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Distributed Energy Aware MAC Layer Protocol For Wireless Sensor Networks

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Abstract

Due to the fact that sensor nodes are untethered and unattended, energy management is a critical issue in communication mechanism of a wireless sensor network. In this paper, we address this problem and propose a novel solution based on media access control technique. Our protocol DE-MAC exploits the inherent features of TDMA to avoid the main sources of energy wastage: collision and control packet overhead. It uses the concept of periodic listen and sleep in order to avoid idle listening and overhearing. However, unlike existing MAC-layer protocols, DE-MAC treats the critical nodes differently in a distributed manner. Motivated by the fact that a weaker node should be used less frequently in a routing in order to accomplish load balancing, DE-MAC performs a local election procedure and chooses the worst-off node/nodes as the winner/winners and makes them sleep more than the other neighboring nodes. Since the election procedure is fully integrated with the TDMA slot assignment, our protocol suffers no extra throughput loss. We evaluate DE-MAC and present the simulation results which explicitly show the gain in performance.

Keywords: Sensor networks, MAC protocols, Energy Conservation, Distributed Algorithms.

1 Introduction

Energy management is a challenging problem in designing communication protocols in a wireless sensor network. Studies reveal that energy wastage occurs mainly from *collision* (two interfering nodes transmit at the same time), *overhearing* (a node receives a packet not destined to it), *control packet overhead* and *idle listening* (the radio of a node is active even when there is nothing to transmit or receive). These problems are present in all shared-medium networks and are generally taken care of by media access control (MAC) techniques. The main goal of a MAC layer protocol is to allocate the shared wireless channels among sensor nodes as fairly as possible and to guarantee that no two interfering nodes transmit at the same time. Because of its potential for avoiding unnecessary energy wastage, media access control in wireless sensor networks has become a broad research area.

Current MAC design for wireless sensor networks can be classified into two categories: contention-based protocols and TDMA protocols. Among the contention-based protocols, the important ones are:

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IEEE 802.11 [1], PAMAS [2] and S-MAC [3]. IEEE 802.11, although widely used because of its simplicity and robustness against the hidden terminal problem, is not an energy-efficient protocol since it does not address the issue of avoiding overhearing and idle listening. PAMAS tries to avoid overhearing. S-MAC, an improvement over PAMAS, reduces further wastage from idle listening by making idle nodes shut off their radios. However, the duration of sleep is the same for each node, which is unfair for the nodes with less energy. Making weaker nodes sleep more can increase efficiency. TDMA protocols have the natural advantage of having no collision or control-packet overhead from which the contention-based MAC protocols all suffer. However, TDMA protocols do not have scalability as good as contention-based protocols. An example of TDMA protocol in wireless networks is the one proposed by Sohrabi and Pottie [4], where each node schedules different time slots to communicate with its known neighbors. The protocol uses FDMA or CDMA to avoid interference between adjacent links. The drawback of this protocol is low bandwidth utilization since a node can talk to only one neighbor at a time slot. Another protocol proposed by Woo and Culler [5] uses an adaptive rate control mechanism based on carrier sense multiple access (CSMA). This protocol tries to achieve a fair bandwidth allocation to all nodes rather than saving energy at each node in a multi-hop network. Designed for low-power ad hoc wireless networks, piconet [7] is another protocol, which like S-MAC, puts nodes into periodic sleep for energy conservation. For synchronization, piconet makes a node broadcast its address before it starts listening. The drawback of this scheme is that if a node wants to talk to its neighbor, it has to wait until it gets the neighbor's address.

In this paper, we propose a TDMA based energy-efficient MAC protocol with good performance characteristics. We name it DE-MAC, since it is a distributed energy-aware protocol. Unlike several existing protcols which treat all nodes equally with respect to energy conservation, our protocol is based on the crucial observation that over a period of time, there are several critical sensor nodes in the network, which must be treated differently (preferentially, in most cases) with respect to energy consumption. The criticality of a sensor node could be based purely on local state information, such as relative energy levels within the neighborhood group of sensors. Alternately, criticality is a function of a sensors location within dynamically changing query routing trees.[2] The proposed MAC layer protocol is an improvement over [6] which uses a TDMA protocol with sensors sleeping when they have nothing to transmit. Our protocol initially assigns the same number of transmission slots to each node in a TDMA frame. Periodically, sensor nodes conduct a local election based on energy of neighboring nodes, which are part of a TDMA group. The local election process is fully integrated with (i.e, part of) the regular TDMA communication schedule. Thus there is no extra throughput loss due to a separate local election phase. A sensor node i can independently decide to initiate an election if its current energy level E_i falls below a threshold value t_r E_w of the *previous winner's then-energy level* E_w. Once an election is initiated, each node transmits special `energy-level' messages which are appended to its regularly scheduled transmission packet during its scheduled time slot. A property of our protocol is that all nodes listen to all transmitted packets i.e., there are no sleeping nodes when other nodes are transmitting. The motivation behind this constraint is to enable the integration of leader-election with regular TDMA communication and thereby save bandwidth/overhead. Since we enforce reception/listening by all nodes of all transmitted packets, there is no ambiguity about when an election is initiated. This approach is different from several standard MAC algorithms where a sensor nodes duty cycle consists of sleep and active periods and nodes can be sleeping while other nodes are active. Finally, the node with least energy in the group declares itself as the leader at the end of the election process. Also note that the entire election phase takes one (asynchronous) TDMA frame starting from the slot when the election is initiated. Once a leader is (or k-leaders are) elected at the end of this process, all the losers reduce their number of slots by a constant factor (we choose two as the constant in our simulations) and the winners have slots twice that of the losers. The advantage behind this reallocation of slots is to reduce the idle listening time of critical nodes (those with lower energy) nodes. Thus nodes can power off/sleep when they they have nothing to transmit during their own slots. Since leaders have more allocated slots, their energy loss due to idle listening is less. Finally, note that the current leader also transmits its energy level once an election is initiated even though it may be a sleeping slot. This is to avoid election of an incorrect leader, which will lead to another unnecessary round of leader election.

The rest of the paper is organized as follows. In section 2, we describe the protocol in details including the data structures that are stored in each node. Section 3 contains the simulation results and their explanation. Section 4 is the conclusion.

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[2] Note that in this case, nodes cannot self identify themselves as critical in a purely distributed scheme.

2 DE-MAC Protocol

DE-MAC, the distributed energy aware MAC protocol is based on TDMA and hence possesses the natural ability of avoiding extra energy wastage. The main advantages of a TDMA-protocol present in DE-MAC are the following.

- Packet loss due to collisions is absent because two nodes do not transmit in the same slot. Although packet loss may occur due to other reasons like interference, loss of signal strength etc.
- No contention mechanism is required for a node to start sensing its packets since the slots are pre-assigned to each node. No extra control overhead packets for contention are required.

DE-MAC uses the concept of periodic listen and sleep. A sensor node switches off its radio and goes into a sleep mode only when it is in its own time slot and does not have anything to transmit. It has to keep the radio awake in the slots assigned to its neighbors in order to receive packets from them even if the node with current slot has nothing to transmit. We describe the protocol in details in the next two subsections.

2.1 Protocol Packets and Data Structures at Each Node

The protocol has two types of packets, data packets and control packets.

- Data packets: These are normal data packets received from higher layer protocols, which are routed to the base station.
- Control packets: The control packet contains two fields. The first field specifies the type of the packet and the second field specifies the value attributed to the type of the packet.
  There are two types of control packets.
  a) Vote packet: This contains the decision of a node, which can be either positive vote or a negative vote. This packet is sent to nodes, which sent their energy values to this node.
  b) Radio-power-mode packet: This packet contains the radio-power-mode of the sender, to indicate whether the sender is using one slot or two slots for transmitting its data packets.

Initially each sensor node is assigned two TDMA slots on which it can transmit packets. It also has a receiver table, a two-tuple <source, slot>, which tells the sensor when to turn on its receiver to listen for a packet coming from its neighbors. It also has extra state variable Radio-power-mode, which tells the MAC to use two slots for transmission if it is set. It also maintains a local state variable Radio-mode[i] for each of its neighbor indicating the Radio-power-mode of the neighbor i. This information about the neighbor is used to set its receiver to listen for packets from its neighbors.

2.2 Protocol Description

Initially each node is assigned two TDMA slots for transmission. The way these slots are assigned is not in the scope of our paper. Each node knows which slots its neighbors will use to transmit packets. The main idea of the paper is to let the nodes exchange information about their energy levels. Based on that energy level information, each node decides to use one or two of the slots for transmission. Initially the Radio-power-mode of all nodes is set to TRUE to allow nodes to transmit in two slots.

Each sensor node can be in any of the two phases.

- Normal operation phase: The nodes operate normally, routing data packets to the base-station.
- Voting phase: Critical nodes enter the voting phase to do a local election to readjust their slots.

A node in the voting phase is integrated with the normal TDMA phase. So, control packets are sent along with normal data packets in the voting phase.

The local voting phase is triggered by criticality of a node. A node is said to be critical if it falls below the previous election winner's energy value. When a node enters this critical phase a local voting phase is triggered. A node in the voting phase is a winner if all its neighboring nodes' energy levels are greater than its own energy level. Otherwise it is declared as a loser.

The sequence of steps followed by a sensor node i in the voting phase is the following.

- The node i sends its current energy value to all of its neighbors.
- The node i collects all the votes from its neighbors. If it receives positive votes from all of its neighbors then it sets Radio-power-mode to TRUE and becomes the winner. Otherwise it sets Radio-power-mode to FALSE and declares itself a loser.
- The sender node i sends its Radio-power-mode and its current energy level to all of its neighbors.

The sequence of steps followed by a receiver node j in the voting phase is the following.

- The receiver node j checks whether the received energy value is less than its own energy value.
- If received energy value is smaller than its own energy value, it sends a positive vote to the sender. Otherwise it sends a negative vote.
- If Radio-power-mode received from node i is set to TRUE then Radio-mode[i] is set to TRUE. Also, Radio-power-mode is set to TRUE at receiver node j.
- If the value of Radio-power-mode is changed at the receiver j then its value is sent to all of its neighbors.

Multiple nodes can initiate the voting phase at the same time. If more than one neighboring nodes initiate the voting phase at the same time, then the node/nodes with the minimum energy level becomes/become the winner.

In normal operation mode, the activity of each node in a time slot is the following:

- If it owns the current slot then it sends its data in that slot. If it has nothing to transmit the radio is put to sleep.
- If it does not own the current slot, it checks by looking at its local state information whether any of the neighbors is transmitting in the current slot.
- If the current slot is being used the radio is put to receive mode. If current slot is not being used the radio is put to sleep.

A low energy node sleeps more than higher energy nodes, thus balancing the energy among the nodes and thus increasing the energy savings and thereby increasing the lifetime of the network. The performance of the TDMA protocol and the performance comparison with and without the Radio-power-mode is presented in the next section.

3 Simulation Environment and Results

Our simulation environment contains a group of 100 nodes distributed in an ad-hoc fashion over an area of 1000×1000-meter square area. Initially all nodes are assumed to have energy 36Asec. We have targets moving in the region at a constant speed of 10 m/s between two points repeatedly every 10 seconds. We used **sensorsim**, an extension of **ns-2** for implementing our simulation, which we ran for 1000 seconds. Our energy consumption models for battery, radio and cpu are taken from [6] which considered a simple linear energy model. The energy at each node is logged every 100 seconds. We use predetermined routes for sending our packets to the base-station in the entire simulation time.

We ran the simulation model with and without the voting mode. The simple TDMA mechanism in [6], gained high-energy savings over contention-based mechanisms. We tested our voting method which is incorporated into general TDMA technique. We have represented our results in two graphs. In the first figure, we have plotted maximum energy difference against time under the two methods. In the second figure, we have plotted average energy difference against time under the two methods.

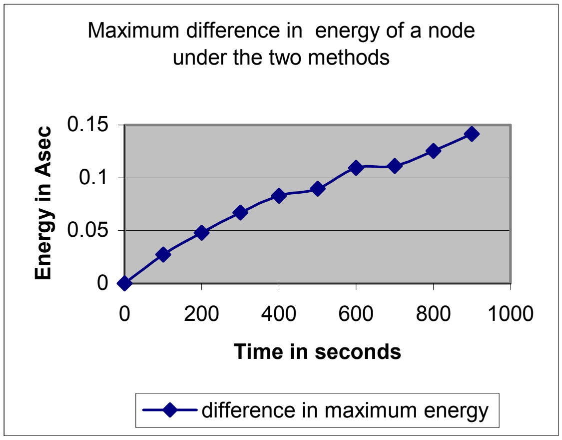

Figure 1

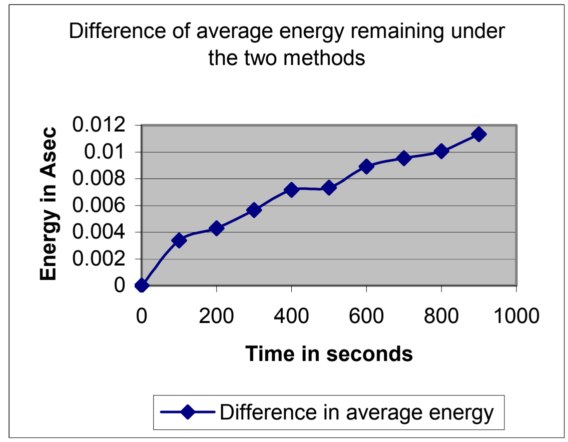

Figure 2

Figure 1 shows the maximum energy gain of the voting scheme over the scheme without voting over time. Figure 2 shows the gain in average energy by the voting scheme over time. It is clear from figures 1 and 2 that the voting scheme achieves a significant amount of energy savings over time compared to a non-voting scheme.

4 Conclusion

In our paper we proposed a novel approach for energy management at the MAC layer in a wireless sensor network. The protocol uses TDMA technique together with periodic listen and sleep to avoid major sources of energy wastage. However, the key feature of our protocol is the leader election method by which the minimum energy node is chosen to evade idle listening. Our simulation results show that DE-MAC achieves a significant gain in energy savings compared to other existing MAC layer protocols.

5 References

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