Mobile Communication Networks

(Intro)
Wireless Local Area Networks

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Part of the material has been obtained from:
Report: Important Dates

- **January 15** (deliver by e-mail: boris.bellalta@upf.edu)
  - Selected topic (1 student, 1 topic) + short explanation about it
  - List of 5 references and a short abstract of each one (~10 lines).
- **January 25** (deliver by e-mail: boris.bellalta@upf.edu)
  - Short presentation (12 slides, 2 slides x reference + 2 for the summary).
- **February 4 - February 18**, (deliver by e-mail: boris.bellalta@upf.edu)
  - Final report (5 pages, without references and with less than 5 figures).
• Ahmad Afouneh: IEEE 802.11e
• Carlos Cabrera: Wireless Mesh Networks
• Andy Foster: IEEE 802.11n
• Urmass Kuresson: IEEE 802.11e
• Pablo Miguel Saval: IEEE 802.11n (slides?)
• Jelena Skulic: Multi-user MIMO in WLANs (broadcast)
• ...
Guidelines for the report

- **IEEE 802.11e / EDCA**
  - Is EDCA needed? How it works? Does it guarantee any QoS?
  - What performance gains can be achieved vs DCF?
- **IEEE 802.11n**
  - How the higher data rates are achieved? What are the “new” mechanisms at MAC and PHY layer?
  - What performance gains can be achieved vs 802.11b/a/g?
- **Wireless Mesh Networks**
  - Overview of the IEEE 802.11s amendment.
  - Advantages of Wireless Mesh Networks.
  - Considerations for Wireless Mesh Networks deployments.
- **Mu-MIMO in WLANs (Broadcast Channel)**
  - Benefits of Multi-user MIMO in broadcast channels.
  - How it can be implemented in WLANs and what benefits can be obtained in terms of throughput, frame delay, contention mitigation, etc.?
Starting Point

Wireless Networks as an Access Technology to Internet

“Internet Protocol (IP) everywhere”
Mobile Communication Networks

Some Internet Objects

IP picture frame
http://www.ceiva.com/

Web-enabled toaster + weather forecaster
Wireless Access Networks

Access Points = \{ WIFI, WIMAX, GSM/GPRS, UMTS, HSDPA, LTE... \}
What's the Internet: a service view

→ The Network provides communication services to applications.
→ The different services are characterized by their capability to provide:
  • Data loss
  • **Timing** (delay)
  • Throughput
  • Security
→ What services provide the current Internet?
  • *IP is a best-effort (there are no loss & delay guarantees)*
  • A reliable service (based on TCP)
  • A non-reliable service (based on UDP)
Types of Traffic vs User perception

- **Elastic flows** (TCP-based): use all the available bandwidth, fair.

- **Streaming/Rigid flows** (UDP-based): use only the required bandwidth.

![Diagram showing user perception and bandwidth for Elastic and Rigid Traffic](chart.png)
### Transport service requirements of common apps

<table>
<thead>
<tr>
<th>Application</th>
<th>Data loss</th>
<th>Throughput</th>
<th>Time Sensitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>file transfer</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>e-mail</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>Web documents</td>
<td>no loss</td>
<td>elastic</td>
<td>no</td>
</tr>
<tr>
<td>real-time audio/video</td>
<td>loss-tolerant</td>
<td>audio: 5kbps-1Mbps</td>
<td>yes, 100’s msec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>video: 10kbps-5Mbps</td>
<td></td>
</tr>
<tr>
<td>stored audio/video</td>
<td>loss-tolerant</td>
<td>same as above</td>
<td>yes, few secs</td>
</tr>
<tr>
<td>interactive games</td>
<td>loss-tolerant</td>
<td>few kbps up</td>
<td>yes, 100’s msec</td>
</tr>
<tr>
<td>instant messaging</td>
<td>no loss</td>
<td>elastic</td>
<td>yes and no</td>
</tr>
</tbody>
</table>
Internet Protocol Stack

**application**: supporting network applications
FTP, SMTP, HTTP

**transport**: process-process data transfer
TCP, UDP

**network**: routing of datagrams from source to destination
- IP, routing protocols

**link**: data transfer between neighboring network elements
- Ethernet, WLAN

**physical**: bits “on the wire/wireless”
Some points (SIP/IMS from the TCP/IP stack)

- SIP can be seen as an application protocol.
- The IP mobile network elements operate in the application layer and use the TCP/IP stack to interchange messages.
Wireless Local Area Networks
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
- 802.11a 2 Mbps
- 802.11b 11 Mbps
- Wi-Fi
- 11a/g 54 Mbps
- 11i secure
- 11e QoS
- 11n 200 Mbps

predecessor WLAN
WLAN cards

STA

AP
BSS (Basic Service Set)
BSS (Basic Service Set)

Bridge learn table

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

STA-2

Associate

Packet for STA-2

ACK

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

- STA-1
- STA-2
- BSS-A
- BSS-B
- Wireless PC-Card
  - Association table
    - STA-1
  - WDS Relay
- Packet for STA-2
- ACK
- Bridge learn table
  - STA-2 2
  - STA-1 2
- Wireless Backbone
- Packet for STA-2
- ACK
- WDS Relay
- STA-2

The diagram illustrates the interaction between BSS-A and BSS-B, showing how packets are relayed and acknowledged within the Wireless Distribution Subsystem (WDS) framework.
Frame Structure
• 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
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>Frequency Band</th>
<th>Bit Rate</th>
<th>Modulation Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11</td>
<td>2.4 GHz</td>
<td>Frequency-Hopping Spread Spectrum, Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4 GHz</td>
<td>Complementary Code Keying &amp; QPSK</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4 GHz</td>
<td>Orthogonal Frequency Division Multiplexing &amp; CCK for backward compatibility with 802.11b</td>
</tr>
<tr>
<td>802.11a</td>
<td>5-6 GHz</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
OFDM

- 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
  - Coverage
  - Speed
Auto Rate Protocols

- Selects the rate to be used for a packet (PHY/MAC cross-layer)
- 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 ($N_{BPSC}$)</th>
<th>Coded bits per OFDM symbol ($N_{CBPS}$)</th>
<th>Data bits per OFDM symbol ($N_{DBPS}$)</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>
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** = $f(\text{number of nodes, bandwidth req. (bps) of each node})$.
- An ARQ Stop & Wait protocol is implemented.
CSMA basic (without RTS/CTS)

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

Source

Destination

Other

Defer Access

Wait for Reattempt Time
DCF (Distributed Coordination Function)

- Collision Avoidance (Back-Off Mechanism, RTS/CTS)
  - When station senses the 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

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

(a) A transmits data frame

C senses medium, station A is hidden from C

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

**CSMA with RTS/CTS**

(a) A requests to send

(b) B announces A ok to send

(c) A sends

Data Frame

C remains quiet
CSMA/CA with RTS/CTS

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></td>
<td></td>
</tr>
<tr>
<td>DIFS</td>
<td>50 $\mu$s</td>
<td>$CW_{min}$</td>
<td>32</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 $\mu$s</td>
<td>$CW_{max}$</td>
<td>1024</td>
</tr>
<tr>
<td>SLOT ($\sigma$)</td>
<td>20 $\mu$s</td>
<td>$m$</td>
<td>5</td>
</tr>
<tr>
<td>EIFS</td>
<td>364 $\mu$s</td>
<td>ACK</td>
<td>112 bits $\times$ $R_{basic}$</td>
</tr>
<tr>
<td>RTS</td>
<td>160 bits $\times$ $R_{basic}$</td>
<td>CTS</td>
<td>112 bits $\times$ $R_{basic}$</td>
</tr>
<tr>
<td>MAC payload</td>
<td>$[0,18496]$ bits $\times$ $R_{data}$</td>
<td>MAC FCS</td>
<td>32 bits $\times$ $R_{data}$</td>
</tr>
<tr>
<td>MAC header</td>
<td>240 bits $\times$ $R_{basic}$</td>
<td>PLCP preamble</td>
<td>144 bits $\times$ $R_{phy}$</td>
</tr>
<tr>
<td>PLCP header</td>
<td></td>
<td>PLCP header</td>
<td>48 bits $\times$ $R_{phy}$</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.

\[
v_k(n) = \lambda_k X_k(n) \quad E\{D_k\} = \frac{E\{Q_k\}}{\lambda_k(1-P_{bk})} \quad P_{b,k}(n) = \frac{1 - v_k(n) v_k(n)^Q}{1 - v_k(n)^{Q+1}}
\]
M/M/1/K (K = Q from previous slide)

\[ P_b = \text{Probabilidad de bloqueo} = BP \]

\[ \lambda^* = \lambda(1 - P_b) = \mu(1 - P_0) \]

\[ TO = \lambda \cdot X = \frac{\lambda}{\mu} = A \text{ erlangs} \]

\[ TC = TO(1 - P_b) = S \text{ erlangs} \]

\[ TP = TC - TO = TO \cdot P_b \text{ erlangs} \]
M/M/1/K

\[ \sum_{i=0}^{K} \pi(i) = 1 \rightarrow \pi(0), \quad \sum_{i=0}^{K} A^i = \frac{\lambda - A^{K+1}}{1 - A^i} \]

\[ \pi(0) = \frac{\lambda - A}{1 - A^{K+1}} \]

\[ \pi(i) = \frac{(\lambda - A) A^i}{1 - A^{K+1}} \]

\[ \pi(1) = A \cdot \pi(0) \]

\[ \pi(2) = A^2 \cdot \pi(0) \]

\[ \vdots \]

\[ \pi(K) = A^K \cdot \pi(0) \]

\[ \sum_{i=0}^{K} \pi(i) = 1 \]
Basic guidelines of the model

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

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

- Average number of transmissions
- Average number of back-off slots
- Average duration of a slot
- Average collision duration
- Average successful duration

EQ_1: Queueing delay
packet arrival (HOL)
packet arrival (queued)
packet departure
packet departure

MN1
BO DATA ACK
BO DATA ACK
1/\lambda_1
X_1
1/\lambda_2
X_2

t

MN2
BUSY BO BUSY
BO DATA ACK
BO DATA ACK
BUSY

EQ_1: Queueing delay
backoff suspension
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