An Energy Efficient Cross-Layer MAC Protocol for Wireless Sensor Networks*

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Abstract. In the area of wireless sensor networks, achieving minimum energy consumption is a very important research issue. A number of energy efficient protocols have been proposed, mostly based on a layered design approach, which means that they are focused on designing optimal strategies for “single” layer only. In this paper, we take an alternative approach i.e., a cross-layer design, and present a new MAC protocol named MAC-CROSS. In this new approach, the interactions between MAC and Routing layers are fully exploited to achieve energy efficiency for wireless sensor networks. More precisely, in the proposed MAC-CROSS algorithm, routing information at the network layer is utilized for the MAC layer such that it can maximize a sleep duration of each node. Through implementation on a Mica Mote platform and simulation study using the NS-2, we evaluate a performance of the presented MAC-CROSS and prove its substantial performance gains.

1 Introduction

A wireless sensor network consists of a number of smart sensors equipped with limited battery power and inexpensive short-range radio communication. Due to their energy critical characteristics and high probability of failures, wireless sensor networks require a design of the efficient MAC protocol. Especially, it is a primary goal for any proposed sensor MAC protocol to minimize energy consumption because a power drain of each sensor node may cease all the necessary functions of the sensor network.

There has been recent attention on developing energy efficient MAC protocols in wireless sensor networks [1]. They are generally based on a mechanism of turning off their radio transceivers whenever they are not involved in communication. Also, they are mainly focused on how to optimize the MAC layer's energy efficiency without fully exploiting the potential synergies of the interaction among different layers. In this paper, we instead follow a cross-layer design approach and propose a new MAC protocol that utilizes a routing policy information from the network layer - hence, we call the proposed MAC protocol as

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"MAC-CROSS". By doing so, we believe that the overall performance gain in terms of energy efficiency can be maximized.

The basic idea of the proposed MAC-CROSS is to minimize the number of nodes that are supposed to wake up when their NAV (Network Allocation Vector) value expires. Remind that, by using NAV information of RTS/CTS packets sent by a data source and a destination, a shared wireless medium can be reserved during the time for exchanging their data packets. Other nodes except for these two communicating nodes are supposed to enter a sleep mode, which is good for saving their energy sources. Now, the problem comes from the fact that all these sleeping nodes must be awake when their NAV timers expire, regardless of whether they are willing to participate in the next packet transmission or not. Such a mandatory and compulsory wake-up strategy may cause some negative effect on the energy perspective, especially for those nodes which are not supposed to be involved in the upcoming transmission phase and therefore will come back to their sleep mode again. In order to solve this problem, our scheme makes only a subset of nodes perform such a mandatory wake-up. The subset of nodes here are the ones, not only whose NAV value becomes expired but also whose current location is along a routing path from a source to a final destination. All other nodes which do not belong to the routing path can stay in their sleep mode until the beginning of the next duty cycle. To decide which node is on the routing path, the proposed scheme utilizes the routing information through a cross-layer design approach. For evaluating analyze the performance, we have implemented the MAC-CROSS over the Mica Mote [15] platform and also the well-known network simulator NS-2 [13]. The results of both tests demonstrate that our scheme is consistently superior more than the adaptive S-MAC protocol [3] in terms of energy efficiency.

2 Related Works

One of the famous energy efficient protocols for wireless sensor network is S-MAC [2, 3]. It is a contention-based random access protocol with a fixed listen/sleep cycle and uses a coordinated sleeping mechanism. A time frame in S-MAC is divided into two parts: one for a listen period and the other for a sleep period. During the listen period, SYNC and RTS/CTS control packets are transmitted based on the CSMA/CA mechanism for the purpose of a synchronization and an announcement for the following data packet transmission. Any two nodes exchanging RTS/CTS packets in the listen period need to keep in an active state and start an actual data transmission without entering a sleep mode. Otherwise, all other nodes can enter the sleep mode in order to avoid any wasteful idle listening and overhearing problems. [1] The basic operation of S-MAC protocol is illustrated in Fig. 1-(a), where the two nodes A and B are keeping awake to

[1] There are four main cases of energy waste: Collision, Control packet overhead, Idle listening and Overhearing. Idle listening is defined as continuously staying in the receive mode even if there is no data traffic, whereas overhearing is defined as receiving a packet that are not destined for the node. For further details, refer to [2].

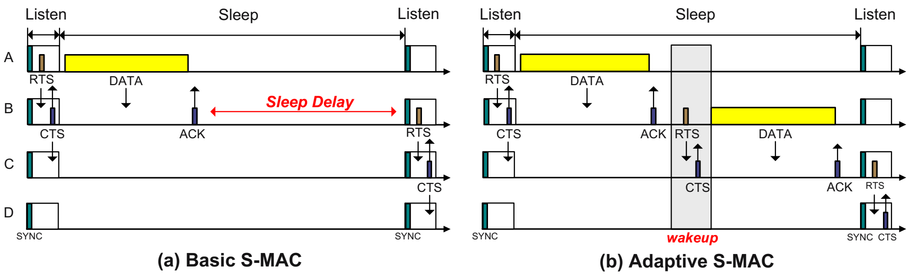

Fig. 1. Operation of basic and adaptive S-MAC [2, 3]

exchange their DATA and ACK packets. Note that in S-MAC, the duration of a listen period is always fixed and therefore causes unnecessary energy waste. For solving this problem, another protocol named T-MAC has been proposed [4]. It can be thought as a variation of S-MAC in that it is yet based on a periodic active/inactive mechanism, but with an adaptive length of active state by fine time out, called TA.

In general, periodic listen/sleep-based schemes have some trade-offs between the energy saving and the latency. To reduce a long end-to-end delay, [3] suggests the adaptive listening scheme in which a node receiving NAV information of RTS or CTS packets will wake up when its NAV timer expires and then try to communicate with its neighbors without waiting for the next listen/sleep cycle. Fig. 1-(b) shows the operation of the adaptive S-MAC [3]. It also has the timeout policy like T-MAC, therefore adaptive S-MAC can be said to have both properties of basic S-MAC [2] and T-MAC [4]. The adaptive S-MAC can provide a solution for the latency problem but produce some disadvantage in the energy saving perspective a unnecessary energy consumption because even nodes that do not participate in communication should wake up when their NAV timers expire. We call this problem as “compulsory wake-up problem.”

A number of papers have discussed about a cross layer design among different layers to improve the performance of wireless ad hoc networks [5]. It is an active research field wireless sensor networks as well. For instance, [6] suggests the two routing algorithms based on the success/failure of CTS or ACK packet. [7] proposes a variable length TDMA scheme where the slot length is assigned according to traffic information and distance between each node pair. [8] suggests a clustered network architecture where the nodes that have the same hop count to the sink is grouped. [9] proposes a new scheduling algorithm that is fully distributed and works through the cooperation with routing and MAC protocols. Overall, these previous works have focused on searching for the new routing metric or establishing more efficient sleep schedules. However, our proposed scheme focuses more on the cross layer solution of compulsory wake-up problem.

For example, in Fig. 2, we assume that a routing path (A, B and C) is already established, and nodes (D-K) that do not participate in communication are outside of the routing path. First, A sends data to B by four handshake communication, and then other nodes enter to sleep during NAV time. After NAV timer expires, B tries to transmit data to C along the routing path. However, other nodes (D-K) also wake up and causes compulsory wake-up problem. If MAC protocol knows the routing path information from its routing agent, only node C which is the next hop for data delivery can be woken up. To support that, our proposed scheme is designed with cross layer concept for getting routing information. Our scheme can cooperate with any routing protocols such as Diffusion [10] or GPSR [11].

3 The Proposed Scheme: MAC-CROSS

A design goal of MAC-CROSS is to minimize energy consumption by continuously turning off the radio interface of unnecessary nodes that are not included in the routing path. In this paper, we categorize nodes into three types depending upon the state defined by data transmission: Communicating Parties, Upcoming communicating Parties and Third Parties. A state may dynamically change whenever data traffic is transmitted.

- **Communicating Parties (CP):** Any node currently participating in the actual data transmission. (like nodes A and B in Fig. 2).
- **Upcoming communicating Parties (UP):** Any node to be involved in the actual data transmission. (like node C in Fig. 2).
- **Third Parties (TP):** Any nodes that are not included on a routing path and hence not involved in the actual data transmission at all. (like nodes D-K in Fig. 2).

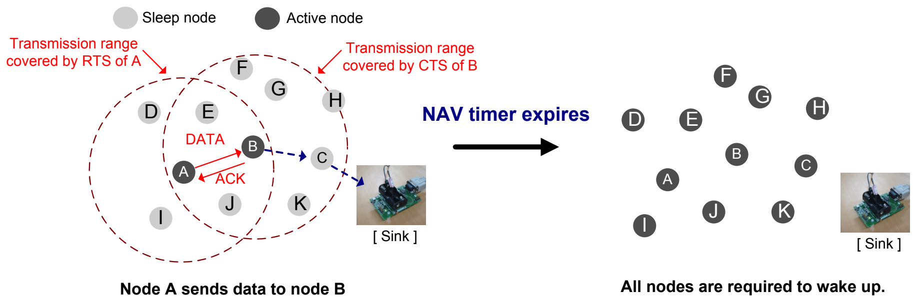

Fig. 2. A drawback of the adaptive S-MAC (in terms of energy efficient)

3.1 The Basic Operation of MAC-CROSS

Now, we explain the proposed MAC-CROSS scheme with the help of the following example. Remind that, in Fig 2 illustrating the main drawback of the adaptive S-MAC, all nodes are being awake when their NAV timer expire and consume unnecessary energy. The proposed MAC-CROSS can overcome this problem, as represented in Fig. 3 with the same scenario to Fig. 2. Thus, with

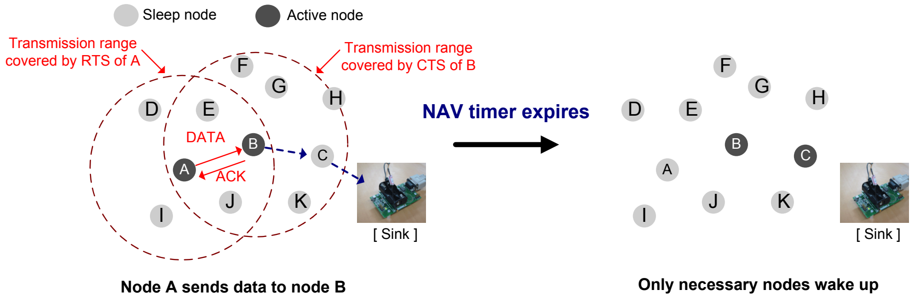

Fig. 3. The main advantage of the proposed MAC-CROSS

10 Bytes

Length	Type	To Addr	From Addr	Duration (NAV)	CRC

(a) The original RTS and CTS frames in TinyOS

10 + 2 = 12 Bytes

Length	Type	To Addr	From Addr	Duration (NAV)	Final Destination Addr	CRC

(b) The new RTS packet frame for MAC-CROSS

Length	Type	To Addr	From Addr	Duration (NAV)	Upcoming communication Parties Addr	CRC

(c) The new CTS packet frame for MAC-CROSS

Fig. 4. RTS and CTS frames modification in MAC-CROSS

the MAC-CROSS, only a few nodes concerned of the actual data transmission (i.e., the necessary UP nodes like nodes B and C in Fig 3) are asked to wake up, while other TP nodes can continuously remain in their sleep modes.

Before describing further details about the MAC-CROSS operation, it should be aware that a format of RTS/CTS control frames needs to be slightly modified from their originals in S-MAC protocol family. This modification is for informing a node the fact that its state is changed to UP or TP in the corresponding listen/sleep period. Fig 4-(a) shows the original RTS and CTS control packet formats for adaptive S-MAC in TinyOS [14] as operation of Mica Mote. Fig 4-(b) and (c) show the new RTS and CTS control packet formats for MAC-CROSS. The new RTS and CTS packet add only one field to the original packets. The newly added field in RTS is Final_Destination_Addr, by which the receiver's routing agent can search for the next hop address. The new field of CTS is UP_Addr and it informs which node is UP to its neighbors.

Referring back to Fig 3, when node B receives A's RTS packet including the final destination address of sink, its routing agent refers to the rouging table for getting the UP (node C) and informs back to its own MAC. The MAC agent of node B then transmits CTS packet including the UP information. After receiving the CTS packet from the B, node C changes its state to UP and other neighbor nodes become aware of the fact that they are TP nodes. UP node has to wake up when NAV timer expires for receiving data, but other nodes continuously sleep even if NAV timer expires for saving energy. Otherwise, if no such information about UP is available in node B's routing agent, it means the routing path is broken or has not yet been established. In this case, MAC-CROSS is performed just like S-MAC without cross layer concept.

3.2 Some Optional Features of the MAC-CROSS

If different addressing mechanisms are assumed on MAC and routing layers separately, our MAC-CROSS needs some address conversion schemes like ARP protocol [12] between the two layers (See Fig. 5). For example, any WLAN-based IPv4 devices have 4-bytes IP address as their network addressing mechanism and 6-bytes NIC address as their MAC addressing mechanism. In this case, MAC-CROSS refers to the address conversion scheme for describing the Final_Destination_Addr of RTS packet. However, in wireless sensor networks, most of paper [2, 3, 4, 8, 9] generally assume the node ID as the address of network as well as MAC. In this case, there is no extra overhead.

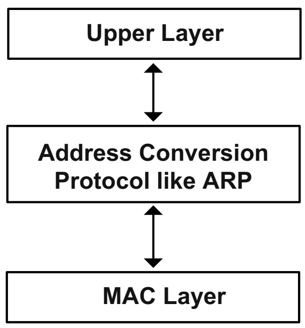

Fig. 5. Address conversion scheme in difference of address mechanisms

In our scheme, if a node obtains the medium access right by contention, the next hop node including the routing path monopolizes the medium access right for reducing compulsory wake-up problem. This solution may cause the unfairness problem. However, most of wireless sensor networks assume that data traffic is very low [10]. So, fairness issue is less important than energy efficiency. If some sensor application requires the fairness, our scheme needs to be modified accordingly. For example, if a node obtains the medium access rights, that node tries to decrease its medium access possibility by increasing its contention window size in the next cycle.

4 Performance Evaluation

4.1 Protocol Implementation on Mica Mote

Mica Mote sensor node has been developed at U.C. Berkeley and is now commercially available from Crossbow Inc [15]. It is equipped with a low-power microprocessor, 128K of program memory, 4 K of SRAM, and low power transceiver for wireless communication. For the purpose of performance comparison with the adaptive S-MAC, we implemented MAC-CROSS modules on Mica Motes. We set a duty cycle of both MAC protocols to be 10% as in [3]. We set the energy model based on S-MAC, which consumes 13.5mW, 24.75mW and 15uW, per receiving, transmitting and sleeping modes, respectively.

The test was performed on a static topology with seven sensor nodes, as illustrated in Fig. 6. Data is transmitted from 1 to 7, and source node 1 generates a packet in every 5 seconds. We measure the total energy consumption of sensor nodes when a data packet arrives at the sink node. Fig. 7 shows the energy consumption results. From the figure, we can observe that: when a number of arrived messages increase, MAC-CROSS consumes less energy than adaptive S-MAC. The reason is that our scheme dose not waste energy by compulsory wake-up, but adaptive S-MAC consumes unnecessary energy when NAC timer

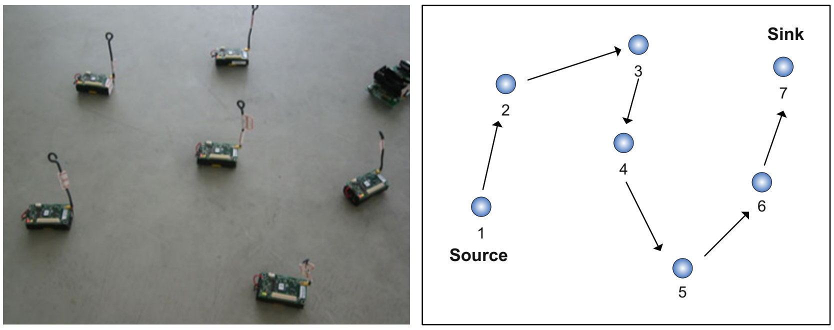

Fig. 6. Mica Mote Test-bed

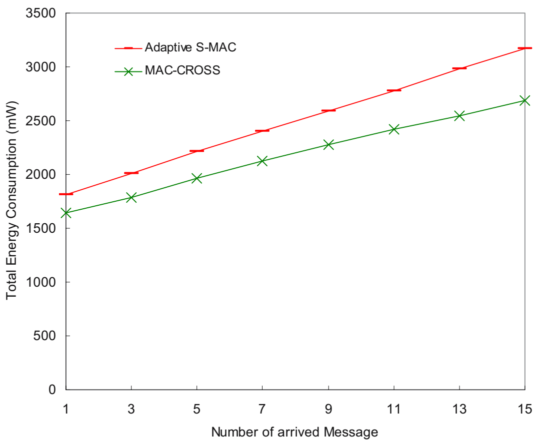

Fig. 7. Total energy consumption according to number of arrived message

expires. Therefore, our proposed scheme is more efficient than adaptive S-MAC as the number of arrived data packets increase.

4.2 Simulation Study

The simulations are done in random topologies with different sets of 30 to 100 nodes. A node transmission range is defined as 40m and its energy model and duty cycle are defined as the same as in implementation test. The routing protocol is based on the greedy approach. Therefore, a next hop node is the nearest neighbor node to the final destination. The size of data packet is fixed at 100 bytes. A sink node is located in the middle of the network and 4 source nodes are

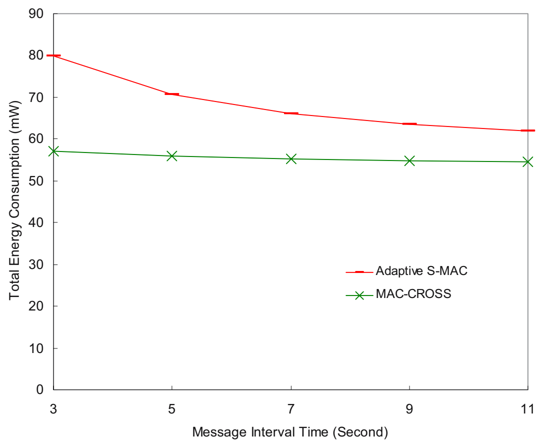

Fig. 8. Energy vs. Message Interval

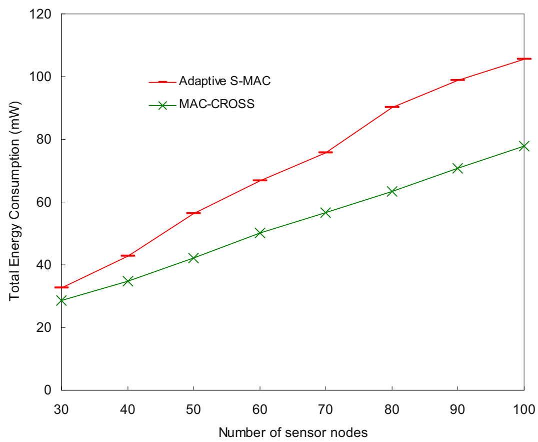

Fig. 9. Energy vs. Number of nodes

deployed in each edge of network. The message interval also varied to analyze the performance of both MAC protocols. The simulation runs for 400 seconds.

In Fig. 8, we show a total energy consumption as the message interval time is increased. When the message interval is 3 seconds, each source generates its data packet in every 3 second during the total simulation time. According to the figure, the performance of our scheme is better than adaptive S-MAC in the environment of high traffic. Since adaptive S-MAC consumes energy by compulsory wake-up whenever data packet is transmitted, our proposed scheme is more efficient as data traffic is increased. In Fig. 9, we change the number of nodes for analyzing the energy consumption of two MAC protocols according to the node density. In the high node density, the number of nodes that receive RTS/CTS control packets increase, meaning that the number of TP nodes also increase when NAV timer expires. In this case, adaptive S-MAC may consume more energy by compulsory wake-up. Therefore, MAC-CROSS results in less energy consumption than the adaptive S-MAC as the number of nodes increase.

5 Conclusion

In this paper, we propose a new MAC protocol for wireless sensor networks, named MAC-CROSS. Our proposed scheme does not have compulsory wake-up problem and maximize sleep duration of sensor nodes by cross-layer design approach. We have implemented the MAC-CROSS on the Mica Mote hardware and NS-2 simulator. Our experimental results demonstrate that our scheme works well and saves significant amount of the energy compared to adaptive S-MAC.

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