Mobile Communication Networks

Wireless Local Area Networks

Boris Bellalta

Part of the material has been obtained from:
Introduction

• Significant growth of IEEE 802.11 (DCF) Wireless LAN in last years.
• Advantages:
  – A broadband wireless “access” to Internet, mobility, low cost and fast deployment.
• Current limitations:
  – Only best-effort services (no QoS mechanisms).
  – Performance problems (not efficient use of resources) with simultaneous TCP-like and UDP-like traffic flows.
Introduction

- Advantages
  - Easy, low-cost deployment
  - Mobility & roaming: Access information anywhere
  - Supports personal devices
    - PDAs, laptops, data-cell-phones
  - Supports communicating devices
    - Cameras, location devices, wireless identification
WLAN standards

- **100 kbps** FHSS
- **2 mbps** DS/FH
- **802.11** 2 Mbps
- **802.11b** 11 Mbps
- **Wi-Fi**
- **11a/g** 54 Mbps
- **11i secure**
- **11e QoS**
- **11n 200 Mbps**

**predecessor WLAN**
WLAN cards

STA

- PC-Card Hardware
  - Radio Hardware
  - 802.11 frame format
  - WMAC controller with Station Firmware (WNIC-STA)
  - 802.3 frame format
  - Platform Computer
    - Driver Software (STADr)
    - Ethernet V2.0 / 802.3 frame format
    - Protocol Stack
  - 802.3 frame format

AP

- PC-Card Hardware
  - Radio Hardware
  - 802.11 frame format
  - WMAC controller with Access Point Firmware (WNIC-AP)
  - 802.3 frame format
  - Bridge Software
    - Driver Software (APDr)
    - Ethernet V2.0 / 802.3 frame format
    - Kernel Software (APK)
    - Ethernet Interface
  - Bridge Hardware
BSS (Basic Service Set)
BSS (Basic Service Set)

Bridge learn table

<table>
<thead>
<tr>
<th>STA-1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA-2</td>
<td>2</td>
</tr>
</tbody>
</table>

Association table

<table>
<thead>
<tr>
<th>STA-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA-2</td>
</tr>
</tbody>
</table>

Inter-BSS Relay

STA-1

Association

Packet for STA-2

ACK

STA-2

Associate

Packet for STA-2

ACK
IBSS (Independent Basic Service Set)
EBSS (Extended BSS)
Wireless Distribution System (WDS)
WDS (Wireless Distribution Subsystem)

BSS-A

- Bridge learn table
  - STA-2: 2
  - STA-1: 2

Wireless PC-Card
- Association table
  - STA-1
- WDS Relay

Packet for STA-2
ACK

Packet for STA-2
ACK

BSS-B

- Bridge learn table
  - STA-2: 2
  - STA-1: 2

Wireless PC-Card
- Association table
  - STA-2
- WDS Relay

STA-1

STA-2
Frame Structure
Frames

- 802.11 designed to
  - Support LLC
  - Operate over many physical layers
PLCPs

Figure 127—Long PLCP PPDU format
Frames

• Control frames
  – Handshaking (RTS and CTS)
  – ACKs during data transfer

• Data frames
  – Data transfer
Frame

- **MAC Header**: 30 bytes
- **Frame Body**: 0-2312 bytes
- **CRC**: CCITT-32 4 bytes CRC over MAC header & frame body

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration/ID</th>
<th>Address 1</th>
<th>Address 2</th>
<th>Address 3</th>
<th>Sequence control</th>
<th>Address 4</th>
<th>Frame body</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>0-2312</td>
<td>4</td>
</tr>
</tbody>
</table>
PHY - layer
PHY layer Specifications

- IEEE 802.11
- IEEE 802.11b
- IEEE 802.11a
- IEEE 802.11g
- IEEE 802.11n

What's new?
- 802.11ac → ready at 2013 (~1 Gbps)
- 802.11ad ?? (60 GHz)
## PHY standards

<table>
<thead>
<tr>
<th></th>
<th>Frequency Band</th>
<th>Bit Rate</th>
<th>Modulation Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>802.11</strong></td>
<td>2.4 GHz</td>
<td>1-2 Mbps</td>
<td>Frequency-Hopping Spread Spectrum, Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td><strong>802.11b</strong></td>
<td>2.4 GHz</td>
<td>11 Mbps</td>
<td>Complementary Code Keying &amp; QPSK</td>
</tr>
<tr>
<td><strong>802.11g</strong></td>
<td>2.4 GHz</td>
<td>54 Mbps</td>
<td>Orthogonal Frequency Division Multiplexing &amp; CCK for backward compatibility with 802.11b</td>
</tr>
<tr>
<td><strong>802.11a</strong></td>
<td>5-6 GHz</td>
<td>54 Mbps</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
</tbody>
</table>
IEEE 802.11n

- Release Date: June 2009
- OFDM.
- Op. Frequency: 2.4 GHz and/or 5 GHz
- Data Rate (Typ): 74 Mbit/s
- Data Rate (Max): 300 Mbits/s (2 streams)
- Range (Indoor): ~70 m

- Two new ideas (PHY layer):
  - 20 / 40 MHz operation to the physical (PHY) layer.
  - MIMO (Multiple Input Multiple Output).
    - antenna diversity
    - and spatial multiplexing
• BASIC IDEA: Channel bandwidth is divided into multiple sub-channels to reduce frequency-selective fading.
SISO, SIMO, MISO and MIMO
Spatial Diversity Spatial Multiplexing

- The “M” antennas are used:
  - to transmit the same “information” (coded properly)
    - Spatial Diversity --> Lower BER
  - to transmit different “information” (coded properly)
    - Spatial Multiplexing → Higher Throughput
- Only Single-user MIMO (point-to-point communications).
Multiple Transmission Rates

- **PHY Rate:**
  - The PHY Preamble and Header are transmitted at this rate (lowest)

- **Basic Rate:** Maximum rate common to all STAs
  - Control frames are transmitted at BASIC rate.
  - MAC Headers are transmitted at BASIC rate.

- **Data Rate:** Rate at which data is transmitted
  - Based on the channel conditions of the STA / AP.
    - Good: Higher rates (less redundancy bits, higher modulations)
    - Bad: Lower rates (more redundancy bits, lower modulations)
Multi-rate transmission (Multiple data rates)

- Direct relationship between communication rate and the channel quality required for that rate
- As distance increases, channel quality decreases
- Therefore: tradeoff between communication range and link speed
- Multi-rate provides flexibility to meet both consumer demands
Efficiency

![Efficiency Graph]

- **Rate (Mbps)**: 11.0, 5.5, 2.0, 1.0
- **Medium Time (milliseconds)**: 0 to 14
- **Bars**:
  - Black: MAC Overhead
  - Gray: Data

The graph shows the distribution of medium time across different rates.
Auto Rate Protocols

- Selects the rate to use for a packet
- ARF
  - Adaptive based on success/failure of previous packets
  - Simple to implement
  - Doesn’t require the use of RTS CTS or changes to 802.11 spec
- Receiver Based Auto Rate (RBAR)
  - Uses SNR measurement of RTS to select rate
  - Faster & more accurate in changing channel
  - Requires some tweaks to the header fields
- Opportunistic Auto Rate (OAR)
  - Adds packet bursting to RBAR
  - Allows nodes to send more when channel conditions are good
  - Implements temporal fairness instead of packet fairness
## IEEE 802.11a Rates

<table>
<thead>
<tr>
<th>Data rate (Mbits/s)</th>
<th>Modulation</th>
<th>Coding rate (R)</th>
<th>Coded bits per subcarrier ($N_{\text{BPSC}}$)</th>
<th>Coded bits per OFDM symbol ($N_{\text{CBPS}}$)</th>
<th>Data bits per OFDM symbol ($N_{\text{DBPS}}$)</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>
IEEE 802.11a

Ideal “rate”, acceptable BER
DCF = MAC / LLC
Distributed Coordination Function

- Random Access based on a CSMA protocol.
- The MAC protocol is independent of the station and/or the traffic to transmit.
  - For the MAC, is the same to transmit an HTTP request than a VoIP packet or a TCP ACK.
- Non-linear performance = f(number of nodes, rate (bps) of each node).
  - We will approximate it by the CSMA/NP protocol if the number of nodes is higher (M > 20).
- An ARQ Stop & Wait protocol is implemented.
CSMA basic (without RTS/CTS)

- **BO**
- **Data**
- **SIFS**
- **ack**
- **DIFS**
- **NAV**

**Defer Access**

**Wait for Reattempt Time**
DCF

- **Collision Avoidance**
  - When station senses channel busy, it waits until channel becomes idle for DIFS period & then begins random backoff time (in units of idle slots)
  - Station transmits frame when backoff timer expires
  - If collision occurs, recompute backoff over interval that is twice as long

- **Receiving stations of error-free frames send ACK**
  - Sending station interprets non-arrival of ACK as loss
  - Executes backoff and then retransmits
  - Receiving stations use sequence numbers to identify duplicate frames
DCF

- Without the RTS/CTS handshake (without the CA).

- The BO time (backoff) is slotted in “empty slots” of duration $\sigma$ [seconds]
Hidden Terminal Problem

(a) A transmits data frame
A

Data Frame

B

C senses medium, station A is hidden from C
C

(b) C transmits data frame & collides with A at B
A

Data Frame

B

C

Data Frame
CSMA with Collision Avoidance (RTS/CTS)

(a) A requests to send

(b) B announces A ok to send

(c) A sends

C remains quiet
CSMA/CA (optional)

Source

BO

RTS

CTS

Data

SIFS

SIFS

SIFS

DIFS

Ack

Destination

Other

NAV (RTS)

NAV (CTS)

NAV (Data)

Defer access
Carrier Sensing (Real and Virtual)

- *Channel busy if either sensing is busy*
  - *Signal > threshold is detected.*

- *Virtual Carrier Sensing* at MAC sublayer
  - Source stations informs other stations of transmission time (in μ sec) for an MPDU
  - Carried in *Duration* field of RTS & CTS
  - Stations adjust *Network Allocation Vector* (NAV) to indicate when channel will become idle
BEB (Binary Exponential Backoff)

- \( k \) retry
- \( CW_{\text{min}} = 32 \)
- \( CW_{\text{max}} = 1024 \)
- \( B(k) = \min(CW(k), CW_{\text{max}}) \)
- \( CW(k) = 2^k \cdot CW_{\text{min}} \)

- A value from 0 to \( CW(k) \) is randomly chosen before to transmit the packet (using a uniform distribution)
## Typical DCF parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{data}$</td>
<td>${11, 5.5, 2, 1}$ Mbps</td>
<td>$R_{basic}$</td>
<td>${11, 5.5, 2, 1}$ Mbps</td>
</tr>
<tr>
<td>$R_{phy}$</td>
<td>${1}$ Mbps</td>
<td>$CW_{min}$</td>
<td>32</td>
</tr>
<tr>
<td>DIFS</td>
<td>$50$ $\mu$s</td>
<td>$CW_{max}$</td>
<td>1024</td>
</tr>
<tr>
<td>SIFS</td>
<td>$10$ $\mu$s</td>
<td>$m$</td>
<td>5</td>
</tr>
<tr>
<td>SLOT ($\sigma$)</td>
<td>$20$ $\mu$s</td>
<td>ACK</td>
<td>$112$ bits @ $R_{basic}$</td>
</tr>
<tr>
<td>EIFS</td>
<td>$364$ $\mu$s</td>
<td>CTS</td>
<td>$112$ bits @ $R_{basic}$</td>
</tr>
<tr>
<td>RTS</td>
<td>$160$ bits @ $R_{basic}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAC payload</td>
<td>$[0, 18496]$ bits @ $R_{data}$</td>
<td>MAC FCS</td>
<td>$32$ bits @ $R_{data}$</td>
</tr>
<tr>
<td>MAC header</td>
<td>$240$ bits @ $R_{basic}$</td>
<td>PLCP header</td>
<td>$48$ bits @ $R_{phy}$</td>
</tr>
<tr>
<td>PLCP preamble</td>
<td>$144$ bits @ $R_{phy}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retry Limit (R)</td>
<td>$R_S = 4$, $R_L = 7$</td>
<td>$K$ (Queue length)</td>
<td>$20$ packets</td>
</tr>
</tbody>
</table>

Table 3.2: System parameters of the IEEE 802.11b specification [1]
Basic guidelines of the model

- Each node is modeled as an M/M/1/Q queue with packet arrival rate $\lambda_k$ and service time $X_k$.
  - Assumption: Poisson arrivals and service time exponentially distributed.
  - The model accounts for: queuing delays, packet losses.

$$v_k(n) = \lambda_k X_k(n) \quad E\{D_k\} = \frac{E\{Q_k\}}{\lambda_k (1-P_{bk})} \quad P_{b.k}(n) = \frac{(1-v_k(n)) v_k(n)^Q}{1-v_k(n)^{Q+1}}$$
Basic guidelines of the model

- Reciprocal influence between nodes.
  - Service time is function of how behave the other nodes.

\[
X_k(n) = N_{T,k}(n)\left(\mathbb{E}\{W_k(n)\} \alpha_k(n) + (N_{T,k}(n) - 1)\bar{T}_c(L_k) + T(L_k)\right)
\]

![Diagram with nodes and packets]
Basic guidelines of the model

- **Transmission Probability**
  - Probability to transmit in a given slot conditioned to have a packet ready in the queue.

- **Conditional Collision probability**
  - *Assumption:* independent from the back-off stage, i.e., geometrically distributed.

\[
\tau_k(n) = \frac{\Pr(Q_k > 0)}{E\{W_k(n)\} + 1} = \frac{\rho_k(n)}{E\{W_k(n)\} + 1}
\]

\[
\rho_k(n) = \lambda_k \left(1 - P_{b,k}(n)\right) X_k(n)
\]

\[
p_k(n) = 1 - \prod_{j \in \Psi, j \neq k} (1 - \tau_k(n))
\]

\[
N_{T,k}(n) \approx \frac{1}{1 - p_k(n)}
\]
Basic guidelines of the model

- Backoff suspension
  - When channel is sensed busy the backoff countdown is suspended.
- Channel states
  - Successful transmission
  - Collision
  - Empty

\[
\alpha_k(n) = p_{e,k}(n)\sigma + p_{s,k}(n)\left(\bar{T}^*(L_k) + \sigma\right) + p_{c,k}(n)\left(\bar{T}_c^*(L_k) + \sigma\right)
\]
Model validation: some results

- Saturation points for streaming traffic (conditioned to the number of elastic flows active).
- DCF is a node based scheduler.
  - Low capacity for streaming flows in presence of elastic (TCP) traffic.
Model validation: some results

- Queue utilization and collision probability.
Transmission Probability

\[ p(n) = 1 - P[NT]^{n-1} = 1 - (1 - \tau(n))^{n-1} \]

\[ P[NT] = P[NT|QE] \cdot P[QE] + P[NT|QNE] \cdot P[QNE] = 1 \cdot (1 - \rho(n)) + \frac{E\{W(n)\} - 1}{E\{W(n)\}} \cdot \rho(n) \]

\[ P[NT] = 1 - \frac{\rho(n)}{E\{W(n)\}} \]
Frame length computation

\[
ET_{c,i}^{ba,*} \approx \frac{\sum_{j \neq i} \sum_{k > j, k \neq i} \max(T_{s,j}, T_{s,k}) \left( \tau_j \tau_k \prod_{u \neq \{j,k\}} (1 - \tau_u) \right)}{\sum_{j \neq i} \sum_{k > j, k \neq i} \left( \tau_j \tau_k \prod_{u \neq \{j,k\}} (1 - \tau_u) \right)}
\]

and

\[
ET_{s,i}^{*} \approx \frac{\sum_{j \neq i} T_{s,j} \left( \tau_j \prod_{u \neq \{i,j\}} (1 - \tau_u) \right)}{\sum_{j \neq i} \left( \tau_j \prod_{u \neq \{i,j\}} (1 - \tau_u) \right)}
\]

\[
ET_{c,i}^{rts,*} = T_{c}^{rts}
\]
Throughput with different types of traffic

DCF does not work well with multimedia traffic