“An Energy-Efficient MAC Protocol for Wireless Sensor Networks”- Wei Ye, John Heidemann, Deborah Estrin

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Wireless Sensor Networks

- Consist of a large number of distributed nodes
- The nodes form a multi-hop wireless network
- The nodes coordinate to perform for a common task (e.g. environment monitoring, medical systems)
- Typically the nodes remain inactive for a long period of time

Designing a MAC protocol for wireless sensor networks

A good MAC protocol for wireless sensor networks should have the following attributes:

- Energy efficiency
- Scalability to the change in network-size and topology
- Fairness and latency (per-node fairness not important for sensor networks)
- Throughput and bandwidth utilization are secondary concerns

Sources of energy waste in a wireless sensor network

- Collision
- Overhearing
- Control packet overhead
- Idle listening

Measurements have shown that idle listening consumes about 50% of the energy required for receiving.

Contribution of the paper

The authors have proposed a new MAC protocol sensor-MAC (S-MAC) for wireless sensor networks that

- reduces energy consumption by nodes
- achieves good scalability and collision avoidance capability
- some reduction in per-hop fairness and increase in latency

Contemporary MAC designs for wireless sensor networks

- Contention-based design (e.g. IEEE 802.11 DCF) – widely used, robust to hidden node problem, high energy consumption in idle mode
- TDMA design (based on reservation and scheduling) – energy efficient but not much scalability, tight synchronization is needed

Assumptions about network and application

- Network is composed of many small nodes deployed in an ad-hoc fashion
- Short-range multi-hop communications instead of long-range communication
- Network is dedicated to a single application or a few collaborative applications
- Applications will have long idle periods and can tolerate some latency

S-MAC Protocol

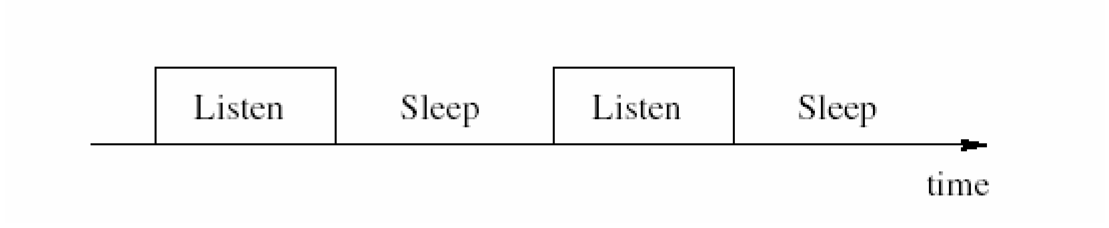
Objective is to prolong network lifetime by reducing energy consumption by nodes.

S-MAC consists of three major components:

- Periodic listen and sleep
- Collision and overhearing avoidance
- Message passing

Periodic listen and sleep

- Nodes are idle for a long time in many applications. S-MAC reduces the listen time by letting nodes go into periodic sleep mode.



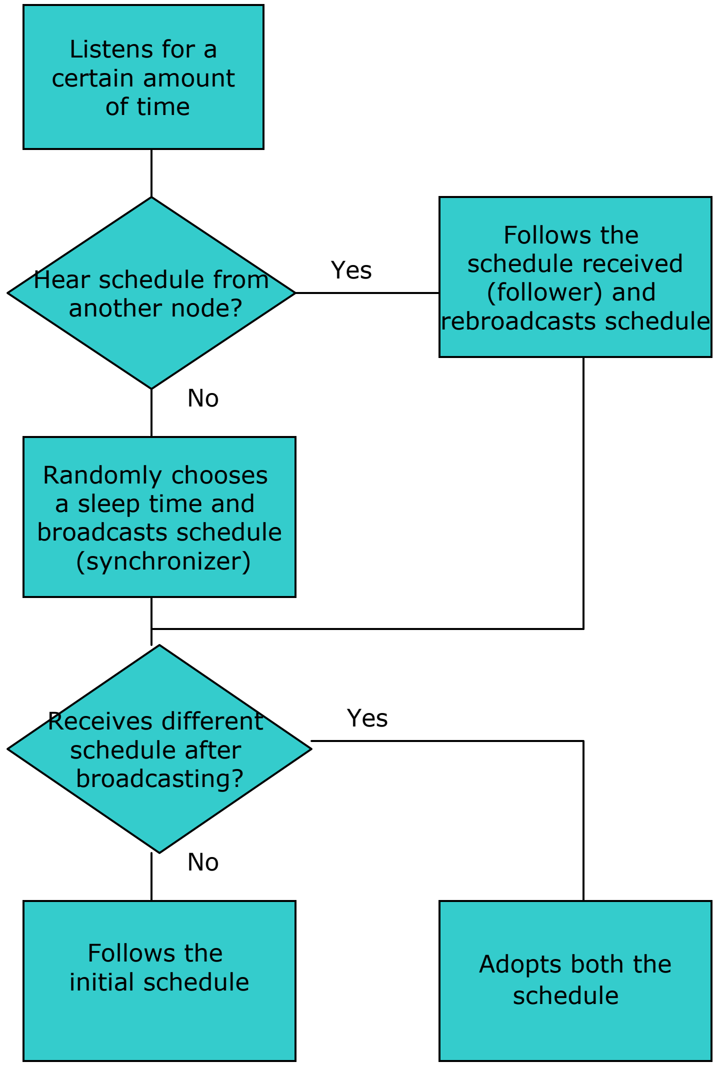
- The duration of time for listening and sleeping can be selected according to the application scenario.
- Periodic synchronization is required among neighboring nodes to remedy their clock drift.
- Compared to TDMA , S-MAC requires looser synchronization

Periodic listen and sleep (Contd.)

- Nodes exchange schedules by broadcasting to all their immediate neighbors.
- Each node maintains its own schedule table that stores schedules of all its known neighbors.
- It is preferable for neighboring nodes to listen and sleep at the same time.

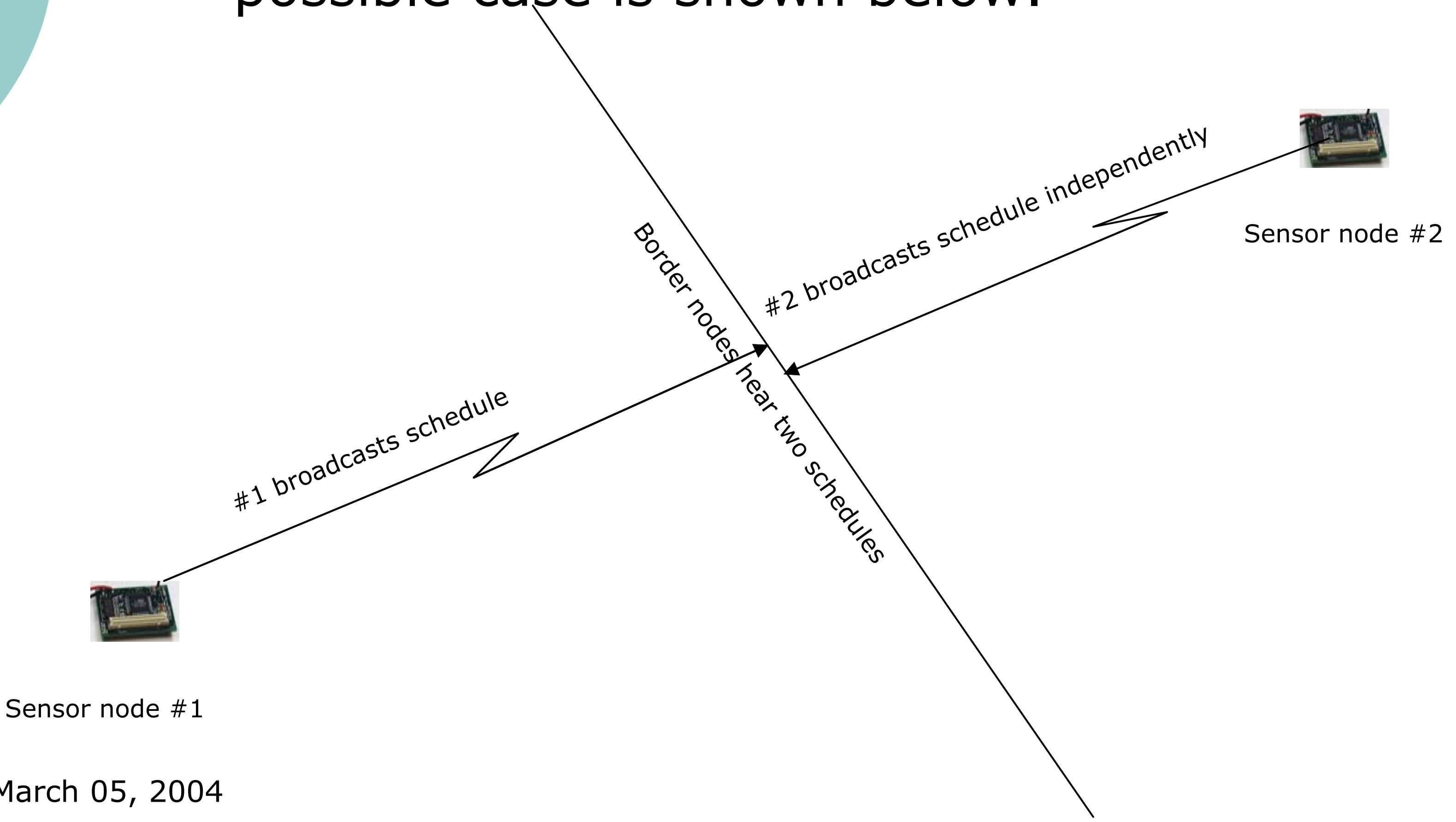
- Not all neighboring nodes can synchronize together.
- If more than one node wants to talk with the same node, they need to contend for the channel when the node is listening.

Choosing and maintaining schedules


Listens for a certain amount of time
Hear schedule from another node?
Yes
Follows the schedule received (follower) and rebroadcasts schedule
No
Randomly chooses a sleep time and broadcasts schedule (synchronizer)
Receives different schedule after broadcasting?
Yes
No
Follows the initial schedule
Adopts both the schedule

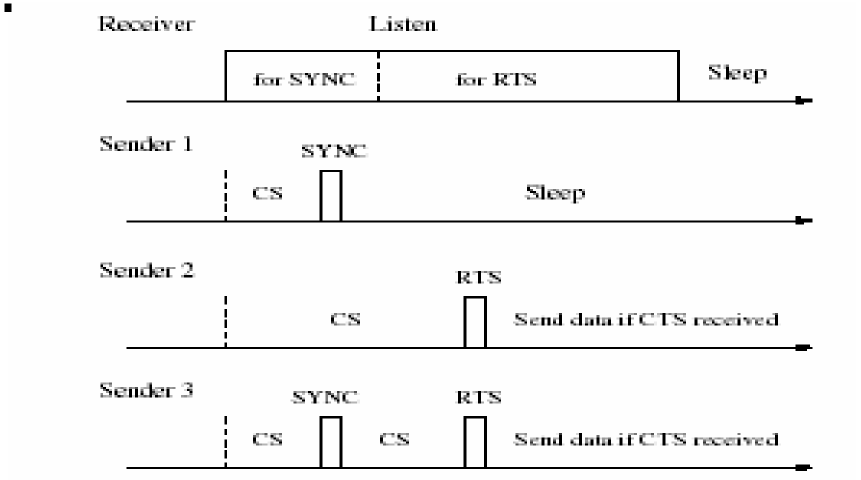
Choosing and maintaining schedules (Contd.)

Nodes rarely adopt to multiple schedules. One possible case is shown below.


Sensor node #2
#2 broadcasts schedule independently
Border nodes hear two schedules
#1 broadcasts schedule
Sensor node #1

Maintaining Synchronization

- Neighbors need to periodically update each other their schedules to prevent long-time clock drift.
- Accomplished by sending a SYNC packet.
- Listen interval is divided into two parts – the first for receiving SYNC packets , the second for data packets.



Collision Avoidance

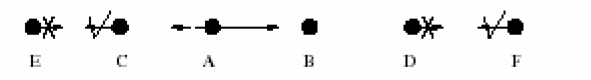
- Collision Avoidance – basic task of MAC protocols
- S-MAC is a contention based protocol and performs virtual and physical carrier sense and RTS/CTS exchange like 802.11
- Unicast packets follow the sequence RTS/CTS/DATA/ACK
- Broadcast packets are sent without using RTS/CTS (and also without ACK)

Overhearing Avoidance

- In 802.11 each node listens to all transmissions from its neighbors to perform virtual carrier sensing.
- S-MAC avoids overhearing by letting interfering nodes go to sleep after they hear RTS or CTS packets.

Example Scenario:

Node A transmitting to node B. What about the neighbors?



Message passing (basically fragmenting large packets)

- Transmitting long packets is disadvantageous
- Fragmenting the packet into independent small packets results in a large control overhead and delay
- S-MAC fragments large packets into small fragments and transmit them in a burst (single RTS/CTS is used)
- Message passing puts nodes into sleep state as long as possible, thereby reducing switching overhead

Difference between S-MAC and 802.11 fragmentation

- In 802.11 RTS/CTS reserves the medium only for the first fragment. The first ACK reserves the medium for second fragment and so on. So neighboring nodes must listen all the time. This is done to maintain per-node fairness.
- Message passing has fewer contentions and a smaller latency* as the RTS/CTS reserves the medium for all the fragments. It does not promote per-node fairness as the goal is application-level fairness.

* - for the current transmission

Delays experienced in S-MAC

A packet moving through a multi-hop network experiences the following delays at each hop

- Carrier sense delay
- Back-off delay
- Transmission delay
- Propagation delay
- Processing delay
- Queuing delay
- Sleep delay

The first six delays are present in 802.11 DCF

Energy Savings vs. Increased Latency

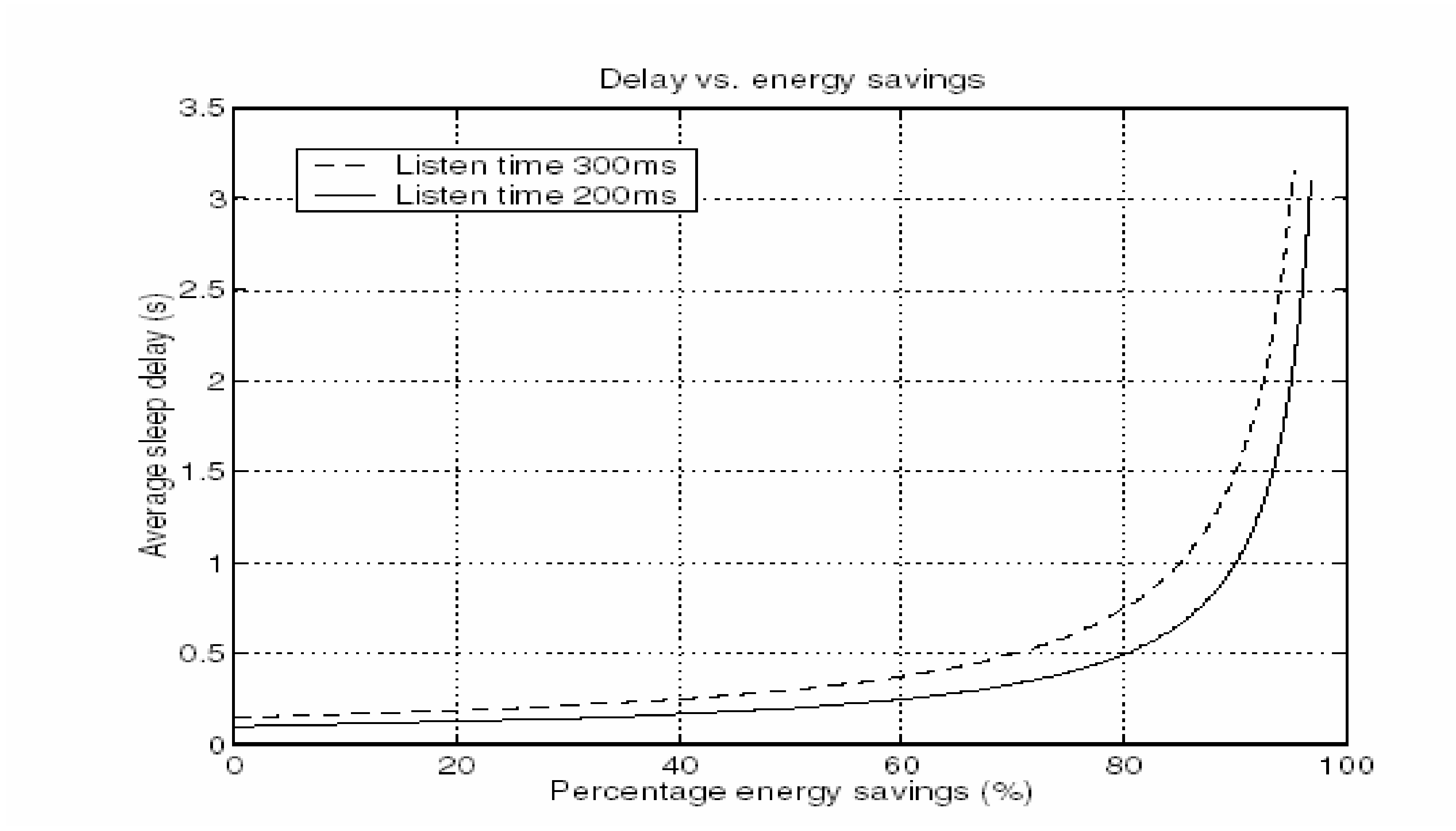
- A frame is a complete cycle of listen and sleep
- Average sleep delay on the sender $D_s = T_{frame} / 2$ where $T_{frame} = T_{listen} + T_{sleep}$ (Does it depend on the duty cycle?)

  Relative energy savings in S-MAC is

  $$E_s = \frac{T_{sleep}}{T_{frame}} = 1 - \frac{T_{listen}}{T_{frame}}$$

  For a certain duty cycle, the listen time should be short to make sleep delay short

Delay vs. Energy savings



Protocol Implementation

- Rene Motes - used as development platform and testbed.

- It uses Atmel AT90LS8535 microcontroller (8 KB of programmable flash and 512 bytes of data memory).
- Radio transceiver [TR1000] has a transmission rate of 19.2 kbps and three working modes – receive, transmit and sleep.

Protocol Implementation (Contd.)

- UCB Rene motes use TinyOS operating system.
- The MAC implementation uses data packet with 6B header, 30B payload and 2B CRC.
- Control packets (RTS/CTS/ACK) has 6B header and 2B CRC.
- The length of header or payload can be changed but once defined, all packets have same length.

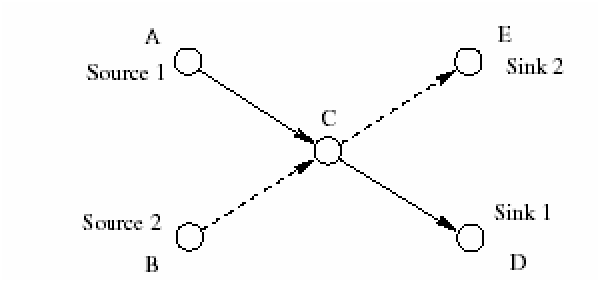
Comparison of MAC protocols

Three MAC protocols have been compared

- Simplified IEEE 802.11 DCF (without exponential back-off)
- Message passing with overhearing avoidance (nodes sleep only when its neighbors are in transmission)
- Complete S-MAC

Experimental Setup

- Listen time – 300 msec
- Sleep time – 1 sec
- Frequency for schedule updates - 10 listen/sleep periods (13 sec)



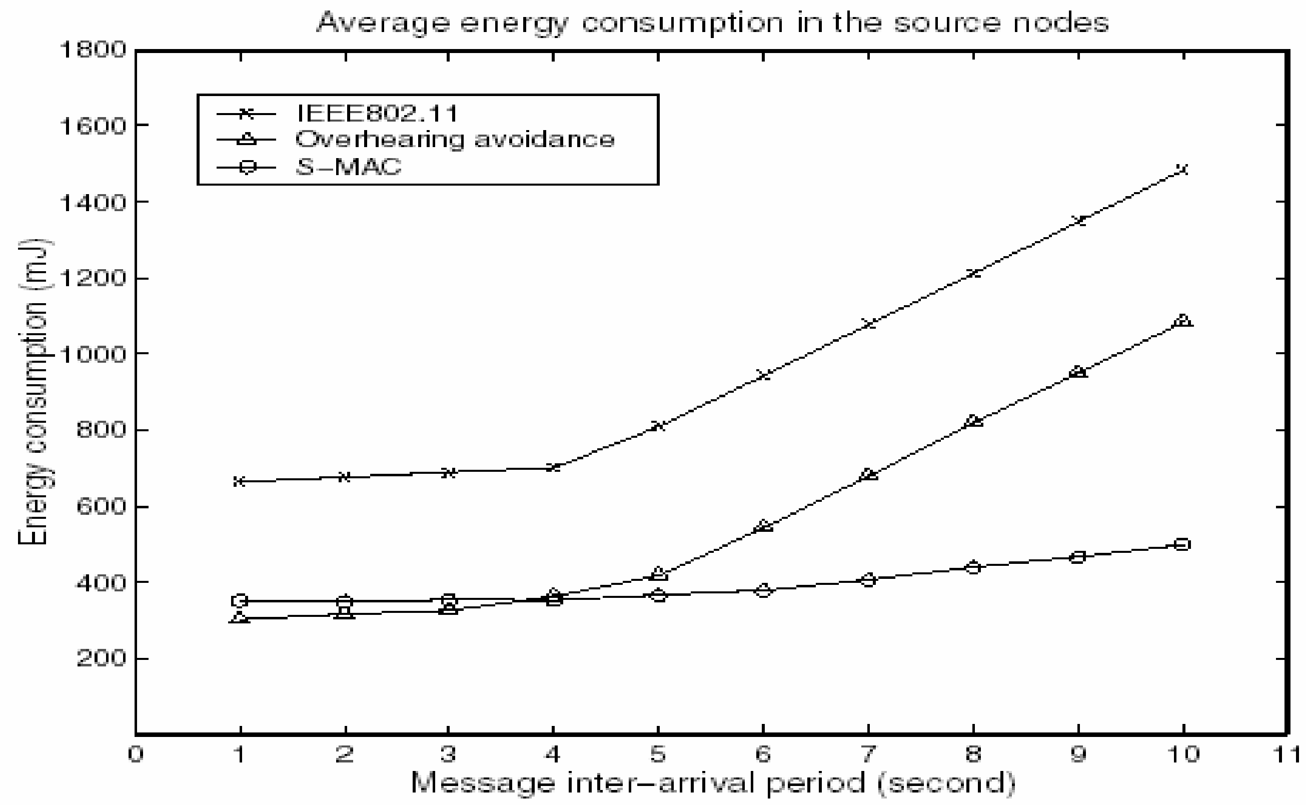
- Two traffic flows A-D and B-E
- Message inter-arrival period [1,10] sec

Experimental Setup (Contd.)

- Each source periodically generates 10 messages, each of which is fragmented into 10 small data packets (TinyOS format).
- Power consumption of the radio transceiver is 13.5 mW for receiving , 24.75 mW for transmitting and 15 μW for sleeping.
- Listening is same as receiving for this radio transceiver.

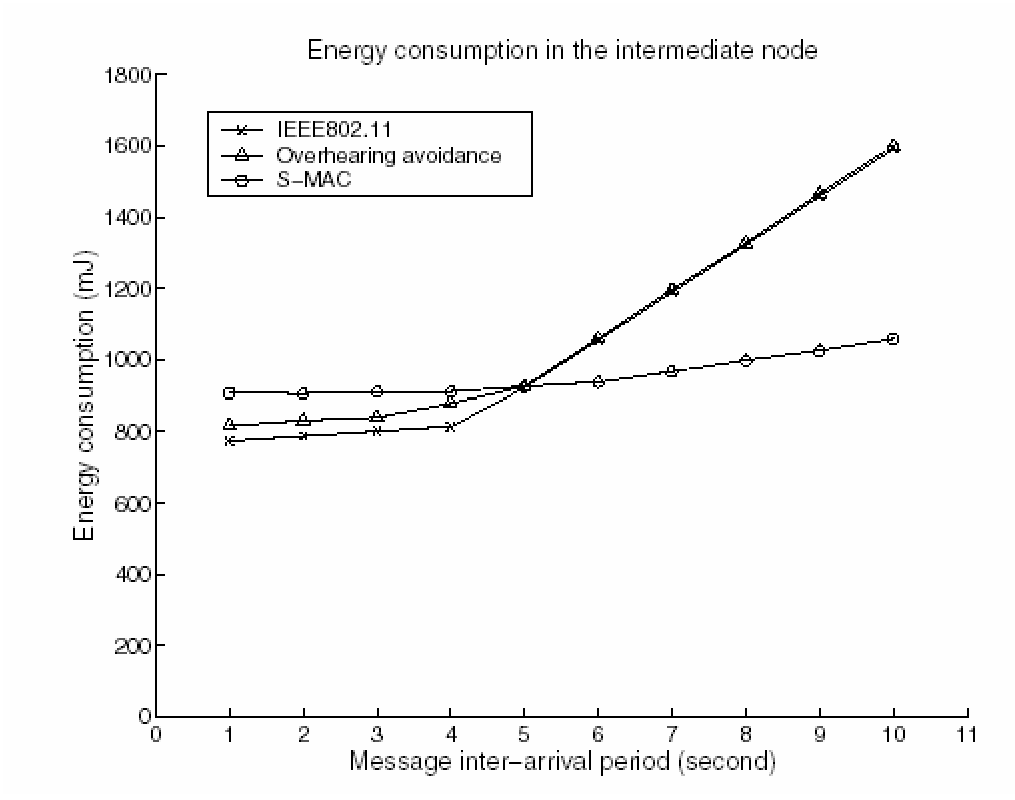
Note: Only the radio sleeps, not the microcontroller.

Simulation Results



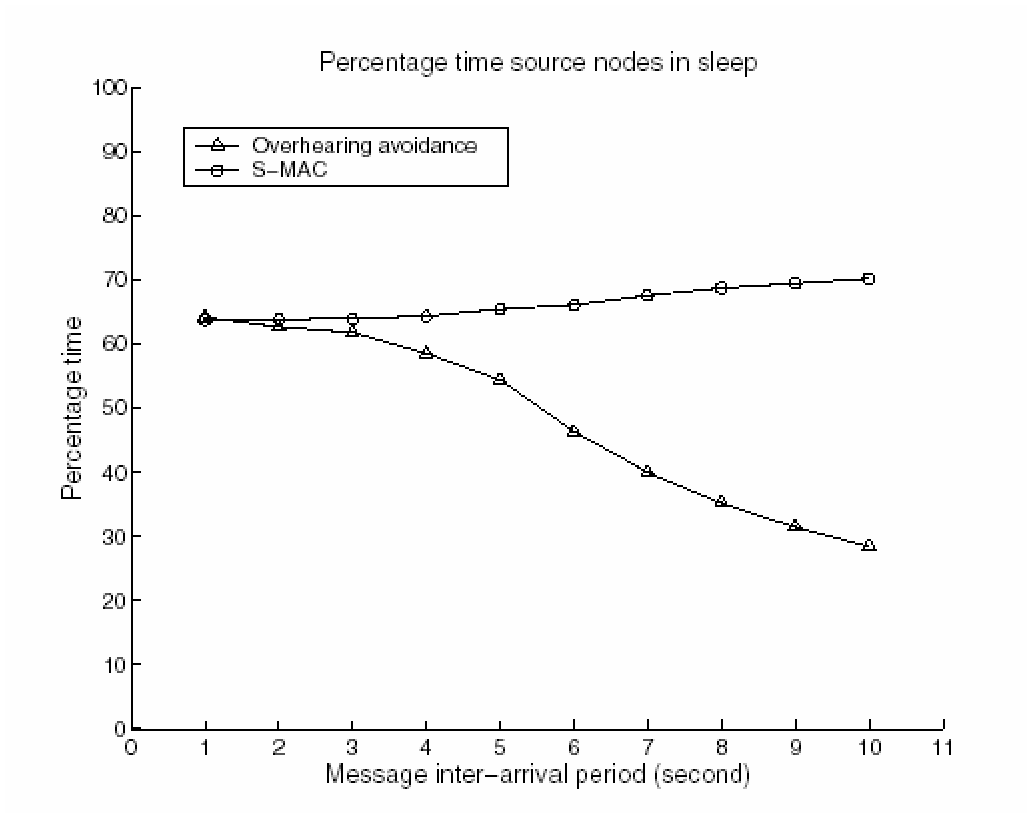
Measured energy consumption at source nodes A and B

Simulation Results (Contd.)



Measured energy consumption in the intermediate node

Simulation Results (Contd.)



Measured percentage of time the source nodes are in sleep mode

Conclusions

- The paper presents a new MAC protocol for wireless sensor networks.
- The protocol is more energy efficient than IEEE 802.11.
- Possible to make trade-offs between energy and latency according to traffic conditions.