of our proposed energy-aware mechanisms in comparison to that of DCF. Also, the impact of parameters b and g on the performance was studied. We implemented our protocol mechanisms in *NS2*, by incorporating the energy-aware features in the existing DCF simulation code. A simple five node sensor network scenario was used, in which four nodes generate and send exponentially distributed traffic to a single sink node. Figure 1 depicts the scenario. In this simple configuration, traffic in each node was defined in a manner sufficient to generate collisions among transmitting nodes to evaluate the performance of our energy-adaptive contention schemes.

The performance results were obtained with parameter values chosen for a typical wireless sensor network [6]. Table 1 lists the parameter values used in simulations. In our implementation, a node piggybacks its energy information in each RTS/CTS transmission and as a result the energy consumed for the handshake is slightly greater than that of DCF.

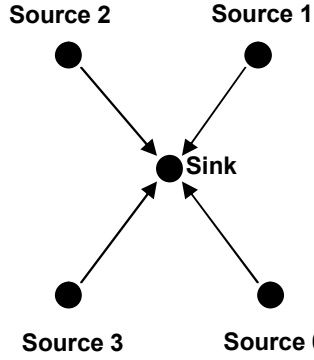


Figure 1. Network topology used in the simulation

Table 1. Simulation parameters

Channel bandwidth	1 Mbps
Average packet size	1000 Bytes
RTS, CTS, ACK size	30 Bytes
Minimum CW size	32 Slots (from DCF)
Maximum CW size	1024 Slots (from DCF)
Reception power	13mW
Transmission power	24.75mW
Idle power	13mW
Sleep power	15 μ W
b, g	Varied

A. Energy Consumption

Figure 2 shows the average energy consumed for DCF [3] and the energy-aware mechanisms (CW implies contention window).

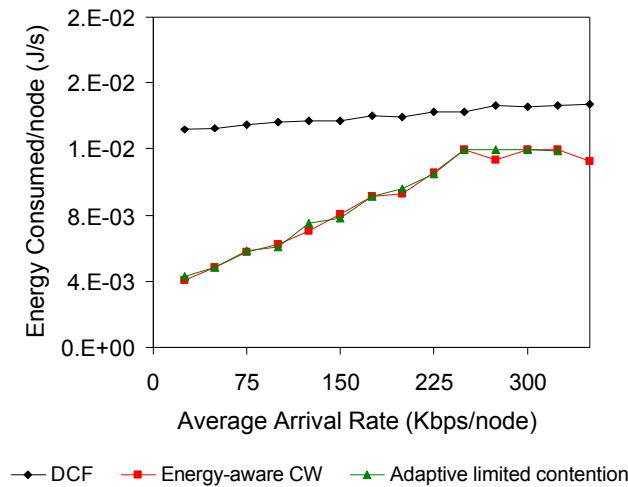


Figure 2. Energy consumption rate for DCF and Energy-aware MACs

The energy behavior of the latter shows significant improvement over DCF and the considerable energy savings is due to, 1) the energy-aware contention schemes allow low energy nodes to transmit with higher probability, thereby reducing the amount of idle listening in low energy nodes during back-off and physical carrier sensing, 2) sleep introduced among inactive nodes that avoids idle listening when the channel is busy serving other nodes.

Figure 3 shows the average energy consumed per byte transmitted at each node. The results were obtained with initial node energy levels for sources 0, 1, 2 and 3 being 50%, 10%, 100%, and 100% of the maximum energy level, respectively. Sink (node 4) was not considered as it did not generate any traffic. From the bar graph we can see that, in the energy-aware window sizing scheme, node 1, which has the least amount of residue energy, has consumed the least amount of energy per byte. The scheme provides similar throughput for low and high energy nodes; but due to the preferential treatment, low energy nodes experience lesser backoff time and reduced

collisions, allowing for considerable energy savings. Adaptive limited contention follows similar pattern, but exhibits higher energy consumption per byte than energy-aware contention window. This is because on a single success the adaptive limited contention resets the contention window size to minimum, which does not retain any memory of network congestion state, thereby resulting in more collisions. In DCF, the energy consumed per byte does not follow preferential pattern for low energy nodes (node 1 has the highest energy consumption), signifying no energy awareness.

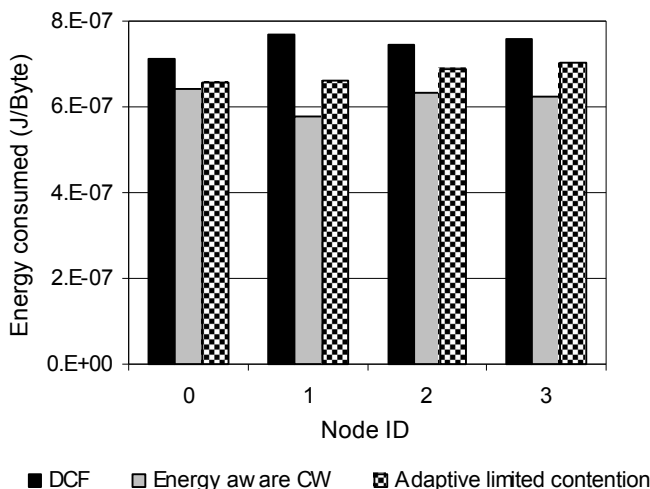


Figure 3. Comparison of Energy consumed per byte for DCF and Energy-aware MAC

B. Throughput and Latency Characteristics

Figures 4 and 5 show the throughput and latency characteristics of our energy-aware contention schemes in comparison to DCF. It can be seen that our schemes offer similar throughput as DCF. The energy-aware window sizing scheme exhibits marginally higher delay per packet, since during high congestion the contention window size stays high (decreases only by a factor of • on success) to reflect the network state thereby increasing the average contention time.

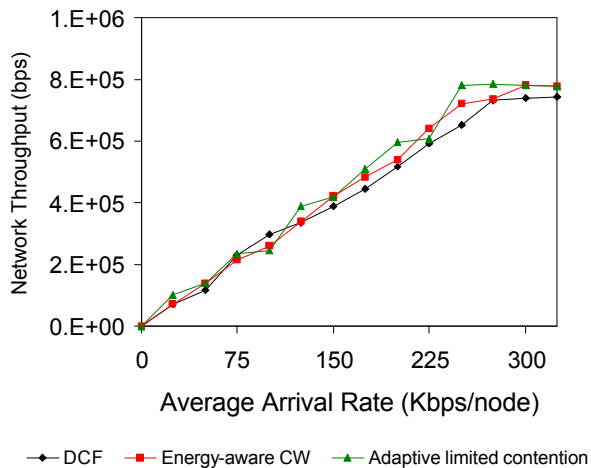


Figure 4. Throughput comparison

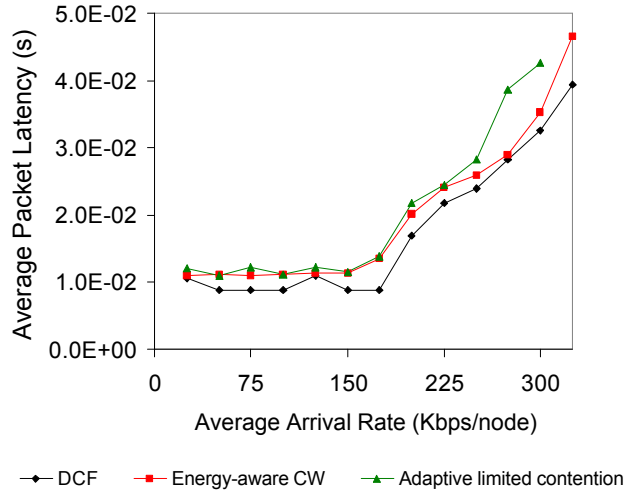


Figure 5. Latency comparison

D. Impact of Energy Factors

Figure 6 shows the performance of the energy adaptive window sizing scheme for different values of energy parameters b and g . The result for the adaptive limited contention scheme is not much different, and thus is omitted here. The REL scaling factor is b and g is the percentile scaling factor. We can infer from the graphs that a larger g results in a higher energy consumption. This is because a small variation in energy level among the neighboring nodes only slightly affects the REL . However, it alters the percentile of the nodes more dramatically. A higher g magnifies this effect and increases the contention window sizes of nodes with higher rankings, thereby increasing the energy spent in contending for the channel.

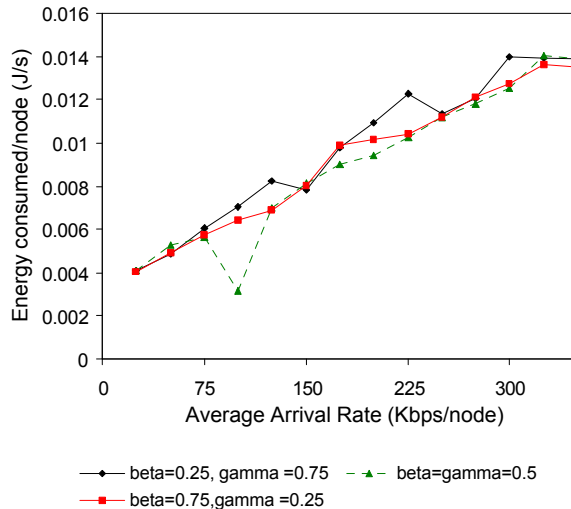


Figure 6. Energy consumption rate for different b and g

The energy consumption rate in the case where b dominates is marginally higher than that in the case where b and g are equal. When the energy differences among neighbors are high, *REL* values respond more dramatically than the percentile values. However, *REL* is susceptible the outlier problem. In our study, we find giving approximately equal weight to the two parameters results in good performance.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we proposed two energy-aware MAC schemes for sensor applications. We compared the performance of the energy-adaptive mechanisms and DCF through simulation. We find the energy-aware schemes result in considerable energy savings with no significant degradation in the throughput and latency behavior.

We plan to follow on by investigating the performance of energy-aware MACs in more complex network scenarios that include multi-hop routing, hidden-nodes and noisy channels (with high packet loss rate), which approach realistic network condition. We also plan to systematically investigate the full range of MAC parameters that can be made energy adaptive.

ACKNOWLEDGMENT

We thank John Mullen, New Mexico State University, for his valuable suggestions to improve the content of the paper.

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