IP is the Future of Ubiquitous Sensor Networks

TinyOS USN applications workshop

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Arch Rock Corp.
The Internet ... that we envisioned
THE Question

If Wireless Sensor Networks represent a future of “billions of information devices embedded in the physical world,”

why don’t they run THE standard internetworking protocol?
The Answer

They should

• Substantially advances the state-of-the-art of both.
• Implementing IP requires tackling the general case, not just a specific operational slice
  – Interoperability with all other potential IP network links
  – Potential to name and route to any IP-enabled device within security domain
  – Robust operation despite external factors
    • Coexistence, interference, errant devices, ...
• While meeting the critical embedded wireless requirements
  – High reliability and adaptability
  – Long lifetime on limited energy
  – Manageability of many devices
  – Within highly constrained resources
IP in TinyOS on Motes is a reality today

* Production implementation on TI msp430/cc2420

- Footprint, power, packet size, & bandwidth

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A Decade Ago we could not imagine IP would scale to Tiny WSNs

- “Resource constraints may cause us to give up the layered architecture.”
- “Sheer numbers of devices, and their unattended deployment, will preclude reliance on broadcast communication or the configuration currently needed to deploy and operate networked devices.”
- “There are significant robustness and scalability advantages to designing applications using localized algorithms.”
- “Unlike traditional networks, a sensor node may not need an identity (e.g. address).”
- “It is reasonable to assume that sensor networks can be tailored to the application at hand.”
Confluence on three fronts
## A Low-Power Standard Link

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<tr>
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<th>802.15.4</th>
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<th>802.11</th>
<th>802.3</th>
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<tr>
<td><strong>Class</strong></td>
<td>WPAN</td>
<td>WPAN</td>
<td>WPAN</td>
<td>WLAN</td>
<td>LAN</td>
</tr>
<tr>
<td><strong>Lifetime (days)</strong></td>
<td>100-1000+</td>
<td>1-7</td>
<td>Powered</td>
<td>0.1-5</td>
<td>Powered</td>
</tr>
<tr>
<td><strong>Net Size</strong></td>
<td>65535</td>
<td>7</td>
<td>243</td>
<td>30</td>
<td>1024</td>
</tr>
<tr>
<td><strong>BW (kbps)</strong></td>
<td>20-250</td>
<td>720</td>
<td>11,000+</td>
<td>11,000+</td>
<td>100,000+</td>
</tr>
<tr>
<td><strong>Range (m)</strong></td>
<td>1-75+</td>
<td>1-10+</td>
<td>10</td>
<td>1-100</td>
<td>185 (wired)</td>
</tr>
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<td><strong>Goals</strong></td>
<td>Low Power, Large Scale, Low Cost</td>
<td>Cable Replacement</td>
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<td>Throughput</td>
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- Low Transmit power, Low SNR, modest BW, Little Frames
Decade of Sensor Network Research - without Architecture

- Application
- Transport
- Network
- Link

Three Key Developments

• Idle listening
  – Radio power: transmit \approx receive \approx just listening
  – All the energy is consumed by listening for a packet to receive
    • $E = P \times \text{Time}$
    \Rightarrow Turn radio on only when there is something to hear

• Reliable routing on Low-Power & Lossy Links
  – Power, Range, Obstructions => multi-hop
  – Always at edge of SNR => loss happens
  \Rightarrow monitoring, retransmission, and local rerouting

• Trickle – don’t flood (tx rate < 1/density, and < info change)
  – Connectivity is determined by physical points of interest, not
    network designer. May have huge number of neighbors, so …
  – never naively respond to a broadcast
  – re-broadcast very very politely
Key IPv6 Contributions

• Large simple address
  – Network ID + Interface ID
  – Plenty of addresses, easy to allocate and manage

• Autoconfiguration and Management
  – ICMPv6

• Integrated bootstrap and discovery
  – Neighbors, routers, DHCP

• Protocol options framework
  – Plan for extensibility

• Simplify for speed
  – MTU discovery with min

• 6-to-4 translation for compatibility
Making sensor nets make sense

LoWPAN – 802.15.4
- 1% of 802.11 power, easier to embed, as easy to use.
- 8-16 bit MCUs with KBs, not MBs.
- Off 99% of the time

Web Services
XML / RPC / REST / SOAP / OSGI
HTTP / FTP / SNMP
TCP / UDP
IP
Ethernet Sonet 802.11
802.15.4, ...
IETF 6lowpan
6LoWPAN adaptation

Diverse Object and Data Models (HTML, XML, …, BacNet, …)

Application (Telnet, FTP, SMTP, SNMP, HTTP)

Transport (UDP/IP, TCP/IP)

Network (IP)

Link

Seria l Modem
ISDN
DSL
GPRS
X3T9.5
FDDI
Sonet

802.3
802.5
802.3a
802.5 Token Ring
802.11
802.11b
802.11g
802.11n
802.15.4 LoWPAN

Ethernet
10bT
100bT
1G bT
13
6LoWPAN Challenges

- Large IP Address & Header => 16 bit short address / 64 bit EUID
- Minimum Transfer Unit => Fragmentation
- Short range & Embedded => Multiple Hops
IPv6 Header Compression

- Link local => derive from 802.15.4 header
- In 802.15.4 header
- Zero

in HC1 byte

uncompressed
Low Impact of 6LoWPAN on Lifetime - Comparison to *Raw* 802.15.4 Frame

Energy Cost of Packet Communication vs. Data Size

- RCV 6LoWPAN Local <= Global
- RCV 6LoWPAN Local <= Local
- RCV Raw 802.15.4
- TX 6LoWPAN Local => Global
- TX 6LoWPAN Local => Local
- TX Raw 802.15.4

* fully compressed header
* additional 16-byte IPv6 address
Complete Embedded IPv6 Stack
Embedded IPv6 in Concept

Structured Decomposition
- Retain strict modularity
- Some key cross-layer visibility

IP Link $\Rightarrow$ Always On
- Retain illusion even when always off

IP Link $\Rightarrow$ “Reliable”
- Retain best-effort reliability over unreliable links

IP Link $\Rightarrow$ Broadcast Domain
- IPv6 can support a semi-broadcast link with few changes
Autoconfiguration
Configuring Large Numbers of Interfaces

**Stateless**
RFC 4861 + 4862

- L2e: 00-17-3B-00-12-58-28
- L2s: 0x0001
- L3: 2001:abcd::1

**DHCPv6**
RFC 3315

- L2e: 00-17-3B-00-57-17-58-39
- L2s: 0x0001
- L3: 2001:abcd::23

- L2e: 00-17-3B-00-79-49-66-23
- L2s: 0x0092
- L3: 2001:abcd::23

- L2e: 00-17-3B-00-07-49-66-23
- L2s: 0x0092
- L3: 2001:abcd::92
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Low Power, Reliability, Scaling

\[ f_{rx} = N f_{ra} + D (f_{rr} + f_{app}) \]
\[ f_{txb} = f_{ra} \]
\[ f_{txu} = (1 + D) (f_{rr} + f_{app}) \]

Data Rate Sensitivity
- (Router)

Data Rate Sensitivity
- (Edge)

Deployment Duty Cycle

Deployment Reliability
event void Boot.booted() { call Udp.bind(7); }

event void Udp.recvfrom(void *buf, uint16_t len, sockaddr_in6_t *from, link_metadata_t *linkmsg) {
    call Udp.sendto(buf, len, from);
}

call Udp.sendto(buf, len, from);
uint8_t m_buf[ BUF_SIZE ];
event void Boot.booted() {
    call Tcp.bind( 7 );
    call Tcp.listen();
}
event bool Tcp.accept( sockaddr_in6_t *to, void **sendbuf,
    uint16_t *sendbuf_size ) {
    *sendbuf = m_buf;
    *sendbuf_size = sizeof(m_buf);
    return TRUE;
}
event void Tcp.connected() {}
event uint16_t Tcp.recv( void *buf, uint16_t len ) {
    return call Tcp.send( buf, len ) == SUCCESS ? len : 0;
}
event void Tcp.acked() {}
event void Tcp.closed() {
    signal Boot.booted();
}
TinyOS and Industry

• TinyOS and the Berkeley Mote has always been an interplay of academia and industry
  – Academic research creates and gives to industry
  – Industry refines and gives back
• BSD license permits commercialization
  – It is not GPL
  – Preserve copyright, but take to market
• Companies give back in many forms
  – Sell products compatible with open reference
  – Hopefully, hardened and improved
Wireless Embedded Internet
- Starting Points

• [http://www.eecs.berkeley.edu/~culler/WEI](http://www.eecs.berkeley.edu/~culler/WEI)
  – Complete set of lectures, labs, and materials (in progress)

• [http://support.archrock.com/toski](http://support.archrock.com/toski)
  – Evaluation version of IPv6 TinyOS Binary Kernel
  – Epic and Telosb platforms

• [http://support/archrock.com/ASD](http://support/archrock.com/ASD)
  – Arch Rock IP/6LoWPAN Software Distribution (ASD) - Atmel RZ Raven
    • Atmega + RF231
  – C kernel with a TinyOS Core
Generation 4 - EPIC

- http://www.eecs.berkeley.edu/~prabal/projects/epic/
- Prototype => Pilot => Production
Epic Family

USB+Power  Storage  Solar + External Sensor

ARCHRock
Epic Interface Board

- Epic core
- Trim Pot
- Power pins
- IO pins
- LEDs
- 2 binaryInputs
- 2 binaryOutputs
- 4 analog Inputs
- external voltage sel.
- Convert switch to digital value
- signal conversion
- USB
- 5v TTL reg
- Li Ion battery
- Alkaline battery
- user button
- reset button
- Alkaline battery
- USB
- Epic USB

ArchRock
Application Solutions

Electric Monitoring and Control

Outdoor Microclimate Monitoring
TinyOS.net - The Open Source

• TinyOS 2.0.2 is released
• TinyOS 2.1 will be a Safe Language
  – Compiler checks ALL pointer and Array references for Safety
  – Technology Path: UCB => MS => Utah => TinyOS Community
• Take & Give Back
  => Contribute Code to the Community
The Next Phase

• TinyOS was invented as a framework for defining key abstractions for intelligent wireless devices embedded in the physical world.
  – Allow the right abstractions to emerge from experience
  – Hardened abstractions, platforms, community => Safety

• Advance on three fronts makes the Internet Architecture viable for this class of devices
  – Structures the problem into manageable pieces
  – Permits greater impact of high quality solutions

• New set of questions within this framework
  – LP MAC really, OS API, Cross layer visibility
  – In-network processing as overlays

• The “IP/USN” is here … today
The IP/USN

LoWPAN-Extended IP Network

IP Network (powered)

IP/LoWPAN Router

IP/LoWPAN Sensor Router

IP Device