SEA-MAC: A Simple Energy Aware MAC Protocol for Wireless Sensor Networks for Environmental Monitoring Applications

Miguel A. Erazo, Yi Qian

Department of Electrical and Computer Engineering
University of Puerto Rico al Mayagüez
Mayagüez, PR 00681
email: {miguel.erazo, yqian}@ece.uprm.edu
Phone: 787-458-4901, Fax: 787-833-3331

Abstract – **In this paper, we propose SEA-MAC, a new energy aware medium access control (MAC) protocol for wireless sensor networks for environmental monitoring applications. The proposed MAC scheme is specifically designed for wireless sensor networks which have periodic traffic. The contributions of this paper are: First, the duty cycle is shortened by making nodes wake up only when an environmental sample is taken. Second, in SEA-MAC only the Base Station can start and maintain synchronization. Consequently, the synchronization is unique in the whole network. The proposed wireless sensor network MAC protocol was tested using simulations and real measurements on an implementation using mica2 motes.**

Keywords: **- wireless sensor networks, medium access control, energy efficiency, ultra-low duty cycle.**

I. INTRODUCTION

Wireless sensor networks have recently come into prominence because they hold the potential to revolutionize many segments of our economy and life. Wireless sensor networks consist of battery-operated sensor devices with computing, data processing, and communication components. Energy conservation is a critical issue in wireless sensor networks since batteries are the only energy source to power the sensor nodes.

Like in all shared-medium networks, medium access control (MAC) protocols enable the successful operation of the network. The MAC protocol in a wireless sensor network must achieve two goals. The first is the creation of the network infrastructure. Since thousands of sensor nodes are densely scattered in a sensor field, the MAC scheme must establish communication links for data transfer. This forms the basic infrastructure needed for wireless communication hop by hop and gives the sensor network self-organizing ability. The second objective is to fairly and efficiently share communication resources between sensor nodes.

Constraints on energy resources made researchers look for energy-efficient MAC protocols. Several MAC protocols for wireless sensor networks with an ultimate goal of increasing the network lifetime by conserving energy have been proposed in the literature.

Our goal in this paper is to develop a new MAC protocol for wireless sensor networks deployed for environmental monitoring. In our scheme, the Base Station (BS) starts and maintains synchronization. After nodes are synchronized, they only wake up on specific times when a sample of an environmental variable is taken.

The main contributions of this paper are:

- Design of a simple listen-sleep schedule where nodes only turn on their radios when a sample is taken of an environmental variable with the objective of consuming the least amount possible of energy.
- Make synchronization unique in the whole network to lower energy consumption by making nodes to follow only one time schedule.
- Comparison of the SEA-MAC performance with that of S-MAC [1] and SCP-MAC [2] in terms of energy consumption in both simulations in ns-2 [6] and implementation in mica2 motes.

In the remainder of the paper, a brief survey of related works is presented in Section II. The description of our new MAC protocol is in Section III. Performance analysis and simulation results are presented in Section IV. Finally, the conclusions are discussed in Section V.

II. RELATED WORK

Many protocols have been proposed for wireless sensor networks. Most of them aim to achieve low energy consumption in transmitting packets between nodes. These protocols also have the goals of low delay and minimum packet loss.

Ye et al. [1] proposed S-MAC, a medium access control (MAC) protocol designed for wireless sensor networks. S-MAC uses a few novel techniques to reduce energy consumption and support self-configuration. First, nodes form *virtual clusters* based on common sleep schedules to reduce control overhead and enable traffic-adaptive wake-up. Second, S-MAC uses in-channel signaling to avoid overhearing unnecessary traffic. Finally, S-MAC applies *message passing* to reduce contention latency.

This research is supported by the National Science Foundation (NSF) under the grant CISE-CNS-0424546.

Ye et al. [2] introduced SCP-MAC, a protocol which uses Scheduled Channel Polling (SCP) to achieve more energy savings than those of protocols that use coordinated transmissions and listen periods. The contributions of SCP-MAC are the ultra low duty cycles it achieves and its capacity to adapt to variable traffic loads.

Dam et al. [3] proposed T-MAC, a contention-based Medium Access Control protocol for wireless sensor networks. Lu et al. [4] proposed D-MAC, a protocol whose objective is to achieve very low latency.

Mainwaring et al. [5] provide an in-depth study of applying wireless sensor networks to real-world habitat monitoring. A set of system design requirements are developed that cover the hardware design of the nodes, the design of the sensor network, and the capabilities for remote data access and management.

In this paper we propose a MAC protocol to achieve very low energy consumption for environmental monitoring applications. In this kind of applications the traffic is completely periodic and SEA-MAC takes advantage of this fact to achieve low energy consumption levels.

III. SEA-MAC DESIGN OVERVIEW

A. *Overview of SEA-MAC Protocol*

The objectives of SEA-MAC are the following: first, to provide a way to achieve low duty cycle for periodic traffic e.g. sampling solar radiation or humidity; and second, to make synchronization simpler and unique in the whole network.

For environmental monitoring applications, it is desirable to sample physical variables periodically. In this way, we know in advance how many samples must be taken in an interval of time and the specific instants when they are taken. In SEA-MAC, nodes periodically wake up when a sample from environment is taken. In this way, nodes save a lot of energy in avoiding idle listening between two consecutive samples. Furthermore, no mechanism is used to wake up the nodes.

Synchronization for SEA-MAC has been designed to be simple and robust. With this, we intend to lower the frequency of synchronization losses in the network. Furthermore, the synchronization in SEA-MAC is unique for the whole network because only the Base Station starts and maintains synchronization while the other nodes only broadcast synchronization packets generated previously.

B. *Time schedule*

SEA-MAC attempts to make use of the advantage that the entire traffic of environmental monitoring applications is periodic. Therefore, it creates a schedule in which nodes only wake up when a sample from environment is taken. No periodic sleep/listen schedule will be necessary as it was proposed in protocols like S-MAC [1], T-MAC [3] or D-MAC [4]. Furthermore, it will be not necessary a short wake-up tone for senders to guarantee rendezvous as it was in SCP-MAC [2] because nodes know in advance they have to turn on its radio to sample environmental variables.

Besides low energy consumption, it is also important that packets from nodes reach its destination, i.e. the Base Station, in sequence and with low delay. For this purpose, listening periods in SEA-MAC are long enough so all packets reach the BS before the next active interval.

Global schedule of SEA-MAC is shown in Figure 1. Synchronization packets originated by the Base Station must have information about the time left for next listen period (t_{NLP}), the length of the listening period (t_{LP}) and the length of the sleeping period (t_{SP}). These variables depend on the type of sampled variables, some variables may need more bytes to be specified and therefore, the listen period should be larger.

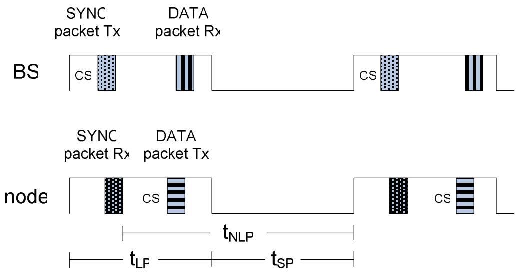

Fig. 1. Time schedule in SEA-MAC

C. *The synchronization*

Nodes running SEA-MAC, upon being turned on, turn on their radios to listen for synchronization (sync) packets from the BS. As stated before, the BS is the only node that can start and maintain synchronization while the other nodes only disseminate synchronization in a multihop environment. This type of synchronization saves energy because every node only follows one time schedule.

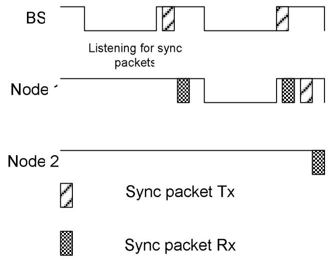

Fig. 2. SEA-MAC synchronization.

In Figure 2, the BS starts following the time schedule as soon as it is turned on. However, when turned on, nodes have not yet received any sync packet, so they keep their radios turned on until a sync packet is received. Then, they start to follow the time schedule. Node 2 can not hear the BS directly; therefore it is node 1, when retransmitting a sync packet, the node that synchronizes node 2.

D. Energy analysis

SCP-MAC can work at a much smaller Duty Cycle (DC) than S-MAC; therefore we assume that SCP-MAC consumes less energy than S-MAC so we compare energy consumption of SEA-MAC against that of SCP-MAC in this section. Later in this paper, we do compare SEA-MAC against S-MAC and SCP-MAC in terms of energy consumption and delay of packets.

For our analysis, we consider a network of n+1 nodes, where all nodes can hear each other directly. In this scenario, n nodes transmit packets to the Base Station, which in turn conveys received packets to the storage and analysis platform. In the following paragraphs, we analyze the energy consumption of SEA-MAC.

The expected energy spent in each node is the sum of the energy consumed in transmitting, receiving, sleeping and sensing states. Each term can be expressed as the average power in that state multiplied by the time the node is on that state. Table 1 summarizes all terms we use. We use the same terms used in [2] to facilitate further comparison between SEA-MAC and SCP-MAC.

TABLE 1

List of symbols used in energy consumption

Symbol	**Meaning**
P_{tx}	Power in transmitting
P_{rx}	Power in receiving
P_{listen}	Power in sleep
P_{sleep}	Power in sleeping
t_{csl}	Average carrier sense time
t_B	Time to Tx/Rx a byte
T_{data}	Data packet period
T_{sync}	Synchronization packet period
r_{data}	Data packet rate ($1/T_{data}$)
r_{sync}	Synchronization packet rate ($1/T_{sync}$)
L_{data}	Data packet length
L_{sync}	Synchronization packet length
t_{tx}	Average time a node is transmitting
t_{rx}	Average time a node is receiving
t_{cs}	Average time a node is on carrier sense
t_{sleep}	Average time a node is sleeping

The energy consumed by a node running SEA-MAC is:

$$\begin{aligned} E &= E_{tx} + E_{rx} + E_{sleep} + E_{cs} \\ &= P_{tx} t_{tx} + P_{rx} t_{rx} + P_{sleep} t_{sleep} + P_{listen} t_{cs} \end{aligned} \qquad (1)$$

In SEA-MAC, with a single-hop configuration, nodes do not transmit synchronization packets. They only transmit data packets every T_{data} time interval. For simplicity we assume that t_{LP} is calculated in such a way that there is not energy consumption because of idle listening, i.e. t_{LP} is large enough so the BS can receive all packets generated by the nodes. The average time a node is transmitting packets in an interval T_{data} is:

$$t_{tx} = \frac{L_{data}\, t_B}{T_{data}} = L_{data}\, t_B\, r_{data} \qquad (2)$$

We considerer that all packets are broadcast packets, so every node will receive exactly n-1 data packets, since the BS does not transmit data packets in an environmental monitoring application. Also, nodes will receive only one synchronization packet originated in the BS in an interval T_{data}, which in SEA-MAC is the only source of synchronization. In this way, the average time a node receives packets in T_{data} is:

$$\begin{aligned} t_{rx} &= \frac{(n-1) L_{data}\, t_B}{T_{data}} + \frac{L_{sync} t_B}{T_{sync}} \\ &= (n-1) L_{data}\, t_B\, r_{data} + L_{sync} t_B r_{sync} \end{aligned} \qquad (3)$$

The average time a node is on carrier sense state in an interval T_{data} is:

$$t_{cs} = \frac{t_{csl}}{T_{data}} = t_{csl}\; r_{data} \qquad (4)$$

If not in any of the other states, the node should be sleeping:

$$t_{sleep} = 1 - t_{tx} - t_{rx} - t_{cs} \qquad (5)$$

Substituting equations (2) to (5) into (1) we obtain the following expression for the energy consumption:

$$\begin{aligned} E = {} & P_{listen}\, t_{csl}\, r_{data} + \left(P_{tx} + (n-1)\, P_{rx}\right) L_{data}\, t_B\, r_{data} \\ & + P_{rx}\, L_{sync}\, t_B\, r_{sync} + P_{sleep}\, (1 - t_{cls}\, r_{data} \\ & - L_{data}\, t_B\, (n) r_{data} - L_{sync}\, t_B\, r_{sync}) \end{aligned} \qquad (6)$$

If we compare equation (6) against the expression for energy consumption for SCP-MAC [2] with explicit synchronization we realize the following: First, SEA-MAC saves energy by not polling the medium for possible transmissions. Second, SEA-MAC saves energy by avoiding transmission of tone packets to wake up nodes. Third, less energy is consumed in synchronization because the BS is the only node that starts synchronization and one packet is enough to synchronize the entire network. Finally, SEA-MAC spends more time sleeping but since the energy consumed in sleeping state is much less than that of being in any other state, we can say that this last factor is negligible.

According to the last expression, we can predict that SEA-MAC will outperform SCP-MAC and S-MAC in the application of monitoring environmental variables. In section IV, we show results of simulations and actual implementation.

IV. EXPERIMENTAL RESULTS

A. Simulation

We have simulated our protocol using ns-2 [6] and compared SEA-MAC energy consumption to that of S-MAC. For our tests we used the network configuration shown in Figure 3, where every node can only listen directly to its immediate neighbor. We made node 0 send data packets at regular intervals to the BS. We ran this test several times for SEA-MAC and S-MAC and averaged the results.

Figure 4 depicts the results obtained for SEA-MAC and S-MAC at 10% of DC. The energy consumed is expressed in Joules and the Message inter-arrival period is the time between consecutive transmissions of node 0.

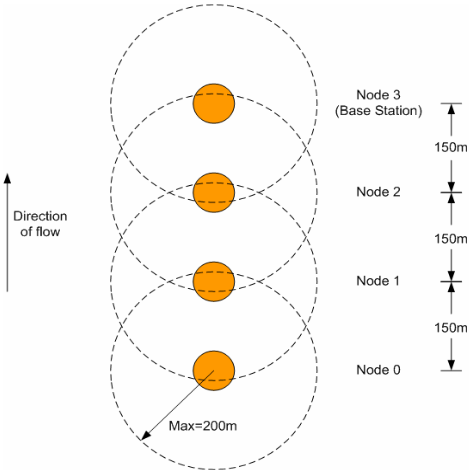

Fig 3. Network configuration used for simulations.

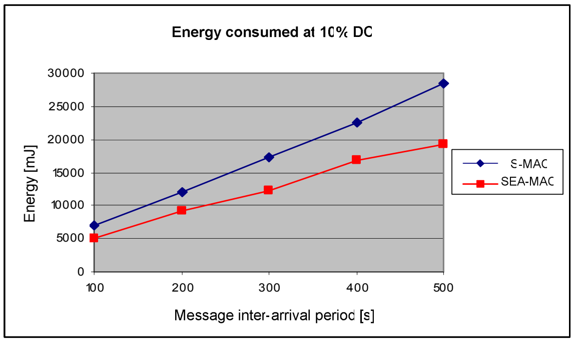

Fig. 4. Energy consumption of SEA-MAC and S-MAC.

Figure 5 depicts the energy consumption for SEA-MAC and S-MAC as a function of number of bits sent in one second by node 0 (bits/second). Results are shown for 10%, 20%, 30%, 40% and 50% values of DC. We can see that SEA-MAC outperforms S-MAC for various values of DC according to results depicted in Figure 5.

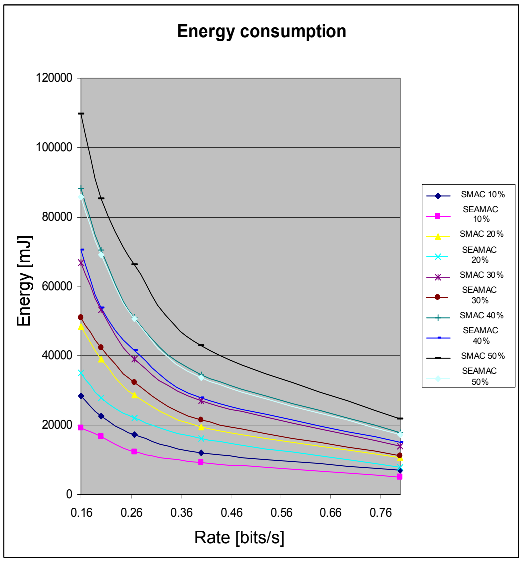

Fig. 5. Energy consumption as a function of the rate of transmission.

B. Experiments

We have also implemented SEA-MAC protocol in mica2 motes running TinyOS [7]. The network configuration we used for the tests is shown in Figure 6. In this, nodes 2 and 3 sample variables, e.g. humidity or barometric pressure, periodically and generate corresponding packets, which have to reach the BS.

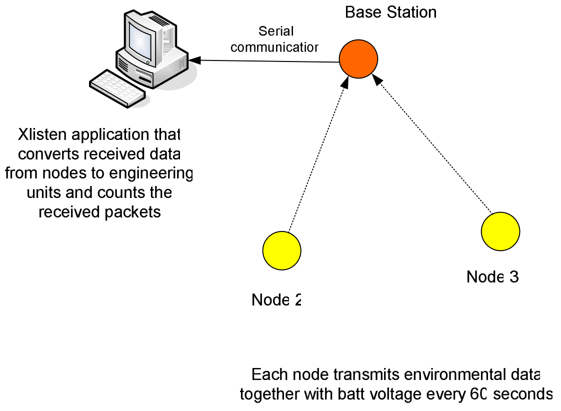

Fig. 6. Network configuration for implementation.

We added NesC components from Crossbow [8] to SEA-MAC, S-MAC and SCP-MAC C++ code to make nodes able to sense environmental variables. Also, we added NesC components to the BS code to transmit packets to the PC through the UART. Finally, we stored sampled data in files together with voltage measures and the time the packets were received.

For our tests, we monitored the battery voltage in each mica2 mote every time they sent a packet. This data is sent in data packets together with sampled data. Nodes 2 and 3 send a data packet every 60 seconds. Upon receiving the packets, the BS sends them to the PC through the UART. Finally, the information about the sampled data is stored in files for further analysis.

In this test we intend to find out which protocol consumes less energy by determining which protocol produces the least voltage drop in 48 hours of continuous test. The results are shown in Figure 7.

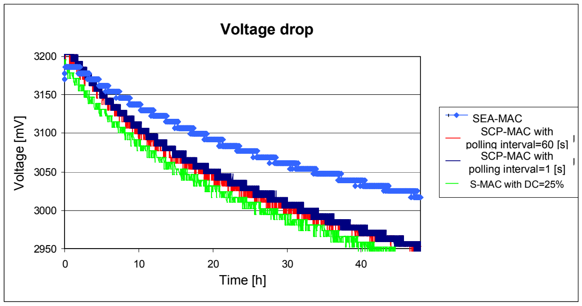

Fig. 7. Voltage drop in 48 hours of test

Figure 7 shows that SEA-MAC produces the least voltage drop and therefore consumes less energy than the other protocols. SCP-MAC was tested at a polling interval of 60 and 1 seconds and S-MAC at a DC of 25%. Additionally, Table 2 shows the voltage drop after 24 hours of test. Clearly, SEA-MAC produces the least voltage drop of the three protocols.

TABLE 2
Voltage drop

PROTOCOL	**Node**	**Voltage Drop [mV]**
SEA-MAC	2	102
SEA-MAC	3	108
	Average=	**105**
S-MAC at 10% DC	2	155
S-MAC at 10% DC	3	198
	Average=	**176.5**
SCP-MAC at 1 [s] polling interval	2	164
SCP-MAC at 1 [s] polling interval	3	190
	Average=	**177**
S-MAC at 25% DC	2	182
S-MAC at 25% DC	3	213
	Average=	**197.5**
S-MAC at 50% DC	2	228
S-MAC at 50% DC	3	206
	Average=	**217**

In the near future, mica2 and mica2dot motes will be installed with SEA-MAC running in the field.

V. CONCLUSIONS

This paper proposes SEA-MAC, a new MAC protocol whose objective is to reduce energy consumption for environmental monitoring applications. SEA-MAC reduces drastically the DC by making that nodes wake up only when a sample is taken from the environment. In this way, idle listening is reduced. Also, synchronization has been made unique in the whole network in order to save energy by making nodes to follow only one time schedule.

Simulation results in ns-2 have shown that SEA-MAC achieves better energy performance that S-MAC at different DC's. Furthermore, tests on mica2 motes have shown that SEA-MAC outperforms S-MAC and SCP-MAC achieving the least voltage drop on the batteries of the motes in tests of 48 hours. Surprisingly, SCP-MAC and S-MAC achieved similar results in energy performance even though SCP-MAC has much lower DC's than S-MAC.

Future work will include an analysis of SEA-MAC performance in multi-hop configurations as well as an analysis of the optimal values of its parameters for minimum consumption of energy.

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