Ultra-Low Energy RF Communication for Wireless Sensor Networks

Ben Cook
Prof. Kris Pister
## Motivation for Lower-Energy RF

### Energetic Cost of 8 Bit Sensor Node Operations

<table>
<thead>
<tr>
<th>Operation</th>
<th>Lowest Energy Published</th>
<th>Commercially Available (off-the-shelf)</th>
<th>Reference [Published], [Commercial]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 bit Analog-to-Digital Conversion</td>
<td>0.031 nJ</td>
<td>13.5 nJ</td>
<td>[Scott JSSC 03], [TLV 0831 <a href="http://www.ti.com">www.ti.com</a>]</td>
</tr>
<tr>
<td>8 bit Microprocessor Instruction</td>
<td>0.012 nJ</td>
<td>0.20 nJ</td>
<td>[Wameke ISSCC 04], [MSP 430 <a href="http://www.ti.com">www.ti.com</a>]</td>
</tr>
<tr>
<td>Compute an 8 bit, 1024 point FFT</td>
<td>80 nJ</td>
<td>-----</td>
<td>[Wang JSSC 05]</td>
</tr>
<tr>
<td>Transmit and Receive one 8 bit sample via RF at up to 20m range</td>
<td>32 nJ</td>
<td>2000 nJ</td>
<td>[Cook ISSCC 06], [CC2420 <a href="http://www.chipcon.com">www.chipcon.com</a>]</td>
</tr>
</tbody>
</table>
Comparison of Published RF for Sensor Networks

<table>
<thead>
<tr>
<th></th>
<th>RX</th>
<th>TX</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Molnar CICC '04</td>
<td>12</td>
<td>1.2</td>
<td>-3 Est.</td>
</tr>
<tr>
<td>B. Otis ISSCC '05</td>
<td>–</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>V. Pieris ISSCC '05</td>
<td>4.5</td>
<td>2.1</td>
<td>-32</td>
</tr>
<tr>
<td>This Work</td>
<td>6.7</td>
<td>0.33</td>
<td>-7.5</td>
</tr>
</tbody>
</table>
Minimum Transmission Energy
@ 2.4GHz from 100% Efficient TX to Zero-Pwr RX

\[ E_{\text{BIT,TX}} = kT \cdot \text{SNR} \cdot NF \cdot P_{\text{LOSS}} = 46\text{pJ/Bit} \]

Ideal TX
\[ e_{PA} = 100\% \]
\[ P_{OH,RF} = 0\text{W} \]

Ideal RX
\[ NF = 0\text{dB} \]
\[ \text{SNR}_{\text{MIN}} = 8\text{dB} \]
Deriving Practical Targets for Energy per Bit

Generic Transceiver Model

Transceiver Performance Data

\( f_0 = 2.4\text{GHz}, BW=500\text{kHz} \)
Transceiver Modeling Yields Practical Targets

![Graph showing energy per bit vs data rate]

Assumptions:
- \( t_{\text{INIT}} = 1 \text{ ms} \)
- \( N_{\text{BITS}} = 1000 \text{ bits} \)

Energy per bit - \( E_{\text{BIT}} \)

\[
E_{\text{BIT}} = \frac{1}{e} \cdot NF \cdot E_{\text{BIT,MIN}} + N \cdot E_{\text{Sample,ADC}} + E_{\text{INIT}} \approx 1nJ/\text{bit@2.4GHz}
\]
Future of Ultra-Low Energy RF

• Current results within 1-2 orders of minimum energy/bit @ 2.4GHz and close to practical targets

• Design Techniques are compatible with standards
  – 802.15.4 / 802.11b / Bluetooth
  – Current design does not comply with any standard

• Ultra-Low Energy targets for standard compliant radios