Wireless LANs
IEEE 802.11
History

• Wireless LANs became of interest in late 1990s
  – For laptops
  – For desktops when costs for laying cables should be saved

• Two competing standards
  – IEEE 802.11 and HIPERLAN
  – IEEE standard now dominates the marketplace

• The IEEE 802.11 family of standards
  – Original standard: 1 Mbit/s
  – 802.11b (WiFi, widespread after 2001): 11 Mbit/s
  – 802.11a (widespread after 2004): 54 Mbit/s
  – 802.11e: new MAC with quality of service
  – 802.11n: > 100 Mbit/s
802.11a PHY layer

- Transceiver block diagram

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802.11a PHY layer

- The following data rates are supported:

<table>
<thead>
<tr>
<th>Data rate (Mbit/s)</th>
<th>Modulation</th>
<th>coding rate</th>
<th>coded bits per subcarrier</th>
<th>coded bits per OFDM symbol</th>
<th>data bits per OFDM symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
11a header and preamble

- Header conveys information about data rate, length of the data packet, and initialization of the scrambler
11a header and preamble

- PLCP preamble: for synchronization and channel estimation
MAC and multiple access

- Frame structure:
  - Contains payload data, address, and frame control into

- Multiple access: both contention-free and contention-based access
IEEE 802.11n standard

• Goals: > 100 Mbit/s on MAC SAP-to-SAP
  – Increased robustness to interference
  – Backwards compatibility
  – Improved flexibility for different applications

• Applications:
  – PC applications: increased data transfer rates at low costs
  – CE applications: even higher quality for high-end AV applications, cost less of an objective
  – HH applications: enable voice-over-IP transmission and other applications for mobile market
History (I)

- 2002: IEEE establishes taskgroup 11n to create a high-throughput mode of 802.11 wireless LANs
- 2004:
  - presentation of more than 20 complete and partial technical proposals (meeting in Berlin September 2004)
  - Formation of 3 major alliances: TGnSync (Intel, Qualcomm), WWise (Broadcom, TI), MitMot (Motorola)
  - Downselection votes are deadlocked
- 2005:
  - Establishment of official “joint proposal” team that should establish compromise between the major alliances
  - Summer: emergence of a new group EWC (Intel, Broadcom,…): establishment and creation of new draft
  - Fall: EWC grow and attracts more and more participants
  - December: EWC finalizes its specifications
History (II)

• 2006
  – January 13th: EWC specs are adopted (with some minor modifications) by the JP team
  – January 18th: JP specs are approved (100 % confirmation) by 802.11n group
  – January 18th: first products are announced
  – Internal review process within 802.11n starts

• 2007/2008
  – Comment resolution and standard “cleanup” continue
  – 2009: issuance of standard
Cyclic Shifts

- To prevent unintentional beam forming during the transmission
- Multiply OFDM symbol with diagonal matrix

\[
[Q_k]_{i,i} = \exp(-j2\pi k\Delta F \tau_{CS}^i)
\]

corresponds to cyclic shift of symbols in time domain

Space-Time Coding (covered in Chapter 20 - Multiantenna Systems)
Overall concept (MIMO) is to transmit different versions of the data stream from different transmit antennas, i.e., delay diversity.
Space-Time Block Coding (STBC) introduces redundancy by sending from each transmit antenna a differently encoded version of the same signal which results in very high diversity
Spatial Expansion

- Allows the transmitter to use more antennas than space-time streams in a manner transparent to the receiver
  - a linear precoding matrix at the transmitter creates an “effective channel”
    \[ H_{\text{effective}} = H_{\text{actual}} \cdot V_{\text{precoding}} \]

- Three Types of Spatial Expansion:
  - CSD expansion
    - Uses cyclic shifts across the antenna array
  - CSD + Orthogonal Matrix
    - Orthogonal matrix may allow better isolation among the space-time streams
    - adding cyclic shifts mitigates beamforming artifacts and power fluctuation at the receiver
  - Beam forming Steering Matrix
STBC - Space Time Block Coding

- Increases rate at range for scenarios with more transmit chains than receive chains
- Useful especially for transmitting to single antenna devices
- Does not require closed-loop operations
- Based on 2x1 orthogonal space-time coding
  - \( N_{ss} = 1 \rightarrow 2 \times 1, 3 \times 1, \text{ and } 4 \times 1 \)
- Extended to scenarios with multiple spatial streams
  - \( N_{ss} = 2 \rightarrow 4 \times 2 \) and \( 3 \times 2 \)
  - \( N_{ss} = 3 \rightarrow 4 \times 3 \)
- Asymmetric MCS sets may be applied
  - Useful when STBC protection is uneven, for e.g. \( 3 \times 2 \) and \( 4 \times 3 \)
  - CSD + Orthogonal mapping used in the above two configurations
- STBC is fully optional
Transmit Beamforming

• Closed loop Tx BF support
  – Increase rate at range by applying a steering matrix at the transmitter
  – Most useful when more transmit chains than space-time streams

• Support in PHY –
  – Support for sounding the channel
  – Support for asymmetric MCSs (modulation coding schemes)
  – Channel state information feedback support
    • Calibration for implicit-feedback beamforming using reciprocity
    • Steering matrix feedback for explicit-feedback beamforming
      – compressed and uncompressed
    • Channel matrix feedback for explicit feedback, calibration, and rate adaptation

• All beam forming and rate adaptation support is optional
Modulation Coding Scheme (MCS)

- Mandatory Symmetrical Sets
  - 8 MCS sets for 20 MHz, 1 spatial stream
  - Range from BPSK rate $\frac{1}{2}$ to 64-QAM rate $\frac{5}{6}$
  - Data rates range from 6.5 Mbps to 65 Mbps (72.2 Mbps with short GI)

<table>
<thead>
<tr>
<th>Index</th>
<th>Modulation</th>
<th>Code Rate</th>
<th>Data Rate (MBPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>BPSK</td>
<td>$\frac{1}{2}$</td>
<td>6.5</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>$\frac{1}{2}$</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>$\frac{3}{4}$</td>
<td>19.5</td>
</tr>
<tr>
<td>3</td>
<td>16-QAM</td>
<td>$\frac{1}{2}$</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>$\frac{3}{4}$</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>64-QAM</td>
<td>$\frac{2}{3}$</td>
<td>52</td>
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<tr>
<td>6</td>
<td>64-QAM</td>
<td>$\frac{3}{4}$</td>
<td>58.5</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>$\frac{5}{6}$</td>
<td>65</td>
</tr>
</tbody>
</table>
Modulation Coding Scheme (MCS)

- Option extension of Symmetric MCSs
  - 40 MHz bandwidth expansion
  - 2, 3, and 4 spatial streams
  - Extension to 32 symmetric MCSs
  - Data rate up to 540 Mbps (600 Mbps with short GI)

- Optional HT duplicate mode in 40 MHz
  - Modulation is duplicated in upper and lower bands (with rotation)
  - BPSK, code rate ½
  - 6 Mbps (6.7 Mbps with short GI)
  - Provides a very robust communications mechanism

- Total of 33 symmetric MCSs
Modulation Coding Scheme (MCS)

• Optional Asymmetric MCS Sets
  – Mix of 64-QAM, 16-QAM, and QPSK
  – Asymmetric MCSs useful for transmit beam forming (TxBF) and STBC situations where some streams are more reliable than others
  – 44 Assymetric MCSs

• Total of 77 MCSs
Three Frame Formats in .11n

- Legacy (Mandatory)
- Mixed Mode (Mandatory)
  - Legacy portion of the preamble provides built in PHY protection
    - Allows mixture of legacy and 11n packets in one network
    - Avoids hidden node issues when beamforming
  - However, the preamble length is increased
- Green Field (Optional)
  - Very efficient preamble
Frame formats

Legacy

```
8u  8u  4u
L-STF L-LTF L-SIG Data
```

Mixed Mode

```
8u  8u  4u  8u  4u
4u per LTF
L-STF L-LTF L-SIG HT-SIG HT-STF HT-LTFs Data
```

Green Field

```
8u  8u  8u
4u per LTF
L-STF HT-LTF1 HT-SIG HT-LTFs Data
```
• Transmitted as a single stream expanded to up to four streams as explained above.
• The HT-SIG is transmitted on two OFDM symbols.
  – The modulation is BPSK rotated by +90°.
• Provides very robust built-in legacy PHY and beam forming-related PHY protection
HT-STF

- HT-STF – High Throughput Short Training Field.
- Used to set the AGC and for acquisition tasks in GF
- Based on the .11a sequence with CSD of -400, -200, -600ns) between channels:
- 4μsec long
HT-LTFs

- Used to train the receiver to the MIMO channel.
- The sequence transmitted is based on the 11a long training field sequence
  - Extended to 56 tones by adding 4 tones in 20MHz
  - In 40MHz, extended to 114 tones first moving the sequence up and down 32 tones, then adding tones between the two channels and in the DC subcarriers
  - In 40MHz the upper channel is +90° rotated compared to the lower channel.
- In the Green Field format, HT-LTF1 has a duration of 8 μsec. (with GI2).
- All other HT-LTFs have a duration of 4 μsec. (with GI of 800 nsec.).
Channel Sounding

• Channel sounding is useful for link adaptation and transmit beam forming
• Three sounding methods
  – Standard packet
    • Limited by need to extract data from packet
    • Channel is sounded using preamble
  – Segmented LTF
    • Allows sounding of spatial dimensions not present in data
    • First the spatial streams in the data are trained, then the “NULL” streams are trained.
  – Zero Length Packet (renamed No Data Frame)
    • Allows sounding of any spatial dimensions (as there is no data)
    • Training is done like a usual packet with the number of streams indicated by the MCS
Sounding with Segmented LTF

<table>
<thead>
<tr>
<th>TX1</th>
<th>L-STF</th>
<th>HT-LTF1</th>
<th>HT-SIG</th>
<th>HT-LTF2</th>
<th>HT-Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-STF</td>
<td>-400ns</td>
<td>HT-LTF1</td>
<td>HT-SIG</td>
<td>HT-LTF2</td>
<td>HT-Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-400ns</td>
<td>-400ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX2</td>
<td>L-STF</td>
<td>HT-LTF1</td>
<td>HT-SIG</td>
<td>HT-LTF2</td>
<td>HT-Data</td>
</tr>
<tr>
<td></td>
<td>-400ns</td>
<td>-400ns</td>
<td>-400ns</td>
<td></td>
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<td></td>
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<td></td>
<td>-400ns</td>
<td></td>
</tr>
<tr>
<td>TX3</td>
<td></td>
<td></td>
<td>- HT-LTF2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX4</td>
<td></td>
<td>HT-LTF2</td>
<td>HT-LTF2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-400ns</td>
<td>-400ns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Contestion-based access

- CSMA (carrier-sense multiple access):

![Diagram of CSMA access](Copyright: IEEE)
Contestion-free access

• Polling:
Further improvements

• 802.11e: improvements in the MAC; provides quality of service
  – CSMA/CA-based Enhanced Distributed Channel Access (EDCA) manages medium access during CP.
  – Polling-based HCF (Hybrid Coordination Function) Controlled Channel Access (HCCA) handles medium access during CFP.
  – BlockACK and delayed blockACK reduce overhead
  – Contention Free Burst (CFB) and Direct Link Protocol (DLP) improve channel efficiency.