Low-Power Acoustic Modem for Dense Underwater Sensor Networks

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Research Goals

- Bring sensor networks underwater
  - lots (10s, 100s)
  - of smart (able to compute and decide locally)
  - communicating (talk with each other, not just central database)
  - sensing and acting computers

- Applications
  - frequent 4-D seismic for shallow- / deep-water fields
  - assistance during underwater construction
  - flocks of underwater robots
underwater nodes
some attached to buoys
  alternative: could be a few wired and attached to sea floor
some attached to robots
one or several “base stations” with internet connectivity

communications
  underwater acoustic modems
  2nd tier of buoy-based radios (802.11?)
multi-access

Architecture described at WCNC, April 2006
Challenges and Approaches

- Acoustic channel is a strong challenge
  - Significant multi-path effects
  - Curved paths due to uneven temperature
  - Various noise such as bubbles and man-made objects
  - Large propagation delay (1500m/s)
  - High transmission power over long distance

- Existing work: increasingly sophisticated physical layer (PHY) techniques

- Our approach: short-range (< 500m) over multiple hops to avoid PHY complexities and conserve energy
Design Rationale

- **Low cost**
  - Enables large deployment of modem-equipped sensors (e.g., hundreds)

- **Low power**
  - Only support short-range communication with simple FSK modulation and non-coherent detection
  - Ultra-low power wakeup receiver enables deep sleep

- **Support higher layer protocols**
  - Time synchronization, RSSI, etc.

- **Match expected channel characteristics**
  - For example can add FEC in software
Frequency Selection

Source: Underwater Acoustic Systems Analysis
William S. Burdic

Graphs showing frequency selection and attenuation.

Noise spectrum level (dB/μPa/Hz) vs. frequency (Hz).

Low Band: Distant shipping
Mid band: Wind-related Kaupen noise
Hi band: Thermal noise

Sea state levels: 0, 1, 3, 6.
Acoustic Transmission Formats

- **Wake-up channel**
  - On-off keying
  - 18 kHz tone
  - Ultra-low power receiver

- **Data channel**
  - Binary Frequency-Shift Keying (BFSK)
  - Mark – 17 kHz
  - Space – 19 kHz
  - Data rate – 1kbps nominal
Experimentation Strategy

- **Goal: acoustic data transmission in an undersea environment**
  - First, develop experimental lab platform

- **Issue: transmission in water vs air**
  - Acoustic impedance – $1.5 \times 10^6$ vs $4.1 \times 10^2$ N-s/m$^2$
  - Preferred transducer in air: electromagnetic (tweeter)
  - Preferred transducer in water: piezoelectric

- **Approach**
  - Design for piezoelectric
  - Add matching networks to enable testing in air
Low Power Wakeup Receiver

ACOUSTIC MODEM BLOCK DIAGRAM
Prototype Wake-Up Receiver

Tweeter Input

Single 5V supply 100 microAmp

AM Detector 2N3906 pnp

Tuned cascode amplifier Dual-gate MOSFETs w/LC loads

Output Buffer 74HC04

Wake-Up Tone Receiver
500 µWatt
ACOUSTIC MODEM BLOCK DIAGRAM

Data Receiver

HYDROPHONE OR MICROPHONE

WAKEUP RECEIVER

DATA RECEIVER

TRANSMITTER

POWER CONTROL

CONTROL LOGIC

LEVEL SHIFT & BUFFERING

PROJECTOR OR LOUDSPEAKER

+5 VOLT

TO CONTROLLER
Prototype Acoustic Receiver

- Four-stage design
  - LC-tuned FET cascode amplifiers
- Single-chip limiter (MAX921)
- FM balanced-slope demodulator
  - OPA2374 summing amp + signal diode rectifiers
- Single-chip output filter
  - LTC1569 switched-capacitor
- 5V supply
Transmitter

ACOUSTIC MODEM BLOCK DIAGRAM
Prototype Acoustic Transmitter

- 555-based Voltage-controlled Oscillator
- FET switch-mode output amplifier
- Single 5V supply
- Separate data & wake-up inputs
- Tweeter Output
- Output level selected by transformer tap
Initial Testing

- Prototype testing completed
- Wakeup Operational
- Closed Loop BER < $1 \times 10^{-5}$ (across room)
Lessons Learned

- Software needs RSSI information
- Poor transmit efficiency
- 5 volt logic not compatible with mote
- Mote has limited I/O ports
Design Modifications

- Data Receiver provides RSSI
  - Philips SA604A IF Chip
- Transmitter efficiency improved
  - Texas Instruments TPA2000D1 amplifier
- Control/Data interface compatible with MOTES
  - 3.3 volt / 5 volt logic levels
  - Coded control logic to save IO pins
Block Diagram

ACOUSTIC MODEM BLOCK DIAGRAM
Rev 1.0 Production Prototype Board

Wake-up Receiver

I/O Logic

Data Receiver

Data Transmitter
Rev 1.0 Modem Hardware
Interface to Microcontroller

- Promote simple interfaces
- Use a minimal set of I/O pins
- Currently use Mica2 motes (Atmel ATmega128L MCU)
- Leverage TinyOS and existing sensor network software

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Function</th>
<th>I/O</th>
<th>Pin No.</th>
<th>Function</th>
<th>I/O</th>
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<tbody>
<tr>
<td>1</td>
<td>Ground</td>
<td>Both</td>
<td>9</td>
<td>Wake Int</td>
<td>Out</td>
</tr>
<tr>
<td>2</td>
<td>Vref (+3.3V)</td>
<td>In</td>
<td>10</td>
<td>RSSI</td>
<td>Out</td>
</tr>
<tr>
<td>3</td>
<td>Tx Data</td>
<td>In</td>
<td>11</td>
<td>Analog Out</td>
<td>Out</td>
</tr>
<tr>
<td>4</td>
<td>Mode</td>
<td>In</td>
<td>12</td>
<td>Digital Out</td>
<td>Out</td>
</tr>
<tr>
<td>5</td>
<td>Data</td>
<td>In</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Wake</td>
<td>In</td>
<td>14</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>Pwr 0</td>
<td>In</td>
<td>15</td>
<td>Vcc(+5V)</td>
<td>In</td>
</tr>
<tr>
<td>8</td>
<td>Pwr 1</td>
<td>In</td>
<td>16</td>
<td></td>
<td></td>
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</table>
Modem Control Interface

- **State control**
  - Each component can be individually powered on/off

- **Tx power control**
  - Currently has 4 levels: 15—33dBm

- **Wakeup interrupt**
  - Microcontroller can enter sleep mode, and be waken up by a wakeup tone

<table>
<thead>
<tr>
<th>Mode</th>
<th>Data</th>
<th>Wakeup</th>
<th>State</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Everything Off</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Wakeup Receiver is on</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Data Receiver is on</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>Both Receivers are on</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Transmitter is ready</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Sending Wakeup tone</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>Sending Data</td>
</tr>
</tbody>
</table>

Our modem provides fine-grained power control on each component
Modem hardware provides bit-level Tx and Rx

- Packet-level communication is implemented in software on microcontroller
  - Physical layer functions, e.g., start symbol detection and synchronization, coding, CRC
  - MAC protocol
  - Support for other protocols, e.g., timestamp, RSSI
- Can either work alone or connect to a host PC through the serial port
Modem Connected with Mote
Mote and Adapter
Modem Performance

- **Power Consumption**
  - Wakeup Rx: 100 uA @ 5 volts, 500 microwatts
  - Data Rx: 4 mA @ 5 volts, 20 milliwatts
  - Tx: > 80% efficient, 2.5 watts at max output

- **Sensitivity**
  - Wakeup Rx: 4 microvolts
  - Data Rx: 15 microvolts

- **Bandwidth**
  - Wakeup Rx: 300 Hz
  - Data Rx: 2000 Hz

- **Transmit Power**
  - Selectable: 32 mW, 125 mW, 500mW, 2 W
Modem Costs

- **Material Cost**
  - Based on quantity 100
  - Per board material cost about $37
    - All electronic components
    - Etched circuit boards

- **Assembly Cost**
  - ???
  - Need to avoid component selection
Transducer Costs

- **In air**
  - Audax tweeter ~$15

- **Underwater**
  - B & K 8103 ~$1730
  - Reson TC4013 ~$1000
  - Aquarian Audio H1-1 $79
  - Naval Postgraduate School
    - Konstantinos Bakas ~$50
    - Miguel Alvarez ~$30
  - MIT - Daniela Rus ???
Hardware Issues

- **Flicker Noise in FET**
  - Reduces sensitivity of Wakeup receiver

- **Producibility**
  - Tunable Inductors
  - Frequency Discriminator
    - Rev 1 PCB uses Quadrature Coil (hard to tune)
    - Will change to Pulse Counting demodulator (74HC221)
Noise Testing
Noise Spectrum
Conclusions

- Inexpensive short-range modem is feasible
- Ramping up internal use
- Final design will be released to public
  - PCB artwork
  - Schematic diagrams
  - Bill of Materials
  - Alignment/Tuning Instructions (if needed)

- Additional Information
  - http://www.isi.edu/ilense