Adaptive Energy-Saving for Multihop Wireless Networks

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Wireless Networking: It’s Kind of a Big Deal

- "The number of WiFi hotspots in the United States increased from 3,400 to 21,500 between 2002 and 2004 [...] that number is expected to grow [...] to 64,200 by 2008, a 31.5 percent compound annual growth rate." – David A. Gross, US Ambassador Bureau of Economic and Business Affairs

- "The number of RFID tags produced worldwide is expected to increase more than 25 fold between 2005 and 2010, reaching 33 billion, according to market research company In-Stat." – EE Times

- "IDC now estimates there will be more than 100 million Bluetooth devices worldwide by the end of the year, and In-Stat/MDR expects a compound annual growth rate of 60 percent from 2003 to 2008." – CNET.com

- TinyOS Sensor Operating System: Typically 50-200 downloads per day – TinyOS Website
Emerging Wireless Applications
Why Use Multihop Wireless?

- **Connectivity**: Extend infrastructure at a low cost
  - Mesh and Community Networks

- **Ease of Deployment**: Extend infrastructure quickly
  - Disaster scenarios
  - Sensor networks
  - Vehicular networks
  - Military operations

- **Performance**: Increased capacity per node
  
  \[
  (W = \text{Channel Bitrate}, N = \text{Number of Nodes})
  \]

  
  Single Hop Network
  \[
  O\left(\frac{W}{N}\right)
  \]

  Multihop Network
  \[
  O\left(\frac{W}{\sqrt{N}}\right)
  \]
Some Research Challenges

- Improve performance
  - Exploit diversity (e.g., multiple channels, bitrates)

- Making that last wire less necessary
  - The power cable has proved remarkably resilient in this “wireless” world

- Security and privacy
  - Resource constraints on cryptography
  - Tapping the channel to eavesdrop is much easier
  - Devices pushed farther away from a centralized, trusted infrastructure
Summary of My Work

- Energy efficient protocols for wireless interfaces to adaptively sleep and listen to the channel
- Exploiting channel diversity for secure key distribution in sensor networks
- Protocol implementation on sensor hardware
Talk Outline

- Background on Energy Efficient Design
- Adaptive Sleeping Protocol
- Adaptive Listening Protocol
- Secure Key Distribution
- Future Research
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The Importance of Energy-Saving Research

✓ Battery life is a concern for wireless designers and users

✓ Energy efficient devices needed for ubiquitous wireless networks to become a reality
Won’t Moore’s Law Save Us?

NO!!!

Necessitates Energy-Saving Protocol Design

From “Thick Clients for Personal Wireless Devices” by Thad Starner in *IEEE Computer*, January 2002
Solution spans multiple areas of research: networking, OS, architecture, and applications

Our work focuses on the networking component

While applicable to laptops, our work is most beneficial to small/no display devices like sensors
How to Save Energy at the Wireless Interface

Specs for Mica2 Mote Radio

<table>
<thead>
<tr>
<th>Radio Mode</th>
<th>Power Consumption (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX</td>
<td>81</td>
</tr>
<tr>
<td>RX/Idle</td>
<td>30</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.003</td>
</tr>
</tbody>
</table>

- Sleep as much as possible!
- Fundamental Question: *When should a radio switch to sleep mode and for how long?*
Common Power Save Protocol Design

- $L$ and $S$ are static values regardless of traffic.
- Design used in IEEE 802.11 as well as sensor protocols (e.g., B-MAC and STEM).
- Used by both in-band and out-of-band protocols.

Listen until Timer Fires to Start Listening
Check for Wake-Up Signal
In-Band Protocol Example

A = Advertisement Pkt
C = ACK Pkt
D = Data Pkt
Out-of-Band Protocol Example

Sender Ctrl. Channel

Receiver Ctrl. Channel

Receiver Data Channel

Sender Data Channel

Wake up in \(S\) time

Idle

Busy

Time

Data

Signal
In-Band vs. Out-of-Band

- In-Band
  - Only requires one, half-duplex channel

- Out-of-Band
  - No synchronization required for control channel
  - Wake-up signaling does not interfere with data communication
Problems With Static Values

- **L** too short: Wake-up signals are missed
- **L** too long: Wasted energy

- **S** too short: Wasted energy
- **S** too long: Increased latency

---

**LISTEN**

**SLEEP**

Check for Wake-Up Signal

Sleep Until Timer Fires to Start Listening
Our Approach: Adaptive Energy-Saving Protocols

- Adapt listening (L) based on channel state
- Adapt sleeping (S) based on traffic arrivals and desired latency
# Protocol Design Space

<table>
<thead>
<tr>
<th></th>
<th>Adaptive Listening</th>
<th>Adaptive Sleeping</th>
</tr>
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<tbody>
<tr>
<td><strong>In-Band</strong></td>
<td><strong>Covered in this talk</strong></td>
<td><strong>Our multilevel routing work</strong></td>
</tr>
<tr>
<td><strong>Out-of-Band</strong></td>
<td><strong>Our in-band techniques are applicable</strong></td>
<td><strong>Covered in this talk</strong></td>
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![Diagram showing the transition between LISTEN and SLEEP modes with intervals marked as L and S](image-url)
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How Do You Choose S?

- If energy is our only concern then S can be arbitrarily large
  - However, the queue may become large
- Since sensors are resource limited, we address this queue constraint
  - If a device’s queue reaches a threshold, Q, then it must start transmitting packets soon
Adaptive Sleeping Overview

- Sender and receiver schedule a future wake-up time based on the traffic rate.
- If the sender’s queue reaches $Q$ packets before a scheduled wake-up:
  - Then the sender wakes up the receiver via the out-of-band control channel.
- All nodes periodically check control channel for wake-up signal:
  - If signal detected $\rightarrow$ Turn on data radio.
  - If data packet is for another node $\rightarrow$ Data radio returns to sleep.
Adaptive Sleeping Example

Sender Ctrl. Channel

Receiver Ctrl. Channel

Receiver Data Channel

Sender Data Channel

\[ Q = 2 \]

Sender’s Queue

Channel Idle

Channel Busy

Time

\[ t_1 \]

\[ t_2 \]

\[ \text{Sig} \]

\[ S \]

\[ < S \]
Adaptive Sleeping Tradeoff: S Too Small

Sender's Packet Queue Arrivals

Receiver Data Channel

Sender Data Channel

Energy Wasted Checking for Data Packet

Time
Adaptive Sleeping Tradeoff:
S Too Large

Sender Ctrl. Channel

Data Channel

Receiver

Neighbor 1

Neighbor N

$Q = 2$

Sender’s Queue

Energy Wasted Waiting for Receiver ID

Time

Figure 1: Illustration of the adaptive sleeping tradeoff when $S$ is too large. The figure shows the time line for control channel and data channel operations. The sender's control channel maintains the queue length $Q$ at 2, while the data channel allows the transmission of $D$ packets. The figure highlights the energy wasted waiting for the receiver ID.
Adaptive Sleeping Tradeoff

**Goal**: Adapt $S$ based on traffic arrivals to minimize energy consumption

- **Optimal Energy Consumption**
Adaptive Sleeping Analysis

Based on analysis, we found that $S$ is optimized according to the equation:

$$S = \gamma \left( \frac{1}{R} \right)$$

- $R =$ Packet arrival rate at sender
  - Can be estimated with a weighted moving average
- $\gamma =$ Function of $Q$ and the number of neighbors of the sender ($nbrs$)
  - Can be calculated offline when $Q$ and $nbrs$ are known
Adaptive Sleeping Results

- Simulated using *ns*-2 and Poisson traffic
- Rate Estimation
  - Proposed protocol with $Q=2$.
- Optimal
  - Optimal value of $S$ which minimizes energy
  - $S = \infty$
    - No timeout triggered wake-ups. Out-of-band wake-ups occur when $Q=2$ packets are in the queue.
- STEM
  - Out-of-band protocol proposed in [Schurgers02Optimizing]. Special case of our protocol with $S = \infty$ and $Q=1$. 
Adaptive Sleeping: Time-Varying Traffic Rate Results

Energy (Joules/Bit)

More Frequent

Rate Estimation

Optimal

STEM

S = ∞
Adaptive Sleeping: Multihop Topology Results

Rate Estimation

$S = \infty$

STEM

Relative Energy (Joules/Bit) vs. Sending Rate (Packets/Sec)
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Our Approach to Adaptive Listening

- Use physical layer carrier sensing to extend the listening period for advertisements
- Previous work has proposed dynamic listening periods for 802.11 power save, but ours is the first for single radio devices in multihop networks
Adaptive Listening Background: RX Threshold vs. CS Threshold

- **RX Threshold**: received signal strength necessary for a packet to be correctly received
- **CS Threshold**: received signal strength to consider the channel busy
- We assume that usually CS range $\geq 2 \times$ RX range
  - If this is not true, our technique gracefully degrades to a fixed listening interval scheme
Using Carrier Sensing for Adaptive Listening

- $t_3 = t_0 + T$
- $t_5 = t_1 + T$
- $t_6 = t_2 + T$
- $t_7 = t_4 + T$
Adaptive Listening: Additional Carrier Sensing Signaling

$N1$ $N2$ $N3$

$A = \text{Adv. Pkt}$

$C = \text{ACK Pkt}$

$D = \text{Data Pkt}$

$S = \text{"Dummy" Pkt}$
Adaptive Listening: Putting It All Together

CS1: Do listening if busy

CS2: Do static $L$ if busy

Adv. Window: If CS1 was busy. Size determined by CS2 feedback

- First CS period indicates whether advertisement window is necessary
- Second CS period indicates whether window size should be fixed or adaptive
  - If a sender repeatedly fails using adaptive listening, it can fallback to the original protocol
Adaptive Listening Results

- Simulated using ns-2
- Five flows with source and destination selected uniformly at random
  - Low traffic = 1 kbps per flow
  - Higher traffic = 10 kbps per flow
- CS Only = Carrier sense signaling at beginning of advertisement window only
- CS+AL = Carrier sense signaling at beginning plus adaptive listening
Low Traffic Results

Energy

- No PSM
- 802.11 PSM
- CS Only
- CS+AL

Latency

- 802.11 PSM
- CS+AL
- CS Only
- No PSM

Latency Increase: (1) Additional CS periods, (2) Packets arriving during AW, (3) For adaptive listening, postponed advertisements
Higher Traffic Results

Differences from Lower Traffic: (1) More Adv. windows have at least one packet, (2) More contention means more deferred Advss.
Adaptive Energy-Saving Summary

- Static sleep and listening intervals can degrade energy efficiency
- We propose adaptive power save methods that can benefit both out-of-band and in-band protocols
  - Adaptive Listening [IEEE MASS 2005]
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Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]

- Symmetric keys are favorable for resource constrained devices, but distribution is difficult
- Our idea: Exploit multiple channels available

Bob

Channel 1

Channel 2

Alice

Eve
Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]

- Given $K$ channels:
  \[
  \Pr(\text{Eve hears Bob’s packet} \mid \text{Alice hears Bob’s packet}) = \frac{1}{K}
  \]

- If Alice hears $M$ of Bob’s packets, then the probability that Eve heard all of those packets is $(1/K)^M$

- As $(1/K)^M \rightarrow 0$:
  The packets Alice heard can be combined to create Alice and Bob’s secret key
Leveraging Channel Diversity for Key Establishment [IEEE Infocom 2006]
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Future Research: Multihop Wireless Networks

Performance
- Efficient use of physical-layer diversity
- Opportunistic channel usage
- Integrating application knowledge in network protocol design

Security and Privacy
- Physical-layer diversity to counter attackers
- Distributed detection of misbehavior
Future Research: Multihop Wireless Networks

- Experimental testbeds
  - Test protocols in a realistic setting
  - Address implementation issues
  - Prior experience
    - Implementation in TinyOS on sensor hardware
    - User-level routing protocol for hybrid networks limited to several hops from access point
Research Summary

- Adaptive Energy-Saving Protocols

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<td>[IEEE MASS 2005]</td>
<td>Multilevel routing</td>
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<td></td>
<td>[IEEE Broadnets 2004]</td>
</tr>
</tbody>
</table>

- Secure Key Distribution [IEEE Infocom 2006]
- Energy-Latency Tradeoff for Broadcast Dissemination [IEEE ICDCS 2005]
- Implementation on Sensor Hardware
Thank You!

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Sources (1/2)
(Ordered by First Appearance)

- *The Other Wireless Revolution* by David A. Gross
  - http://www.state.gov/e/eb/rls/rm/2005/48757.htm

- Report: RFID production to increase 25 fold by 2010 in EE Times
  - http://tinyurl.com/aangg

- CNET's quick guide to Bluetooth headsets on CNET.com
  - http://tinyurl.com/dslev

- TinyOS Community Forum: Stats
  - http://www.tinyos.net/stats.html

- NCSA/UIUC Internet Visualization Graphic
  - http://tinyurl.com/d7qgr
Sources (2/2)

- Champaign-Urbana Community Wireless Network (CUWiN)
  - http://cuwireless.net/
- DakNet
Properties of Preamble Sampling

- No synchronization necessary
  - We require synchronization

- Larger preambles increase chance of collisions
  - We restrict CS signals to a time when data is not being transmitted
  - In our technique, interference is tolerable between CS signals

- Broadcasts require preamble size be as long as a BI
  - Exacerbates broadcast storm
  - We do not require extra overhead for broadcast

- Only one sender can transmit to a receiver per BI
  - We allow multiple senders for a receiver per BI
Is time synchronization a problem?

- Motes have been observed to drift 1 ms every 13 minutes [Stankovic01Darpa]
- The Flooding Time Synchronization Protocol [Maróti04SenSys] has achieved synchronization on the order of one microsecond
- Synchronization overhead can be piggybacked on other broadcasts (e.g., routing updates)
- GPS may be feasible for outdoor environments
- Chip scale atomic clocks being developed that will use 10-30 mW of power [NIST04]
Transition Costs Depend on Hardware [Polastre05IPSN/SPOTS]

<table>
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<tr>
<th>Mote Radio Model</th>
<th>Wake-Up Time (ms)</th>
<th>TX/RX/Sleep (mW)</th>
<th>Bitrate (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR1000 (1998-2001)</td>
<td>0.020</td>
<td>36/12/0.003</td>
<td>40 ASK</td>
</tr>
<tr>
<td>CC1000 (2002-2004)</td>
<td>2</td>
<td>42/29/0.003</td>
<td>38.4 FSK</td>
</tr>
<tr>
<td>CC2420 (2004-now)</td>
<td>0.580</td>
<td>35/38/0.003</td>
<td>250 O-QPSK</td>
</tr>
</tbody>
</table>
Related Work

- **Carrier Sensing**
  - B-MAC [Polastre04SenSys]: Make the packet preamble as large as the duty cycle
  - WiseMAC [ElHoiydi04Algosensors]: Send the packet preamble during the receiver’s next scheduled CS time
  - **We apply CS to synchronous protocols**

- **Dynamic Listening Periods**
  - T-MAC [VanDam03SenSys]: Extends S-MAC to increase the listen time as data packets are received
  - DPSM/IPSM [Jung02Infocom]: Extends 802.11 for dynamic ATIM windows in single-hop environments
  - **We use physical layer CS to work in multihop environments without inducing extra packet overhead**
Other Research

  - Probabilistic protocol gives flexibility to choose tradeoffs in energy, latency, reliability, and overhead for broadcast dissemination

- Routing using multiple power save states
  - Metrics to find energy-efficient states for nodes on a path while achieving a desired latency