Introduction to IEEE 802.15.4

IEEE 802.15.4

• Short range, low bit rate, low power consumption
  • Home
  • Automotive
  • Industrial applications
  • Games
  • Metering
802.15.4

- PHY speeds
  - 250 kbps
  - 40 kbps
  - 20 kbps.
- Basic topologies
  - Star
  - Peer-to-Peer
- Modulation: BPSK for 20 and 40 kbps, O-QPSK with DSSS for 250 kbps

802.15.4

<table>
<thead>
<tr>
<th>MAC</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>PHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>868 MHz</td>
</tr>
<tr>
<td>915 MHz</td>
</tr>
<tr>
<td>2400 MHz</td>
</tr>
</tbody>
</table>
802.15.4 Physical layer

- Channels
  - 16 channels in the 2.4 GHz ISM band
  - 10 channels in the 915 MHz ISM band in the USA and Australia
  - 1 channel in the European 868 MHz band
  - 1 channel in China's 784 MHz band

IEEE 802.15.4 PHY Overview

Operating Frequency Bands

868 MHz PHY

- 868.3 MHz
- In Europe

915 MHz PHY

- 2 MHz
- 902 MHz to 928 MHz
- In the USA and Australia

2.4 GHz PHY

- 2 MHz
- 2.4 GHz to 2.4835 GHz
- Worldwide
IEEE 802.15.4 PHY Overview

Packet Structure

**PHY Packet Fields**
- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field

Some more details later.

802.15.4 Architecture
IEEE 802.15.4 MAC Overview
Design Drivers

- Extremely low cost
- Ease of implementation
- Reliable data transfer
- Short range operation
- Very low power consumption

IEEE 802.15.4 MAC Overview
Device Classes

- Full function device (FFD)
  - Any topology
  - Network coordinator capable
  - Talks to any other device

- Reduced function device (RFD)
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation
IEEE 802.15.4 MAC Overview

Star Topology

- PAN Coordinator
- Master/slave

Full function device
Reduced function device

Communications flow

IEEE 802.15.4 MAC

Peer-Peer Topology

- Point to point
- Cluster tree

Full function device

Communications flow
Types of Frames

- Data Frame
- Beacon Frame
- Acknowledgment Frame
- MAC Command Frame
**Data Frame Structure**

**MPDU**

Bytes: 2 1 4 to 20 0 to 102 2

<table>
<thead>
<tr>
<th>Bytes</th>
<th>Sequence</th>
<th>Address</th>
<th>Data payload</th>
<th>FCS</th>
</tr>
</thead>
</table>

**PPDU**

Bytes: 4 1 1

<table>
<thead>
<tr>
<th>Bytes</th>
<th>Sequence</th>
<th>Start of Frame</th>
<th>Frame Length</th>
<th>MPDU</th>
</tr>
</thead>
</table>

**Beacon Frame Structure**

**MPDU**

Bytes: 2 1 4 or 10 2 k m n 2

<table>
<thead>
<tr>
<th>Bytes</th>
<th>Beacon Sequence</th>
<th>Data Address Information</th>
<th>Beacon Frame Specific</th>
<th>GTS</th>
<th>802.11 Information</th>
<th>Beacon Payload</th>
<th>FCS</th>
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</table>

Bytes: 4 1 1

<table>
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<th>Bytes</th>
<th>Sequence</th>
<th>Start of Frame</th>
<th>Frame Length</th>
<th>MPDU</th>
</tr>
</thead>
</table>

**PPDU**
ACK Frame Structure

MPDU

Bytes: 2 1 2
Frame Control  Frame Number  FCS

Bytes: 4 1 1
Preamble  Sequence  Start of Frame  Frame Length  MPDU

PPDU

Command Frame Structure

MPDU

Bytes: 2 1 4 to 20 1 n 2
Frame Control  Destination Address  Command Type  Command Payload  FCS

Bytes: 4 1 1
Preamble  Sequence  Start of Frame  Frame Length  MPDU

PPDU
**Frame Structure**

**Frame control**

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<thead>
<tr>
<th>Frame Type</th>
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<td>ACK</td>
<td>Command</td>
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**Exercise**

1. The payload in data frames for data applications is typically 30 to 60 bytes long. Calculate the transmission time for the Data frame with a 45-byte payload if the transmission rate is 250 kbps.

2. Calculate the maximum transmission time for the Data frame if the transmission rate is 250 kbps.

3. Calculate the transmission time for an ACK frame.
Three Channel Access Mechanisms

1. Slotted CSMA/CA
2. CSMA/CA
3. Contention Free (Guaranteed Time Slots)

IEEE 802.15.4 MAC
Beacon Enabled 802.15.4 Mode

- Beacons are transmitted periodically by the coordinator
- Used to
  - Synchronize associated nodes
  - Identify the PAN
  - Delimit the beginning of a superframe
  - Channel access mostly by Slotted CSMA/CA
  - Also possible to allocate contention free Guaranteed Time Slots (GTSs).
Superframe Structure

Superframe duration SD = \( a_{\text{BaseSuperframeDuration}} \times 2^{n} \)

Beacon Interval BI = \( a_{\text{BaseSuperframeDuration}} \times 2^{n} \)

- \( a_{\text{BaseSuperframeDuration}} = 960 \) symbols or 15.36 ms (for 250 kbps)
- The backoff slot or backoff period, \( t_{b_{\text{slot}}} \) (to be used in CSMA/CA), equals 20 symbols (320 µs)
- SD is always composed of 16 slots numbered 0 to 15 (not the same as \( t_{b_{\text{slot}}} \))
- \( 0 \leq \text{SFO} \leq \text{BCO} \leq 14 \)

There can be one or more guaranteed time slots GTS here

Optional Inactive period

slotted CSMA/CA

Optional Inactive period
Initial BE = 3  Initial CW = 2  The backoff slot or backoff period $t_{b\text{-}slot}$ equals 20 symbols (320 µs)

1. Wait for next time slot boundary
2. Wait backoff $(0, 2^{\text{BE} - 1}) \times t_{b\text{-}off}$
3. Perform CCA (128 µs) on CW backoff slots starting at the slot boundaries
4. Transmit frame

**slotted CSMA/CA**

---

192 µs are the turnaround time

SIFS = 12 symbol times, used after frames whose MPDU length ≤ 18 bytes.
LIFS = 40 symbol times, used after long frames whose MPDU length > 18 bytes
If the ACK has not arrived after 864 µs (54 symbol times), the frame needs to be retransmitted.
The backoff slot or backoff period $t_{b\text{-}slot}$ equals 20 symbols (320 µs)
The 392 µs are the turnaround time

**unslotted CSMA/CA**

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Initial BE = 3

SIFS = 12 symbol times, used after frames whose MPDU length ≤ 18 bytes.
LIFS = 40 symbol times, used after long frames whose MPDU length > 18 bytes
If the ACK has not arrived after 864 µs (54 symbol times), the frame needs to be retransmitted.
The backoff slot or backoff period $t_{b\text{-}slot}$ equals 20 symbols (320 µs)
The 392 µs are the turnaround time
Exercise

• Calculate the maximum data rate for a transmission using unslotted CSMA/CA with the maximum length assuming that ACKs are used and that no retransmissions are required.

Establishing a WPAN

1. WPAN Coordinator selects an available channel
2. Association procedure for devices to associate with it
Channel selection

- Find a channel which is free from interference
- Use energy detection scan over all the channels in the appropriate frequency band

Association procedure

1. Search for available WPANs
2. Select the WPAN to join
3. Start the association procedure with the WPAN coordinator or with another FFD device, which has already joined the WPAN.
Search for available WPANs

- Passive scan:
  - In beacon-enabled networks: eavesdrop on beacons transmitted periodically by associated devices
- Active scan:
  - In non beacon-enabled networks: beacons are explicitly requested by the device through beacon request command frames.

Select the WPAN to join

- No logic is given in the standard 80215.4
- This is, therefore, implementation-dependent
Association procedure

- Device sends an association request frame
- An association response command frame is sent to the requesting device
- The MAC association is referred to as a parent-child relationship

Routing

- Implemented at the Zigbee NWK layer (802.15.4)
- Based on Ad-hoc On-Demand Distance Vector (AODV)
Characteristics

• No loops are formed
• Converge also when a node moves
• On-demand algorithm (finds routes only if source asks for them)

Used Commands

• Route request Command
  – Search for a route to a specified device
• Route reply Command
  – Response of a route request
• Route Error notification
• Leave notification
• Route Record
  – Notification of list of nodes used in relaying a frame.
• Rejoin request notification
• Rejoin response
Route Choice

• Based on total link cost*

D1
D2
D3
D4
D5
D6
D7
D8

*The devices along the route were numbered sequentially and the equations in subsequent slides will use this assumption too. This is only done so that the equations can be written in a more compact form.

Route Choice in many practical applications

• The total link cost is often just the number of hops
• In the case of the route in the figure hereunder, the cost would be 3.
Route Choice according to Zigbee specification

- The total link cost of path $P$ is calculated using the following equations:

\[ P = \{[D_1, D_2], [D_2, D_3], \ldots, [D_{L-1}, D_L]\} \]

\[ C\{P\} = \sum_{i=1}^{L-1} C\{[D_i, D_{i+1}]\} \]

\[ C\{[D_i, D_{i+1}]\} = \min(7, \text{round}\left(\frac{1}{p_{i,i+1}}\right)) \]

Where $p_{i,i+1}$ is the probability that a packet will be delivered correctly between nodes $i$ and $i+1$.

Example

We are given the number of packets transmitted and received between the nodes in the three hops shown in the figure (see next slide)
Number of received packets per 100 packets transmitted by neighbor

| Number of received packets for each 100 transmitted packets |
|-----------------|---|---|---|
|                 | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
| $D_1$           | 30    |       |       |       |
| $D_2$           |       | 10    |       |       |
| $D_3$           |       |       | 80    |       |

Probabilities

<table>
<thead>
<tr>
<th>$P_{i,j}$</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$P_{1,2}$</td>
<td>0.30</td>
</tr>
<tr>
<td>$P_{2,3}$</td>
<td>0.10</td>
</tr>
<tr>
<td>$P_{3,4}$</td>
<td>0.80</td>
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</table>
### Cost per hop

<table>
<thead>
<tr>
<th>$C_{[D_1,D_2]}$</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{[D_2,D_3]}$</td>
<td>7</td>
</tr>
<tr>
<td>$C_{[D_2,D_3]}$</td>
<td>2</td>
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</tbody>
</table>

### Total cost

<table>
<thead>
<tr>
<th>$C_{[D_1,D_2]}$</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{[D_2,D_3]}$</td>
<td>7</td>
</tr>
<tr>
<td>$C_{[D_2,D_3]}$</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16</strong></td>
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</table>
Path discovery

• When a device has data to transmit, it launches a path discovery procedure explained in the next few slides

Path discovery

• If a node has a packet it wants to transmit
  – It broadcasts a Route Request (RREQ) to neighbors
  – The neighbors rebroadcast the packet to their neighbors
  – Intermediate nodes reply with RREP if they have a route to destination with higher dsn
Path discovery

- The Route Reply (RREP) is a unicast packet

<table>
<thead>
<tr>
<th>Src. Address</th>
<th>Dest Address</th>
<th>Dest Seq. #</th>
<th>Hop Count</th>
<th>Life Time</th>
</tr>
</thead>
</table>

Example D1->D4
### Sequence of packets

#### Recherche de route de D1 à D4

<table>
<thead>
<tr>
<th>NWK Adresse</th>
<th>D1</th>
<th>D2</th>
<th>Type de message</th>
<th>Src Seq #</th>
<th>Dest Seq #</th>
<th>Hops</th>
<th>Dest</th>
<th>Type de message</th>
<th>Hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>D1</td>
<td>D7</td>
<td>RREQ</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>D1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broadcast</td>
<td>D1</td>
<td>D2</td>
<td>RREQ</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>D2</td>
<td></td>
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<tr>
<td>Broadcast</td>
<td>D2</td>
<td>D1</td>
<td>RREQ</td>
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<td>1</td>
<td>1</td>
<td>Bcast</td>
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</tr>
<tr>
<td>Broadcast</td>
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<td>D2</td>
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<td>1</td>
<td>D2</td>
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#### Nueva entrada en la tabla de rute

<table>
<thead>
<tr>
<th>NWK Adresse</th>
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<th>D2</th>
<th>Type de message</th>
<th>Src Seq #</th>
<th>Dest Seq #</th>
<th>Hops</th>
<th>Dest</th>
<th>Type de message</th>
<th>Hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>D1</td>
<td>D7</td>
<td>RREQ</td>
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<td>1</td>
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<td>D1</td>
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<tr>
<td>Broadcast</td>
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<td>D2</td>
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<tr>
<td>Broadcast</td>
<td>D2</td>
<td>D1</td>
<td>RREQ</td>
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<td>1</td>
<td>Bcast</td>
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<tr>
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<td>D2</td>
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<td>1</td>
<td>1</td>
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#### Unicast -> D1

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<th>Src Seq #</th>
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**Ecarter puisque déjà reçu**