BSAC IAB
4th Semi-annual
Mini-Workshop
on
Wireless Sensor Networks

Agenda

1:00-2:00 Introduction
   – History, Technology, Standards (Kris Pister)
2:00-3:00 Commercial Perspectives I
   – Coronis Systems (Jeff Braid)
   – Crossbow (Michael Dierks)
   – Streetline Networks (Mark Noworolski)
   – WIT (Jim Evans)
3:15-3:30 Break
3:30-4:30 Commercial Perspectives II
   – Moteiv (Joe Polastre)
   – Pirelli/Telecom Italia (Claudio Borean)
   – Adura (Charlie Huizenga)
4:30-5:00 University Update
Wireless Sensor Networks
History, Technology, Standards

Kris Pister
Prof. EECS, UC Berkeley
Co-Director, Berkeley Sensor & Actuator Center

(Founder & CTO, Dust Networks)

Outline

• The Past
• What Went Wrong
• Technology Status
• Applications
• Technology Directions
Autonomous Microsensor Networks with Optical Communication Links

- PI: Kris Pister
- Source: Hughes (MICRO)
- Funding: $25k, $10k matching, 0% ovhd,
- Duration: 1 year
- Comments: Collaboration w/ Prof. Joe Kahn under separate MICRO

GOAL:
- Get our feet wet

RESULT:
- Cheap, easy, off-the-shelf RF systems
- Fantastic interest in cheap, easy, RF:
  - Industry
  - Berkeley Wireless Research Center
  - Center for the Built Environment (IUCRC)
  - PC Enabled Toys (Intel)
- Fantastic RF problems
- Optical proof of concept
### Berkeley Demos – 2001

- Intel Developers Forum, live demo
  - 800 motes, 8 level dynamic network,
  - Motes dropped from UAV, detect vehicles, log and report direction and velocity

| Seismic testing demo: real-time data acquisition, $200 vs. $5,000 per node | 50 temperature sensors for HVAC deployed in 3 hours. $100 vs. $800 per node. |

### Cost of Sensor Networks

![Cost of Sensor Networks Diagram](image)

- **Time**
- **$**
- **Computing Power**
- **Mesh Networking**
- **Installation, Connection and Commissioning**
- **Sensors**
Sensor Networks Take Off!

Industry Analysts Take Off!

$8.1B market for Wireless Sensor Networks in 2007

Low Data Rate WPAN Applications

Zigbee

security
HVAC
AMR
lighting control
access control

security
HVAC
AMR
lighting control
access control

TV
VCR
DVD/CD remote

mouse
keyboard
joystick

security
HVAC
lighting control
access control

lawn & garden irrigation

RESIDENTIAL/
LIGHT COMMERCIAL
CONTROL

PERSONAL HEALTH CARE

BUILDING AUTOMATION

INDUSTRIAL CONTROL

CONSUMER ELECTRONICS

PC & PERIPHERALS
(... but I heard that it doesn’t work …)

- Industrial automation
  - Decades of false starts

- Defense
  - NEST fallout

- Home, health care, HVAC, security, …
  - Failed investments in using chips & stacks
  - “We tried it w/ x, and couldn’t get it to work”

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### Barriers to Adoption

- Reliability
- Standards
- Ease of Use
- Power consumption
- Development cycles
- Node size

OnWorld, 2005
Dust Networks

- Focused on reliability, power consumption
- Bad CEO 2003
- OK CTO 2004—date
- Developed TSMP
  - Time Synchronized Mesh Protocol
  - >99.9% reliability
  - Lowest power per delivered packet

Time-synchronized communication

- Assume all motes share a network-wide synchronized sense of time, accurate to ~1ms
- For an optimally efficient network, mote A will only be awake when mote B needs to talk

A wakes up and listens

B transmits

B receives ACK

A transmits ACK

Expected packet start time

Worst case A/B clock skew
### Timing – imperfect synchronization (latest possible transmitter)

<table>
<thead>
<tr>
<th>CCA, RX startup, listen, RX→TX</th>
<th>Transmit Packet: Preamble, SS, Headers, Payload, MIC, CRC</th>
<th>RX startup or TX→Rx</th>
<th>TX</th>
<th>RX ACK</th>
</tr>
</thead>
</table>

- **$T_{CCA}$** = 0.512 ms to be standards compliant
  - Worst case is a receive slot followed by a transmit slot to a different partner, as radio will be finishing up the ACK TX just as it needs to look for a clear channel, so
  - $T_{CCA} = T_{TX→RX} + T_{channel assessment} + T_{RX→TX} = 0.192 ms + 0.128 ms + 0.192 ms$
  - With gold24, we believe we can do a faster turnaround, so we’d get 0.228 instead of 0.512
- **$T_{packet}$** = 4.256 ms for a maximum length packet
  - Preamble+SS+packet = 4+1+128B = 133B = 1064 bits @ 250kbps
- **$T_{crypto}$** needs to be chosen. For gold24 it will be about 0.25 or 0.5 ms. For the cc2420 it appears to be a bit slower – maybe 0.5 to 1 ms.
- **$T_{gACK}$** needs to be chosen. It is the tolerance to variation in $T_{crypto}$ and/or mote B’s turnaround time from RX to TX
- **$T_{ACK}$** is a function of the ACK length. It is likely to be just under 1 ms.
- $T_{slot} = T_{CCA} + 2T_g + T_{packet} + T_{crypto} + T_{gACK} + T_{ACK} = 0.512 + 2 + 4.256 + 1 + 0.1 + 1 = 9$ ms

### Packet transmission and acknowledgement

- **Mote Current**
  - Radio TX startup
  - Packet TX
  - ACK RX
  - Radio TX/RX turnaround
  - Energy cost: 295 uJ

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*Image of a diagram showing the timing and packet transmission process.*
Fundamental platform-specific energy requirements

- Packet energy & packet rate determine power
  - \( \frac{Q_{TX} + Q_{RX}}{T_{listen}} \)
  - E.g. \( \frac{300 \text{ uC} + 200 \text{ uC}}{10 \text{s}} = 50 \text{ uA} \)

Idle listen (no packet exchanged)

- Mote
- Current
- Radio RX startup
- ACK RX

Energy cost (2003): 70 uC
Scheduled Communication Slots

- Mote A can listen more often than mote B transmits
- Since both are time synchronized, a different radio frequency can be used at each wakeup
- Time sync information transmitted in both directions with every packet

Latency reduction

- Energy cost of latency reduction is easy to calculate:
  - \( \frac{Q_{\text{listen}}}{T_{\text{listen}}} \)
  - E.g. 70uC/10s = 7uA
- Low-cost “virtual on” capability
- Latency vs. power tradeoff can vary by mote, time of day, recent traffic, etc.
Multi-hop routing

- Global time synchronization allows sequential ordering of links in a “superframe”
- Measured average latency over many hops is $T_{frame}/2$

TSMP Foundations

- Time Synchronization
  - Reliability
  - Power
  - Sensor
- Reliability
  - Frequency diversity
    - Multi-path fading, interference
  - Spatial diversity
    - True mesh (multiple paths at each hop)
  - Temporal diversity
    - Secure link-layer ACK
- Power
  - Turning radios off is easy
Oil Refinery – Double Coker Unit

- Scope limited to Coker facility and support units spanning over 1200ft
- No repeaters were needed to ensure connectivity
- Electrical/Mechanical contractor installed per wired practices
- >5 year life on C-cell
### Standards

- IEEE 802.15.4
- Wireless HART
- ISA SP100

### WirelessHART

- HART – Highway Addressable Remote Transducer
  - Wired standard, ~2 decades old
  - 25 million sensors deployed
- Wireless HART
  - Based on TSMP 2.0
  - Out to ballot 3/07
### Industrial Automation Use Cases

- Monitoring
- Diagnostics
- Configuration
- Handheld
- Peer to Peer (Phase II)

Simulation of a 250 node network (courtesy Bob Karschner)

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### Performance Limits

- **Data collection**
  - 100 pkt/s per gateway channel
  - 16*100 pkt/s with no spatial reuse of frequency

- **Throughput**
  - ~80kbps secure, reliable end-to-end payload bits per second per gateway
  - 16 * 80k = 1.28Mbps combined payload throughput w/ no spatial reuse of frequency

- **Latency**
  - 10ms / PDR per hop
  - Statistical, but well modeled

- **Scale**
  - > 1,000 nodes per gateway channel
ISA SP100

- ISA - International Society of Automation
- SP100 - Standards Project 100
  - Wireless standard for industrial automation
  - Political wrangling
    - Default PHY: 802.15.4
    - Alternate PHY: NB/FHSS
  - Draft 2008?

802.15.4

- IEEE 802.15.4
  - PHY, low-MAC
  - Basis for
    - Zigbee 2003
    - Zigbee 2006
    - Zigbee Pro
    - WirelessHART
    - SP100
    - All incompatible

- WirelessHART & SP100 goal:
  - Fold TSMP back into 802.15.4 (-2009?)
## Standards

- IEEE 802.15.4
- Wireless HART
- ISA SP100

### The De-facto Standard

12 Manufacturers, 1 Network – Dust Networks’ TSMP
Excerpts from Customer Presentations at the Emerson Process Users Conference October 2-5, 2006

A Shift In Total Data Acquisition Cost Will Drive A New Asset Management Paradigm

- Field Device ~$1,500*
- Conduit / Wiring / Dwgs ~$9,500 *
- I/O / Loop Check / Config ~$500 *

* Budgetary estimates per point

Integrate into:
- DeltaV
- AMS
- ROC/RTU
- Historian
- Standard PC
- 3rd Party Hosts

5-10x $ Reduction

Total Cost per Point
Presenters

• Marty Gering
  – Wireless Coordinator, Cherry Point Refinery

• Dan Carlson
  – Sr. Wireless Engineer, Rosemount

Installation

• No site Survey
• Installed Like a Wired Device
• Commissioned like a Wired Device
• Operates Like a Wired Device
• Trend Data
• >99.9% Reliable

Installation Site

• Operator: Encana Oil and Gas
• Parachute, Colorado
• Natural Gas Compressor Station
• System: DeltaV
• Architecture:
  – Fieldbus control
  – Wireless monitoring
Robust Solar Panel

Fine paint spray

Challenges

- Challenges faced with this type of device
  - Trying to find a location that would not work
  - The electricians did not like the ease of installation(sp)
    - Less work
    - Less wire
    - Less conduit....

- It just worked!
Streetline Networks

Streetline™ & Streetlink API™ Product Sheet

All Streetline parking data is geo-coded and can be linked with any GIS system. This screenshot shows real-time parking data in San Francisco displayed in Google Earth.

Federspiel Controls

HVAC System Retrofits

Demonstrated Energy Savings:

- 3.7 kWh/sf/yr
- 0.34 therms/sf/yr
- Higher savings than conventional retrofits
Barriers to Adoption

<table>
<thead>
<tr>
<th>Feature</th>
<th>Percentage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>&gt;99.9%</td>
<td>Wireless HART, SP100</td>
</tr>
<tr>
<td>Standards</td>
<td></td>
<td>“It just worked”</td>
</tr>
<tr>
<td>Ease of Use</td>
<td></td>
<td>5-10 years</td>
</tr>
<tr>
<td>Power consumption</td>
<td></td>
<td>Complete networks</td>
</tr>
<tr>
<td>Development cycles</td>
<td></td>
<td></td>
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<tr>
<td>Node size</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OnWorld, 2005

2.4 GHz Transceiver Front End

- Cook et al., ISSCC 2006
- Active Area: 0.8mm²
- Zero external RF components
Radio Performance

With software:
10 years $\rightarrow$ D cell

With software:
10 years $\rightarrow$ coin cell

RF Time of Flight Ranging in a Coal Mine Tunnel

Steven Lanzisera
Mote on a Chip? (circa 2001)

- **Goals:**
  - Standard CMOS
  - Low power
  - Minimal external components

UCB Hardware Results ~2003

- 2 chips fabbed in 0.25μm CMOS
  - “Mote on a chip” worked, TX only
  - 900 MHz transceiver worked

- Records set for low power CMOS
  - ADC, Mike Scott, M.S.
    - 8 bits, 100kS/s
    - 2μA@1V
  - Microprocessor, Brett Warneke, PhD.
    - 8 bits, 1MIP
    - 10μA@1V
  - 900 MHz radio – Al Molnar M.S.
    - 100kbps, “bits in, bits out”
    - 20 m indoors
    - 0.4mA @ 3V
Mote on a Chip, 2009

**Goals:**
- Standard CMOS
- Low power
- Minimal external components

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**Conclusion**

- 10 years later, a real market emerges
- Reliable, low power, standards-based technology is no more expensive than junk
- The lowest power radios in the world come from UCB/EECS/BSAC
- The best software and algorithms for WSN come from UCB/EECS/BSAC
Time Slot and Channel Mapping

The two links from B to A are dedicated.
D and C share a link for transmitting to A.
The shared link does not collide with the dedicated links.

Timing – perfect synchronization

A transmits to B
TX, RX ACK timing