ENERGY EFFICIENT WIRELESS SENSOR NETWORKS
Paul Haugen and Chris Hunter
APPLICATIONS

• Medical
• Environmental
  • Oceanic
  • Rain Forests
  • Seismic
  • Volcanic
• Military
• Security
• Space Frontier

Monnit Wireless Sensor Solutions for Asset Management
APPLICATIONS

• Medical
• Environmental
  • Oceanic
  • Rain Forests
  • Seismic
  • Volcanic
• Military
• Security
• Space Frontier

$7 Billion Industry
(Frost & Sullivan 2009)
APPLICATIONS

• Honey Bees vs. Explosives (Gaidos 2008)
APPLICATIONS

- Habitat Monitoring (Mainwaring 2002)
REQUIREMENTS

• Scalability (100s - 1000s of nodes)
• Cost
• Low Power

• Bandwidth
• Throughput
CONSTRAINTS

Low Power

\[ P_C = N_T [P_T (T_{ON} + T_{ST}) + (P_{OUT}(T_{ON}))]
+ N_R [P_R (R_{ON} + R_{ST})] \]

(Akyildiz 2001)

PHY and MAC layer

- \( P_C \): radio power consumption
- \( P_{T/R} \): transmitter/receiver power consumption
- \( P_{OUT} \): transmitter output power
- \( T/R_{ON} \): transmitter/receiver on time
- \( T/R_{ST} \): transmitter/receiver start-up time
- \( N_{T/R} \): number of times transmitter/receiver is switched on per unit time
OUTLINE

• Physical Layer (PHY)
  • Mica platform technique
• Medium Access Control Layer (MAC)
  • S-MAC
  • T-MAC
## OBSERVATIONS

<table>
<thead>
<tr>
<th></th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx is expensive</td>
<td>$E_{TX} &gt; E_{RX}$</td>
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“Idle Listening”
OBSERVATIONS

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MICA: A WIRELESS PLATFORM FOR DEEPLY EMBEDDED NETWORKS

(2002) 781 citations

Jason L. Hill
David E. Culler
University of California, Berkeley
PHYSICAL LAYER

Tx

Rx

\( \Delta t \) governed by preamble

Payload

Preamble

Payload
weeks of battery life $\rightarrow$ 38 years of battery life
## MEDIUM ACCESS CONTROL

<table>
<thead>
<tr>
<th>Scheduled Access</th>
<th>Random Access</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>• Only listen sometimes</td>
<td>• Easy</td>
</tr>
<tr>
<td>• Collision-free</td>
<td>• Scalable</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td><strong>Cons</strong></td>
</tr>
<tr>
<td>• Not scalable (e.g. bluetooth)</td>
<td>• Collision-prone</td>
</tr>
<tr>
<td>• Very difficult to coordinate</td>
<td>• Always have to listen</td>
</tr>
</tbody>
</table>
An Energy-Efficient MAC Protocol for Wireless Sensor Networks

Wei Ye, John Heidemann, Deborah Estrin

Medium Access Control With Coordinated Adaptive Sleeping for Wireless Sensor Networks

Wei Ye, Member, IEEE, John Heidemann, Member, IEEE, and Deborah Estrin, Fellow, IEEE
S-MAC PROTOCOL

Goal:

<table>
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<th>Active</th>
<th>Sleep</th>
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Problem: Don’t know when you might receive something

Solution: Form a *Virtual Cluster* with neighbors
$\Delta t_A$ going to sleep in $\Delta t_A$ seconds

$\Delta t_B = \Delta t_A - (t_1 - t_0)$

$\Delta t_C = \Delta t_A - (t_2 - t_0)$
S-MAC EVALUATION

Rene Motes

University of California, Berkeley
S-MAC EVALUATION

Rene Motes

- Microcontroller – Atmel
  - AT90LS8535
  - 8K bytes of programmable flash
  - 512 bytes of data memory
- Transceiver – RF Monolithics, Inc.
  - TR1000
  - 19.2 Kbps transmission rate
- Operating System – TinyOS
  - event-driven

Very limited processing - MAC must be simple
S-MAC EVALUATION

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Very limited processing - MAC must be simple

Three modes of operation:
- receiving: 4.5mA
- transmitting: 12mA
- sleep: 5μA
S-MAC EVALUATION
Test Setup

• **IEEE 802.11 / CSMA**
  • radios do not have sleep mode

• **Partial S-MAC**
  • no periodic sleep
  • only disable on neighbors’ RTS/CTS

• **Complete S-MAC**
  • includes periodic sleep
  • Settings:
    • listen time: 300 ms
    • sleep time: 1 s
    • schedule update frequency: 13 s
S-MAC EVALUATION
Test Setup
S-MAC EVALUATION
Energy Consumption Metrics

- amount of time used to pass packets
- % time radio spent in each mode
- Recall:
  - receiving: 4.5mA
  - transmitting: 12mA
  - sleep: 5µA
RESULTS

Average energy consumption in the source nodes

- IEEE802.11
- Overhearing avoidance
- S-MAC

Overhearing avoidance
Idle-listening
RESULTS

Percentage time source nodes in sleep

- Overhearing avoidance
- S-MAC

Duty-cycle limited
RESULTS

Energy consumption in the intermediate node

- IEEE802.11
- Overhearing avoidance
- S-MAC

Energy consumption (mJ)

Message inter-arrival period (second)

Diagram showing network topology:
- Source 1 to C
- Source 2 to C
- C to Sink 1
- C to Sink 2
- Sink 1 to Sink 2
RESULTS

S-MAC must be tuned to your application
PROBLEMS

We lied: sometimes performance does matter

• Periodic applications (e.g. temperature habitat monitoring)
  • S-MAC is great; highly predictable traffic structure
• Event-driven applications (e.g. natural disasters)
  • Traffic can be very bursty; suddenly throughput/delay matter

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1. INTRODUCTION
Communication in wireless sensor networks can, like most network communication, be divided into several layers. One of those is the Medium Access Control (MAC) layer. This layer is described by a MAC protocol, which tries to ensure that no two nodes are interfering with each other’s transmissions, and deals with the situation when they do.

Wireless sensor networks have an additional aspect: as sensor nodes are generally battery-operated, energy consumption is very important. The radio on a sensor node is usually the component that uses most energy. Not only transmitting costs energy; receiving, or merely scanning the ether for communication, can use up to half as much, depending on the type of radio [8].

While traditional MAC protocols are designed to maximize packet throughput, minimize latency and provide fairness, protocol design for wireless sensor networks focuses on minimizing energy consumption. The application determines the requirements for the (modest) minimum throughput and maximum latency. Fairness is usually not an issue, since the nodes in a wireless sensor network are typically part of a single application and work together for a common purpose.

1.1 Communication patterns
It is important to design and test the behavior of MAC protocols based on the kind of traffic they have to handle. We have identified two main communication patterns in sensor applications:

- Local uni-/broadcast: When a real-world event in the network occurs, we expect nodes to perform some in-network processing. This will generally involve local messages being exchanged between neighbors.

- Nodes to sink reporting: After processing a local event, or just periodically, nodes may want to report something. We expect messages to be directed to one or a few sink nodes, which are hooked up to an external network or a computer. Messages from different nodes may, or may not, be aggregated along the way. We do not specify an exact routing protocol, but we expect some random variation in message paths—messages flow ‘roughly’ in the correct direction. In this communication pattern, we see a more or less unidirectional flow of messages through the network.

(2003) 1547 citations
T-MAC PROTOCOL

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T-MAC PROTOCOL

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Infrequent Traffic
T-MAC PROTOCOL

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</thead>
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Frequent Traffic
T-MAC PROTOCOL

Active

Very frequent traffic

standard 802.11
T-MAC EVALUATION
Simulation Results

Event triggered reporting

energy used [avg. mA / node]

<table>
<thead>
<tr>
<th></th>
<th>CSMA</th>
<th>S-MAC</th>
<th>T-MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
**T-MAC EVALUATION**

Hardware Implementation Results

<table>
<thead>
<tr>
<th>msg / s</th>
<th>transmit mA</th>
<th>receive mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.138</td>
<td>0.138</td>
</tr>
<tr>
<td>1</td>
<td>0.400</td>
<td>0.246</td>
</tr>
<tr>
<td>10</td>
<td>1.516</td>
<td>0.890</td>
</tr>
<tr>
<td>max</td>
<td>9.590</td>
<td>7.473</td>
</tr>
</tbody>
</table>

CSMA Idle Draw: 4mA

\[
\frac{0.138}{4} \approx 3\%
\]
CONCLUSIONS

• Techniques at multiple layers to deal with energy efficiency

• Gains can be significant

• Application-aware; no one-size-fits-all solution