Energy and Rate based MAC Protocol for Wireless Sensor Networks

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***Abstract*— Sensor networks are typically unattended because of their deployment in hazardous, hostile or remote environments. This makes the problem of conserving energy at individual sensor nodes challenging. S-MAC and PAMAS are two MAC protocols which periodically put nodes (selected at random) to sleep in order to achieve energy savings. Unlike these protocols, we propose an approach in which node duty cycles (i.e sleep and wake schedules) are based on their criticality. A distributed algorithm is used to find sets of winners and losers, who are then assigned appropriate slots in our TDMA based MAC protocol. We introduce the concept of of** *energy-criticality* **of a sensor node as a function of energies and traffic rates. Our protocol makes more critical nodes sleep longer, thereby balancing the energy consumption. Simulation results show that the performance of the protocol with increase in traffic load is better than existing protocols, thereby illustrating the energy balancing nature of the approach.**

Keywords: Wireless Sensor Networks, Energy-Efficiency, MAC protocols, TDMA.

I. INTRODUCTION

Wireless sensor networks (WSN) have become increasing popular due to their wide range of applications in both military and civilian environments, ranging from battlefield surveillance to natural habitat monitoring. A typical WSN consists of a large number of autonomous sensor nodes that self-organize to form a multi-hop network [1]. Sensor nodes are battery operated, equipped with integrated sensors, and have embedded processing and short-range radio communication ability. Unlike standard wireless/ad-hoc networks, WSNs are severely resource constrained and energy conservation/efficiency is of paramount importance. The wireless radio-communication interface consumes a significant fraction of node energy. While substantial research has been done on the design of low-power electronics to reduce energy consumption at sensor nodes, due to fundamental hardware limitations further energy efficiency can only be achieved through the design of energy-aware communication protocols.

In this work we focus on the design of energy-efficient link layer protocols for sensor networks. Traditional MAC protocols focus on improving fairness, latency, bandwidth utilization and throughput (which are secondary for WSNs) and lack energy conserving mechanisms. Studies reveal that energy wastage in existing MAC protocols occurs mainly from collision, overhearing, control packet overhead and idle listening [4]. MAC protocols for sensor networks should try to avoid the above energy wastage while allocating shared wireless channels among sensor nodes as fairly as possible and prevent nodes from transmitting at the same time.

We present a MAC protocol specifically designed for wireless sensor networks. Our TDMA-based approach achieves significant energy savings by eliminating collisions, reducing idle listening and control packet overhead. Our protocol uses the periodic listen and sleep mechanism introduced in S-MAC [4]. Our paper introduces a new notion: *energy-criticality of a node* which is a measure of the lifetime of the node. In our approach the entire network is divided into TDMA groups based on neighborhood information. We define the energy-criticality (henceforth called criticality) of a node as a function of the residual energies and traffic flow rates of

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its neighbors. We identify two parameters that define the criticality of a sensor node.

- The residual energy level of the sensor node.
- The packet flow rate through the node.

At certain times, a node may be more actively transmitting packets than the rest of the nodes. In such a case this node is assigned more number of slots to transmit its data packets. A node with lower energy level is also critical. Even if this node is not active it is assigned more transmission slots than its neighbors. During these slots, the node will be idle thereby reducing its energy costs due to listening. In our algorithm a set of leaders are elected based on their criticalities. Non-critical nodes are assigned fewer transmission slots. Since they are listening more frequently, future traffic will be predominantly routed through them, thereby balancing energy consumption across the link layer. Our adaptive slot assignment allows the energy management strategy to vary as the traffic and residual energy levels change.

Previous research on sensor networks ([4], [3], [8], [7]) does not consider the fact that critical nodes may deplete their energy faster then the remaining nodes. This may lead to the formation of holes in the network or even disconnect it, thereby reducing network lifetime substantially. Existing work, to the best of our knowledge, treats all nodes equally and tries to minimize energy consumption at a single given node which will not necessarily extend the lifetime of the entire network. In the dynamic environment of wireless sensor networks, none of the previous schemes are optimal in terms of energy efficiency all the time.

Balancing energy consumption among nodes is the key solution to extending network lifetime. A centralized approach, though optimal will not be feasible in a distributed sensor network. A distributed mechanism which uses partial local information to achieve global benefit is the best approach to overall energy balancing. Under heavy and moderate traffic load existing MAC protocols designed for wireless sensor networks have negative effect on energy savings. This is due to the extra synchronization overhead and periodic exchange of sleeping schedules. An algorithm which balances the energy consumption among all the nodes is suitable for higher traffic loads.

This paper is organized as follows: In section 2 we describe some related work. Sections 3 and 4 describe the protocol scheme. In section 5 we describe the simulation results. We have tested the performance of our protocol using the ns-2 simulator. Our simulation results show the improved gains in energy savings using our protocol.

II. RELATED WORK

Current MAC design for wireless sensor networks can be broadly classified into two categories: contention-based protocols and TDMA protocols. IEEE 802.11 [2], 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 [3] tries to avoid overhearing but does not avoid collisions, which is a significant wastage of energy. Collisions can occur between probe messages or RTS/CTS messages. S-MAC [4], an improvement over PAMAS, reduces further wastage from idle listening by making idle nodes shut off their radios. It does not avoid collisions between two RTS or CTS messages, which is a significant wastage of energy. Also, 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. S-MAC assigns sleep schedules without taking into account the criticality of a node. This also has the same problem as PAMAS: two nodes simultaneously sending RTS packets can cause collisions. Another protocol proposed by Woo and Culler [6] 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. Similar to S-MAC, Piconet [8] is another protocol which puts nodes into periodic sleep mode 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.

TDMA protocols have the natural advantage of having no collision or control-packet overhead from which the contention-based MAC protocols suffer. However, TDMA protocols are not as scalable as contention-based protocols. An example of TDMA protocol in wireless networks is the one proposed by Sohrabi and Pottie [5], 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 during a time slot and collisions can occur when two neighboring nodes transmitting in the same slot are assigned the same frequency or code.

III. PROPOSED MAC PROTOCOL: BASIC SCHEME

In this paper, we propose a TDMA based energy-efficient MAC protocol with good performance characteristics. 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 and traffic flows within the neighborhood group of sensors. Alternately, criticality is a function of a sensors location within dynamically changing query routing trees. The proposed MAC layer protocol is an improvement over [7] 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.

A. *Sensor Node Criticality*

Certain nodes may have more active participation in the sensing events or may be part of many routes in the event propagation trees. Hence, some nodes will deplete their energies faster then other nodes. Let E_i be the residual energy level of a sensor node. We label the flow rate of node as F_i which is obtained by counting the number of packets originating at the sensor node and routed through the node periodically. We define the criticality C_i of a node to be

$$C_i = \frac{E_i}{max\{E_j\}} + \frac{F_i}{max\{F_j\}} \tag{1}$$

for all sensor nodes j in the TDMA-group(s) containing i. We assume that sensor nodes in a TDMA-group exchange their energy levels and flow rates periodically or whenver a new leader election phase is triggered.

B. *Leader Election*

Sensor nodes conduct a local election based on the criticalities 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.

IV. ER-MAC PROTOCOL

ER-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 ER-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.

ER-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.

A. *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 normal 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.

B. *Protocol Description*

Initially each node is assigned two TDMA slots for transmission. The algorithm for assigning these slots is not within the scope of this paper. Each node knows the transmission slots of its neighbors. Nodes periodically exchange information about their energy levels and criticality and determine whther to use one or two 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 following two phases.

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

The voting phase is triggered by criticality of a node. A node becomes critical if its energy falls below a threshold factor of the previous winner's (then) energy value. The critical node then triggers a local voting phase. A node in the voting phase is a winner if criticality values of all its neighbors are greater than its own. Otherwise it declares itself a loser. The voting phase is integrated with the normal TDMA phase and control packets are sent along with normal data packets when necessary.

The sequence of steps followed by sensor node i triggering the voting phase are as follows:

- Node i broadcasts its current energy and flow rate to all its neighbors.
- At the end of one TDMA cycle, node i calculates criticality values of all nodes based on obtained energy and traffic information.
- If $C_i < C_j$ for all j, where j is the set of neighbors of i, 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.
- At the end of the voting phase node i sends its current value of Radio-Power-Mode to all its neighbors.

The sequence of steps followed by each receiver node j in the voting phase are as follows:

- Node j broadcasts its current energy and flow rates during its transmission slot.
- If the Radio-power-mode value received from i is TRUE then it adjusts its TDMA frame to accomadate slots for i.

Note that multiple nodes can become critical and initiate the voting phase at the same time, i.e., during the same TDMA cycle. At the end of one TDMA cycle, starting from the slot of the *first* node initiating the voting phase (node i), all critical nodes have complete neighbor energy and flow information and can determine the winner. To save slots, node i declares the identity of the winner during its transmission slot.

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 any available data. If it has nothing to transmit, the radio is put to sleep.
- If it does not own the current slot, it checks its slot table to see whether this is the second slot of the current winner. If so, the slot is idle and it puts its listening radio to sleep.

A critical (low energy/high rate) node sleeps longer, thus balancing energy consumption among the nodes and 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.

V. SIMULATION SETUP

ER-MAC was tested using the ns-2 simulator. In our experimental simulation we had 100 nodes distributed in a 1000X1000 meter area grid. We used the battery energy models for CPU, radio and sensor agent from [7]. In our simulation we have target nodes moving in the field, which transmit signals, and sensor nodes sense these signals. These signals are sent to the sensor application which sends the packets to be routed the user node. We run our simulation for a period of 1000 seconds. The targets move in the field between two points at constant speed of 10m/s repeatedly. We test our protocol with varying number targets moving across the grid. We change the packet traffic density by varying the number of targets moving across the region, which trigger more number of sensors to participate in the detection. We also, study the impact of increase in the radio range of networks to the lifetime of the network. We test the above setup with two radio ranges for each of the sensor node. Higher radio range will decrease the overall number of packet transmissions. But the high power consumption for longer transmissions might in effect cause more energy to be wasted. The purpose of our simulation is to test the energy savings at the nodes using our protocol. We compare our protocol with the basic TDMA protocol in [7] which uses a single slot for transmission for each of its node. We choose to use the following metrics for our simulation.

- Average energy remaining at the nodes with time.
- The minimum energy node in the network with time.
- Maximum gain in the energy at a node with time. The gain in the energy is difference in the energy remaining at the nodes under the two schemes. i.e. with and without energy balancing.
- The number of slots the radio is in sleep mode.

A. *Effect of Traffic Density*

We test our protocol under varying traffic densities. The number of targets moving in the region is slowly increased so that more sensor nodes will participate in target detection. Each of the targets starts at different points in the grid and move repeatedly across two points at the speed of 10m/s. The performance of our protocol is tested using the metrics mentioned above. We perform the test suite with single target, two targets and three targets moving in the region. Our simulation tests the performance of our MAC protocol under various traffic loads.

Figure 1 shows the performance of our protocol compared to the basic TDMA in [7]. We get a significant improvement in the energy savings, which is due to the balancing of the nodes in the energy consumption. Our protocol gives a higher gain in energy with slightly increasing the traffic load. In light traffic and lightly heavier traffic our protocol gives a significant savings in the energy. As traffic load increases the some of the nodes get depleted faster. Then our protocol saves energy at these nodes by reducing their idle listening time to half. This is the reason why our protocol is more effective in higher traffic loads. Other existing protocols,

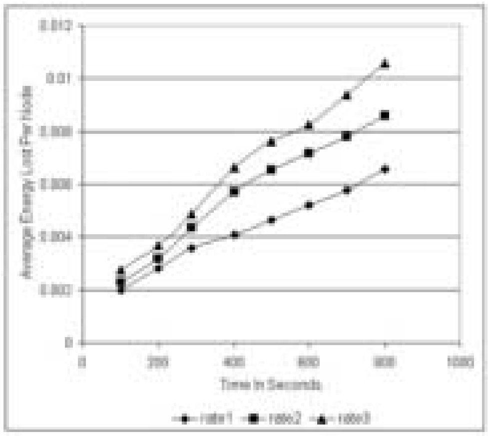

Fig. 1. Difference in Average Energy of a Node Under ER-MAC versus Basic TDMA.

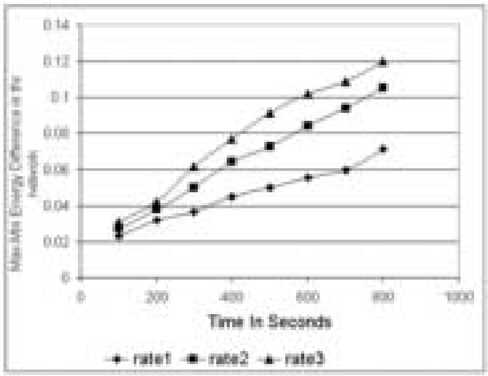

Fig. 2. Difference in Ranges of Energy of the Network Under ER-MAC versus Basic TDMA.

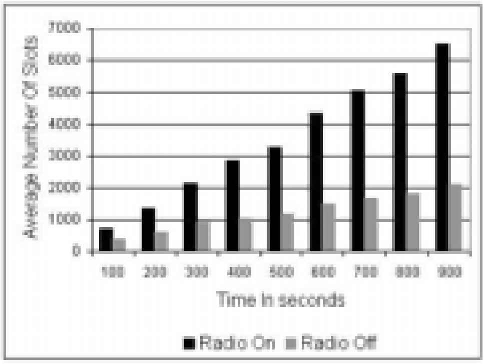

Fig. 3. Average Number of Slots a Node is Awake and is Asleep .

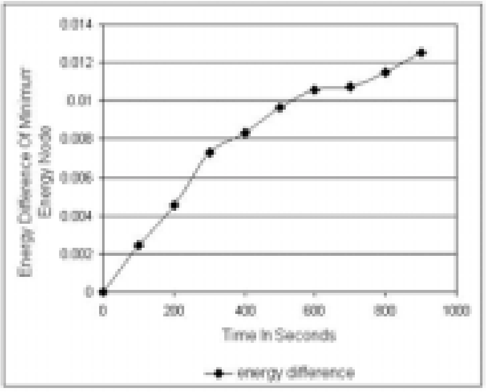

Fig. 4. Difference in Energy of Minimum Energy Node under ER-MAC versus Basic TDMA.

which do not balance the energy consumption among the sensor nodes, have fewer saving in energy at higher traffic loads. Even in extremely heavy traffic our protocol does some energy savings by dividing the energy load among all the possible nodes. Our leader election phase and the slot assignment is integrated with normal TDMA packet transmission. Because of this integration our protocol does not require extra synchronization and extra control packets. This makes the protocol more beneficial in higher traffic densities.

B. Energy Savings

Figure 2 shows the energy difference in the minimum energy nodes under the two methods (with and without energy balancing). The difference between the minimum energy nodes is always increasing. This shows that our approach maximizes the lifetime of the network by both maximizing the lifetime of a single sensor node as well as the entire network. This is due to the inherent energy balancing nature of the approach. Figure 3 shows the average number of slots a senor node's radio is in power and the number of slots it is switched off. The TDMA frame has some unused slots in which neither any node nor any of its neighbors is transmitting. In this idle slots the sensor node;s radio is also put to sleep. Figure 3 does not include these idle slots in calculating the number of slots radio is put to sleep. Figure 3 shows that our protocol puts the nodes to sleep 25 percent of the time; this is without even counting the idle slots. With the inclusion of idle slots the gain in energy is even higher, which comes natural with TDMA protocols.

Figure 4 shows that our protocol has higher minimum energy node in the network than the basic scheme without energy balancing.

VI. CONCLUSIONS

We have proposed a novel approach for energy management at the MAC layer in a wireless sensor network. The protocol uses TDMA along with periodic listen and sleep to avoid energy wastage. The key feature of our protocol is the leader election method by which the most critical node is chosen to evade idle listening. Our simulation results show that ER-MAC achieves a significant gain in energy savings compared to other existing MAC layer protocols.

REFERENCES

[1] I.F. Akyldiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, Vol. 38, No. 4, pp. 393-422, March 2002.

[2] LAN MAN Standards Committee of the IEEE Computer Society, Wireless LAN medium access control (MAC) and physical layer (PHY) specification, IEEE, New York, USA, IEEE Std 802.11 - 1997 edition, 1997.

[3] S.Singh and C.S.Raghavendra, "PAMAS: Power Aware Multi-access Protocol With Signaling for Ad Hoc Networks," ACM Computer Communication Review, vol.28, no.3, pp.5-26, July 1998.

[4] Wei Ye, John Heidemann and Deborah Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," Proc. of 12th IEEE International Conference on Computer Networks, INFOCOM 2002, New York, NY, USA, June 2002.

[5] Katayoun Sohrabi and Gregory J. Pottie, "Performance of a Novel Self-organization Protocol for Wireless Ad Hoc Sensor Networks", Proc. of the IEEE 50th Vehicular Technology Conference, pp.1222-1226, 1999.

[6] Alec Woo and David Culler, "A Transmission Control Scheme for Media Access in Sensor Networks," Proc. of the ACM/IEEE International Conference on Mobile Computing and Networking, Rome, Italy, July 2001.

[7] S. Park, A. Savvides and M. B. Srivastava, "SensorSim: A Simulation Framework for Sensor Networks," Proc, of MSWiM 2000, Boston, MA, August 11, 2000.

[8] Frazer Bennett, David Clarke, Joseph B. Evans, Andy Hopper, Alan Jones, and David Leask, "Piconet embedded mobile networking", IEEE Personal Communications, 4(5):8-15, October 1997.

[9] T. S. Rappaport, "Wireless Communications", Prentice-Hall, 1996.

[10] R. Steele, "Mobile Radio Communications", Pentech Press, London, 1992.