Wireless Protocols for IoT Part II: IEEE 802.15.4 Wireless Personal Area Networks

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These slides and audio/video recordings of this class lecture are at: http://www.cse.wustl.edu/~jain/cse574-16/
Overview

1. Internet of Things and Wireless Protocols for IoT
2. IEEE 802.15.4: Topologies, MAC, PHY
4. IEEE 802.15.4e Enhancements

Note: This is the 3rd lecture in series of class lectures on IoT. Bluetooth and Bluetooth Smart are also used in IoT and were covered in the previous lectures. Future lectures will cover ZigBee and other protocols.
IEEE 802.15.4

- Used by several “Internet of Things” protocols: ZigBee, 6LowPAN, Wireless HART, MiWi, and ISA 100.11a

<table>
<thead>
<tr>
<th>Application</th>
<th>ZigBee</th>
<th>6LoWPAN</th>
<th>Wireless HART</th>
<th>MiWi</th>
<th>ISA 100.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network</td>
<td>802.15.4</td>
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<td>MAC</td>
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<td>PHY</td>
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<td>802.15.4</td>
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</tbody>
</table>
IEEE 802.15.4 Overview

- Low Rate Wireless Personal Area Network (LR-WPAN)
- 2.4 GHz (most common). 16 5-MHz channels
- 250 kbps PHY ⇒ 50 kbps application data rate
- Peak current depends upon symbol rate ⇒ multilevel 4b/symbol)
- Similar to 802.11: Direct Sequence Spread Spectrum, CSMA/CA, Backoff, Beacon, Coordinator (similar to Access point)
- Lower rate, short distance ⇒ Lower power ⇒ Low energy
- Each node has a 64-bit Extended Unique ID (EUI-64):
  
<table>
<thead>
<tr>
<th>U/M</th>
<th>G/L</th>
<th>OUI</th>
<th>40 bits assigned by the manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>1b</td>
<td>22b</td>
<td>40b</td>
</tr>
</tbody>
</table>

- No segmentation/reassembly. Max MAC frame size is 127 bytes with a payload of 77+ bytes.
IEEE 802.15.4 Topologies

- Star and peer-to-peer
- Two types of devices: Full Function device (FFD), Reduced Function device (RFD)

Ref: IEEE 802.15.4-2011
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Coordinator

- FFDs can become coordinator and can also route messages to other nodes
- RFDs cannot become coordinator and can only be a leaf
- FFD that starts a PAN becomes the coordinator
- In star topology, all communication is to/from the coordinator
- In P2P topology, FFDs can communicate directly also.
- Each piconet has a PAN ID and is called a **cluster**.
- Nodes join a cluster by sending association request to the coordinator. Coordinator assigns a 16-bit short address to the device. Devices can use either the short address or EUI-64 address.
Cluster Tree Network

- A coordinator can ask another FFD to become a coordinator for a subset of nodes. Tree ⇒ No loops

Ref: IEEE 802.15.4-2011
Washington University in St. Louis
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IEEE 802.15.4 MAC

Beacon-Enabled CSMA/CA

- Coordinator sends out beacons periodically
- Part of the beacon interval is inactive ⇒ Everyone sleeps
- Active interval consists of 16 slots
- Guaranteed Transmission Services (GTS): For real-time services. Periodic reserved slots.
- Contention Access Period (CAP). Slotted CSMA.

Ref: IEEE 802.15.4-2011
Washington University in St. Louis
http://www.cse.wustl.edu/~jain/cse574-16/
IEEE 802.15.4 MAC (Cont)

- **Beaconless Operation**: Unslotted CSMA
  - If coordinator does not send beacons, there are no slots
- Acknowledgements if requested by the sender.
- Short inter-frame spacing (SIFS) if previous transmission is shorter than a specified duration. Otherwise, Long inter-frame spacing (LIFS)

**Acknowledged Transmissions**

```
<table>
<thead>
<tr>
<th>Long Frame</th>
<th>ACK</th>
<th>Short Frame</th>
<th>ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_{ack}</td>
<td>LIFS</td>
<td>t_{ack}</td>
<td>SIFS</td>
</tr>
</tbody>
</table>
```

**Unacknowledged Transmissions**

```
<table>
<thead>
<tr>
<th>Long Frame</th>
<th>Short Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIFS</td>
<td>SIFS</td>
</tr>
</tbody>
</table>
```
802.15.4 CSMA/CA

- Wait until the channel is free.
- Wait a random back-off period
  If the channel is still free, transmit.
- If the channel is busy, backoff again.
  Backoff exponent limited to 0-2 in battery life-extension mode.
- Acknowledgement and Beacons are sent without CSMA-CA.
An impulse in time domain results in a ultra wide spectrum in frequency domain and essentially looks like a white noise to other devices.
Ultra-Wideband (UWB)

- FCC rules restrict the maximum noise generated by a wireless equipment \((0 \text{ dBm} = 1\text{ mW}, -40 \text{ dBm} = 0.1 \mu\text{W})\)
- It is possible to generate very short (sub-nano sec) pulses that have spectrum below the allowed noise level
  \(\Rightarrow\) Possible to get Gbps using 10 GHz spectrum
- FCC approved UWB operation in 2002
- UWB can be used for high-speed over short distances
- UWB can see through trees and underground (radar)
  \(\Rightarrow\) collision avoidance sensors, through-wall motion detection
- Position tracking: cm accuracies. Track high-value assets

FCC Part 15 Limit = -41.3 dBm/MHz

<table>
<thead>
<tr>
<th>Power dBm/MHz</th>
<th>Cell phones</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>FCC Part 15 Limit = -41.3 dBm/MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GHz</th>
<th>Power (dBm/MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-40</td>
</tr>
<tr>
<td>2</td>
<td>-40</td>
</tr>
<tr>
<td>4</td>
<td>-40</td>
</tr>
<tr>
<td>6</td>
<td>-40</td>
</tr>
<tr>
<td>8</td>
<td>-40</td>
</tr>
<tr>
<td>10</td>
<td>-40</td>
</tr>
</tbody>
</table>

- Cell phones
Sub-nanosecond impulses are sent many million times per second
Became feasible with high-speed switching semiconductor devices
Pulse width = 25 to 400 ps
Impulses may be position, amplitude, or polarity modulated
0.25 ns Impulse $\Rightarrow$ 4 B pulses/sec $\Rightarrow$ 100's Mbps
802.15.4 uses pulse position and binary phase shift keying modulation
Advantages of UWB

- Very low energy consumption: Good Watts/Mbps
- Line of sight not required. Passes through walls.
- Sub-centimeter resolution allows precise motion detection
- Pulse width much smaller than path delay
  ⇒ Easy to resolve multipath
  ⇒ Can use multipath to advantage
- Difficult to intercept (interfere)
- All digital logic ⇒ Low cost chips
- Small size: 4.5 mm² in 90 nm process for high data rate designs
Direct sequence (DS-UWB)

- Championed by Motorola/XtremeSpectrum
- Uses CDMA with multiple chips per bit
- Chips are encoded using pulse
- This is the scheme used in 802.15.4
- Low power density ⇒ Good for body area network
IEEE 802.15.4e Enhancements

- Low latency deterministic operation: pre-assigned slots
- Channel adaptation: Different channels used by different nodes for contention free period
- Time slotted channel hopping: Higher layers coordinate the slot allocation along with its frequency. Good for harsh industrial environments.
- Each device can select its listening channel
- Transmitter and receiver coordinate their cycles (very low duty cycle)
- Transmit only when requested by receiver
1. IoT fueled initially by smart grid is resulting in several competing protocols: Bluetooth Smart, ZigBee Smart, ...

2. IEEE 802.15.4 is a low-data rate wireless personal area network and is the PHY and MAC layer used by many IoT protocols, such as ZigBee, and WirelessHART.

3. 802.15.4 uses full function and reduced function devices. FFDs can act as coordinator. Allows a star, mesh, or a cluster tree topology.


5. UWB allows transmission with very low average power spread over a large band.
Reading List

References

- J. T. Adams, “An introduction to IEEE STD 802.15.4” IEEAC paper #1055, Dec 30, 2005, 8 pp.,
  http://sonoma.edu/users/f/.../802_intro_01655947.pdf


References (Cont)

- H. Schwetlick, “PSSS-Parallel Sequence Spread Spectrum – A Potential Physical Layer for OBAN?,”
  [http://oban.tubit.tu-berlin.de/5-PSSS-Schwetlick.pdf](http://oban.tubit.tu-berlin.de/5-PSSS-Schwetlick.pdf)

- Z. Ianelli, “Introduction to Chirp Spread Spectrum (CSS) Technology,”
  IEEE 802 Tutorial,
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6LowPAN</td>
<td>IPv6 over Low Power Personal Area Network</td>
</tr>
<tr>
<td>AMCA</td>
<td>Asynchronous Multi-Channel Adaptation</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ANT</td>
<td>Name of a company</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>BPM</td>
<td>Burst Position Modulation</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>COSEM</td>
<td>Company Specification for Energy Metering</td>
</tr>
<tr>
<td>CPS</td>
<td>Cyber-Physical Systems</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>CSL</td>
<td>Coordinated Sampled Listening</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>CSS</td>
<td>Chirp Spread Spectrum</td>
</tr>
<tr>
<td>dBm</td>
<td>deci-Bell milli-Watt</td>
</tr>
</tbody>
</table>
### Acronyms (Cont)

- **DLMS**  
  Device Language Message Specification
- **DQPSK**  
  Differential Quadrature Phase-shift keying
- **DSME**  
  Deterministic and Synchronous Multi-Channel Extension
- **DSSS**  
  Direct Sequence Spread Spectrum
- **ETSI**  
  European Telecommunications Standards Institute
- **EUI-64**  
  Extended Unique Identifier
- **FCC**  
  Federal Communications Commission
- **FFD**  
  Full Function device
- **FSK**  
  Frequency Shift Keying
- **GFSK**  
  Gaussian Frequency-Shift Keying
- **GHz**  
  Giga Hertz
- **GTS**  
  Guaranteed Transmission Services
- **HART**  
  Highway Addressable Remote Transducer Protocol
- **ID**  
  Identifier
- **IEEE**  
  Institution of Electrical and Electronics Engineer
- **IoT**  
  Internet of Things
### Acronyms (Cont)

- ISA: International Society of Automation
- LECIM: Low energy critical infrastructure monitoring
- LIFS: Long Inter-frame Spacing
- LLDN: Low-Latency Deterministic Network
- LR-WPAN: Low-Rate Wireless Personal Area Networks
- MAC: Media Access Control
- MHz: Mega Hertz
- MPSK: m-ary Phase-Shift Keying
- OFDM: Orthogonal Frequency Division Multiplexing
- OUI: Organizationaly Unique Identifier
- PAN: Personal Area Network
- PCA: Priority Channel Access
- PHY: Physical Layer
- PLC: Powerline Communications
- PPDU: Physical Layer Protocol Data Unit
- PSSS: Parallel Sequence Spread Spectrum
Acronyms (Cont)

- QPSK: Quadrature Phase Shift Keying
- RFD: Reduced Function device
- RFID: Radio Frequency Identifier
- RIT: Receiver Initiated Transmission
- RPL: Routing Protocol for Low Power and Lossy Networks
- RX: Receiver
- SCADA: Supervisory control and data acquisition
- SIFS: Short inter-frame spacing
- SUN: Smart metering utility network
- TSCH: Time Slotted Channel Hopping
- UWB: Ultra Wide Band
- WPAN: Wireless Personal Area Network
Related Modules

Internet of Things,
http://www.cse.wustl.edu/~jain/cse574-16/j_10iot.htm

Wireless Protocols for IoT Part I: Bluetooth and Bluetooth Smart,
http://www.cse.wustl.edu/~jain/cse574-16/j_11ble.htm

Wireless Protocols for IoT Part III: ZigBee,
http://www.cse.wustl.edu/~jain/cse574-16/j_13zgb.htm

Low Power WAN Protocols for IoT,
http://www.cse.wustl.edu/~jain/cse574-16/j_14ahl.htm

Audio/Video Recordings and Podcasts of Professor Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw