Short Distance Wireless and Its Opportunities

Jan M. Rabaey
Fred Burghardt, Yuen-Hui Chee, David Chen, Luca De Nardis, Simone Gambini,, Davide Guermandi, Michael Mark, and Nathan Pletcher

BWRC, EECS Dept.
Univ. of California, Berkeley
Short Distance Wireless
(from microns to tens of cm)

A Giant Window of Opportunity

• Below the radar screen in the wireless world
  – “Short distance” currently means around 10m (Bluetooth, 802.15.4, 802.15.4a)
• RF-ID the most visible member so far
• What exists is mostly at hoc; nothing really in place in terms of standards, or classification
• The only constraints are the power levels in the different spectrum bands

Crucial challenges: Power, Energy per useful bit, Size!
Short-Distance Wireless: Why?

- Wireless bio-monitoring and actuation
- Ad-hoc wireless assembly
- Ultra-dense networks - “paintable computing”

Smart Objects

Paint Operating Environment:

- Each node fitted with a wireless comm system which supports network connectivity to spatially proximal nodes.
- Communication radius < 2 cm
- Node size < 2 mm²
- Node clocked different clock rates (no inter-node synchrony)
- Network neighborhood size: 10-30 nodes
- Spatial distribution of particles: 2D or 3D (implementation dependent)
- Medium: likewise implementation dependent. Eg.
  - 3D ensemble suspended in viscous liquid
  - 2D ensemble laminated into planar carrier
- Node orientation: constrained or unconstrained
Smart Objects

Example: Intelligent Tires

Sensors embedded in liner of tire collect and transmit information about tire deformation, temperature gradients, etc to assist engine control and braking systems.

Challenges: weight and size of sensor nodes (< 5g), high data rate (> 100 kbs), reliability
Ad-hoc Wireless Assembly

Capacitive
Example: Sutherland et al, ISSCC04, HotInterconnect05

Inductive (Example: Kuroda)
Going One Step Further: Dense Networks

Artificial Skin

Communication Backplanes

Smart Surfaces

Real-time Health Monitoring
Classifications / Design Choices

- Radiative versus Reactive
- Wideband (pulse-based) versus Narrowband (sinusoidal)
- Passive versus Active
- Power source
**Power versus Size**

**Circuit’s Perspective**
- Lower frequency
  - Lower power
  - Smaller energy scavenging/storage devices

**Radiation’s Perspective**
- Large antennas (~\(\lambda/4 - \lambda/2\))
  - Efficient radiators

Tradeoff between size and power

Can we operate with small antennas and low frequency circuits?
Electrically Small Antennas

For frequency < 100 MHz, size < 1 cm³ and free space propagation
⇒ Electrically small antennas

Electrically small antennas

\[
\frac{\text{Electrical Path Length}}{\text{Wavelength}} < 0.1
\]

For frequency < 100 MHz, size < 1 cm³ and free space propagation
⇒ Electrically small antennas

\[
\left(\frac{\text{Electrical Path Length}}{\text{Wavelength}}\right) \text{ vs. Frequency (Hz)}
\]

N = 3, a = 5mm

Courtesy: Y.H. Chee
Radiative versus Reactive

\[ P_r = \frac{\pi}{3} \zeta \cdot I^2 \left( \frac{l}{\lambda} \right)^2 \left[ 1 - j \left( \frac{\lambda}{2\pi r} \right)^3 \right] \]  
(Power Density)

\[ \frac{\lambda}{2\pi} \gg r \]
Reactive Near-Field  
(inductive or capacitive)

\[ \frac{\lambda}{2\pi} \ll r \]
Radiative Far-Field

\[ \lambda/2\pi \gg r \]

\[ \lambda/2\pi \ll r \]
# Near Field vs Far Field Communications

<table>
<thead>
<tr>
<th></th>
<th>Near Field</th>
<th>Far Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication method</td>
<td>Reactive (lossless)</td>
<td>Radiative (lossy)</td>
</tr>
<tr>
<td>Transfer quantity</td>
<td>E or H field</td>
<td>Power</td>
</tr>
<tr>
<td>Antenna design</td>
<td>Maximize coupling</td>
<td>Impedance match to medium</td>
</tr>
<tr>
<td>Roll-off</td>
<td>$1/r^3$</td>
<td>$1/r^2$</td>
</tr>
<tr>
<td>• Range</td>
<td>Short</td>
<td>Very long</td>
</tr>
<tr>
<td>• Interference</td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td>• Dynamic range (for 10X ↑ in range)</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
<tr>
<td>Antenna design</td>
<td>Maximize coupling</td>
<td>Impedance match to medium</td>
</tr>
</tbody>
</table>
Narrow Band versus Wide Band

• **Narrow Band**
  – Advantages: Receiver inherently simpler; interference robustness
  – Disadvantages: Needs accurate frequency components; on-time may be large; fading

• **Wide Band**
  – Advantages: Duty-cycling reduces power dissipation; fading robustness through spreading
  – Disadvantages: Needs accurate timing
A Design Example

Dense networks (paintable electronics)

Power extremely limited (tens of μW)
Average distance between nodes < 5 cm
Frequency smaller than 1 GHz
(a = 0.4 cm, r < 5 cm, λ > 30 cm)
Design Option 1: Narrow Band

Passive receiver:
- 200 nW power
- -38 dBm sensitivity (not good enough)

Solution: add gain and coding

FBAR filter

LNA

Envelope detector

ADC

Digital baseband

Signal

<1µW 4µW Few µW

N. Pletcher (and B. Otis)
Narrow Band: Providing Gain

For 20 kbits/sec:
PTX $\cong$ 20 $\mu$W
PRX $\cong$ 200 $\mu$W

One Option: Super-regenerative

D. Guermandi and S. Gambini, UCB
Design Option 2: Wide Band

Transmitted pulse

Frequency Content

- EN Sync with pulses
- 3 nsec
- 5 cm
- 600 MHz
Precise Timing the Main Challenge in Reducing Power Consumption

How to avoid precise synchronization components (Xtals)?
Avoiding Accurate Timing Elements or Expensive Synchronizers

Through local, collaborative strategies

- Nodes synchronize by overhearing neighbors
- A small number of precise timing elements (anchors)
- Anchors synchronize to global beacon
- Opportunity for self-organization?

Courtesy: L. De Nardis

Example: 400 nodes, 4 anchors
Prototype Inductive Transceiver

Transmitter ≈ 30 pJ per Bit
- 0.6 μA @ 20 kbps, 9.6 μA @ 320 kbps
- 6.0 mA @ full speed (200 Mbps)

Receiver (analog part) ≈ 500 pJ per bit
- 10 μA @ 20 kbps, 160 μA @ 320 kbps
- 3.2 mA (always on @ full bandwidth)

PLL (analog part, including references)
- Ring Oscillator VCO ≈ 20 uA
- Loop filter & CP ≈ 40 uA

In Fab (May 06)

Courtesy: D. Guermandi
Most applications for short-distance wireless are battery-averse (not accessible, high density, ...)

Scavenging of power for data acquisition, storage, and transmission hence a necessity

Challenges: mass, size, reliability

Courtesy: P. Wright, S. Roundy, M. Koplow
## Figures of Merit

<table>
<thead>
<tr>
<th>System</th>
<th>Range</th>
<th>Peak Operating Power</th>
<th>Data Rate (Pulse Rate)</th>
<th>Energy/Bit (Energy/Pulse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[IMEC_UWB]</td>
<td>1m</td>
<td>N.R.</td>
<td>20MP/s</td>
<td>1.44nJ/P</td>
</tr>
<tr>
<td>[Kuroda_UWB]</td>
<td>1m</td>
<td>5mW</td>
<td>1MP/s</td>
<td>1nJ/P</td>
</tr>
<tr>
<td>[Otis_NB]</td>
<td>10m</td>
<td>400uW</td>
<td>20Kb/s</td>
<td>20nJ/B</td>
</tr>
<tr>
<td>[Pister_NB]</td>
<td>10m</td>
<td>400uW</td>
<td>100Kb/s</td>
<td>3nJ/B</td>
</tr>
<tr>
<td>[UCB_WB]</td>
<td>5cm</td>
<td></td>
<td>20Kb/s –200 Mb/s</td>
<td>30/500pJ/bit</td>
</tr>
<tr>
<td>[Atmel]</td>
<td>9.25m</td>
<td>16.7uW</td>
<td>250Kb/s</td>
<td>60pJ/B</td>
</tr>
<tr>
<td>[EPFL_UWB]</td>
<td>12m</td>
<td>2.7uW</td>
<td>1Mb/s</td>
<td>2.7pJ/B</td>
</tr>
</tbody>
</table>

Extremely hard to compare or normalize numbers:
- Energy per useful bit (TX, RX, Combined)
- Sensitivity
- BER
- Energy source

**Need to device meaningful set of metrics**
Summary

- Short distance wireless presents huge window of opportunity
- Needs clear metrics to allow for classification of different approaches in terms of energy and size efficiency
- Combining energy and data transmission very attractive, but somewhat contradictory
- May ultimately lead to novel computation and communication models
Maybe not the most efficient communication mechanism, but …

- Generic architectural approach for dealing with failure – not dependent upon fault mode
- Reliability transparent to the algorithm
- Graceful degradation of performance

Sources: K. Ramchandran (UCB), D. Jones (UIUC)