IEEE 802.11 Wireless LANs

Introduction
WLAN History

- **Original goal:**
  Deploy “wireless Ethernet”
  First generation proprietary solutions (end ’80, begin ’90)
  WaveLAN (AT&T))
  HomeRF (Proxim)
  Abandoned by major chip makers (e.g. Intel: dismissed in april 2001)

- **IEEE 802.11 Committee formed in 1990**
  Charter: specification of MAC and PHY for WLAN
  First standard: june 1997
  1 and 2 Mbps operation
  Reference standard: september 1999
  Multiple Physical Layers
  Two operative Industrial, Scientific & Medical unlicensed bands
  » 2.4 GHz: Legacy; 802.11b/g
  » 5 GHz : 802.11a

- **1999: Wireless Ethernet Compatibility Alliance (WECA) certification**
  Later on named Wi-Fi
  Boosted 802.11 deployment!!

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Why so much talking about of 802.11 today?

- **802.11:** no more “just” a WLAN
- **Hot-spots**
  Where the user goes, the network is available: home, school, office, hotel, university, airport, convention center…
  Freedom to roam with seamless connectivity in every domain, with single client device
- **May compete (complement) with 3G for Wireless Internet access**
  Mesh networks, community networks, etc.
WLAN vs. PCS

- Public Cellular Systems:
  - Global coverage: network level for addressing a node within the whole national-wide network
  - Circuit services: each user may receive a dedicated channel (time slot, frequency, code..) radio resources are assigned
  - Resource reuse thanks to complex planning and management operations performed by network providers

- Wireless Local Area Networks:
  - Local coverage: hotspots; no network level; addressing in guaranteed only within the hotspot;
    - Other network levels (e.g. IP) can be used for going outside the hotspot
  - Data services: one shared channel among all users, in which each user acquired the right to transmit for a limited amount of time
  - No coordination: no central planning for coordinating different hot-spots and very limited management operation

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One shared channel: On which bandwidths?

- Classical approach: narrow frequency band, much power as possible into the signal
  Authority must impose rules on how RF spectrum is used.
  Licenses restrict frequencies and transmission power

- However.. Several bands have been reserved for unlicensed use
  To allow consumer market for home use, bands for “industrial, scientific and medical” equipment (ISM bands): e.g. 2.4 Ghz, 5 Ghz
  Limitations only on transmitted power
  “unlicensed” does not mean “plays well with others”

**WIFI WORKS ON UNLICENSED BANDWIDTHS!**

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The 2.4 (wifi) GHz spectrum

- 2.4 GHz bandwidth: 2.400-2.483.5
- Europe (including Italy):
  13 channels (each 5 MHz)
  - 2.412 – 2.417 –
  - 2.422 – 2.427 –
  ...... – 2.472

Channel spectrum: (11 MHz chip clock) about 22 MHz

Max speed related to bandwidth

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DSSS Frequency Channel Plan

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The 5.0 (OFDM) GHz spectrum

**US regulation:**
- 3 x 100 MHz channels
  - 5.150-5.250 (40 mW)
  - 5.250-5.350 (200 mW)
  - 5.725-5.825 (800 mW)
- Operating 20 MHz channels
  - 5.180, 5.200, 5.220, 5.240
  - 5.260, 5.280, 5.300, 5.320
  - 5.745, 5.765, 5.785, 5.805

20 MHz / 64 subcarriers = 0.3125 MHz per subcarriers (52 used)

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WLAN data rates

**Legacy 802.11**
Work started in 1990; standardized in 1997
1 mbps & 2 mbps

**The 1999 revolution: PHY layer impressive achievements**
802.11a: PHY for 5 GHz
Published in 1999
Products available since early 2003

802.11b: higher rated PHY for 2.4 GHz
Published in 1999
Products available since 1999
Interoperability tested (wifi)

2003: extend 802.11b
802.11g: OFDM for 2.4 GHz
Published in June 2003
Products available, though no extensive interoperability testing yer
Backward compatibility with 802.11b Wi-Fi

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<table>
<thead>
<tr>
<th>Standard</th>
<th>Transfer Method</th>
<th>Frequency Band</th>
<th>Data Rates Mbp</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11 legacy</td>
<td>FHSS, DSSS, IR</td>
<td>2.4 GHz, IR</td>
<td>1, 2</td>
<td></td>
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<tr>
<td>802.11b</td>
<td>DSSS, HR-DSSS (PBCC)</td>
<td>2.4 GHz</td>
<td>1, 2, 5.5, 11</td>
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<td>&quot;802.11b+&quot; non-standard</td>
<td>DSSS, HR-DSSS (PBCC)</td>
<td>2.4 GHz</td>
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<tr>
<td>802.11a</td>
<td>OFDM</td>
<td>5.2, 5.5 GHz</td>
<td>6, 9, 12, 18, 24, 36, 48, 54</td>
<td></td>
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<tr>
<td>802.11g</td>
<td>DSSS, HR-DSSS, OFDM</td>
<td>2.4 GHz</td>
<td>1, 2, 5.5, 11; 6, 9, 12, 18, 24, 36, 48, 54</td>
<td></td>
</tr>
</tbody>
</table>
Why multiple rates?
“Adaptive” coding/modulation

<table>
<thead>
<tr>
<th>Speed (Mbps)</th>
<th>Modulation and coding rate (R)</th>
<th>Coded bits per carrier[¹][²]</th>
<th>Coded bits per symbol</th>
<th>Data bits per symbol[³][⁴]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK, R=1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9</td>
<td>BPSK, R=3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK, R=1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK, R=3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM, R=1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM, R=3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM, R=2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM, R=3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>

Example: 802.11a case

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PHY distance/rate tradeoffs

(Open Office)

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Coverage performance
Cisco Aironet 350 Access Point

Configurable TX power:
50, 30, 20, 5, 1 mW
(100 mW outside Europe)

Greater TX power, faster battery consumptions!

Question: how to select transmission rate?
STA does not explicitly know its distance from AP.
More later (implementation-dependent)

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WLAN NIC addresses

- **Same as Ethernet NIC**
  48 bits = 2 + 46

- **Ethernet & WLAN addresses do coexist**
  Undistinguishable, in a same (Layer-2) network
  Role of typical AP = bridge
  » To be precise: when the AP acts as “portal” in 802.11 nomenclature

C:> arp –a
192.168.1.32 00.0a.e6.f7.03.ad dinamico
192.168.1.43 00.06.00.32.1a dinamico
192.168.1.52 00.82.00.11.22.33

802 IEEE
48 bit address
1 bit = individual/group
1 bit = universal/local
46 bit address

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802.11: “just” another 802 link layer
802.11 MAC Data Frame

MAC header:
- 28 bytes (24 header + 4 FCS) or
- 34 bytes (30 header + 4 FCS)

Details and explanation later on!

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IEEE 802.11 WLAN

Wireless LAN Networks and related Addressing

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Basic Service Set (BSS)
group of stations that can communicate with each other

- **Infrastructure BSS**
or, simply, BSS
Stations connected through AP

- **Independent BSS**
or IBSS
Stations connected in ad-hoc mode

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Frame Forwarding in a BSS

BSS: AP = relay function
No direct communication allowed!

IBSS: direct communication between all pairs of STAs

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Why AP = relay function?

- **Management:**
  Mobile stations do NOT need to maintain neighbor relationship with other MS in the area
  But only need to make sure they remain properly associated to the AP
  Association = get connected to (equivalent to plug-in in a wire to a bridge)

- **Power Saving:**
  APs may assist MS in their power saving functions
  by buffering frames dedicated to a (sleeping) MS when it is in PS mode

- **Obvious disadvantage:** use channel bandwidth twice...
ESS: created by merging different BSS through a network infrastructure (possibly overlapping BSS – to offer a continuous coverage area)

Stations within ESS MAY communicate each other via Layer 2 procedures
APs acting as bridges
MUST be on a same LAN or switched LAN or VLAN (no routers in between)
The concept of Distribution System

MSs in a same ESS need to
1) communicate each other
2) move through the ESS

No standard implementation, but set of services:
Association, disassociation, reassociation,
Integration, distribution

Basically. DS role:
- track where an MS is registered within an ESS area
- deliver frame to MS

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Association and DS

**Typical implementation (media)**
Switched ethernet backbone
But alternative “distribution medium” are possible
E.g. wireless distribution system (WDS)

**DS implementation:**
- an AP must inform other APs of associated MSs MAC addresses
- proprietary implementation no interoperability
- standardized protocol IAPP (802.11f) in june 2003

**Current trend:**
- Centralized solutions (Cisco, Aruba)- CAPWAP?

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Wireless Distribution System

DS medium:
- not necessarily an ethernet backbone!
- could be the 802.11 technology itself

Resulting AP = wireless bridge
Addresses

- At least three addresses
  - Receiving station
  - Transmitting station
  - BSS address
    - To make sure a frame is valid within the considered BSS
    - For filtering purpose (filter frame within a BSS)
BSSID

 Address of a BSS

 Infrastructure mode:
 AP MAC address

 Ad-hoc mode:
 Random value
 » With universal/local bit set to 1
 Generated by STA initiating the IBSS

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Addressing in an IBSS

SA = Source Address
DA = Destination Address

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Addressing in a BSS?
Addressing in a BSS!

Frame must carry following info:
1) Destined to DA
2) But through the AP
What is the most general addressing structure?

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Addressing in a BSS (to AP)

Address 2 = wireless Tx
Address 1 = wireless Rx
Address 3 = dest

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Addressing in an ESS

Idea: DS will be able to forward frame to dest (either if fixed or wireless MAC)
Addressing in a BSS (from AP)

Address 2 = wireless Tx
Address 1 = wireless Rx
Address 3 = src

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From AP: do we really need 3 addresses?

DA correctly receives frame, and send 802.11 ACK to … BSSID (wireless transmitted)

DA correctly receives frame, and send higher level ACK to … SA (actual transmitter)

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Addressing within a WDS

Wireless Distribution System

Address 4: initially forgotten…

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### Addressing: summary

<table>
<thead>
<tr>
<th>Function</th>
<th>To DS</th>
<th>From DS</th>
<th>Address 1</th>
<th>Address 2</th>
<th>Address 3</th>
<th>Address 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBSS</td>
<td>0</td>
<td>0</td>
<td>RA = DA</td>
<td>SA</td>
<td>BSSID</td>
<td>N/A</td>
</tr>
<tr>
<td>From AP</td>
<td>0</td>
<td>1</td>
<td>RA = DA</td>
<td>BSSID</td>
<td>SA</td>
<td>N/A</td>
</tr>
<tr>
<td>To AP</td>
<td>1</td>
<td>0</td>
<td>RA = BSSID</td>
<td>SA</td>
<td>DA</td>
<td>N/A</td>
</tr>
<tr>
<td>Wireless DS</td>
<td>1</td>
<td>1</td>
<td>RA</td>
<td>TA</td>
<td>DA</td>
<td>SA</td>
</tr>
</tbody>
</table>

- **BSS Identifier (BSSID)**
  - unique identifier for a particular BSS. In an infrastructure BSSID it is the MAC address of the AP. In IBSS, it is random and locally administered by the starting station. (uniqueness)

- **Transmitter Address (TA)**
  - MAC address of the station that transmit the frame to the wireless medium. Always an individual address.

- **Receiver Address (RA)**
  - to which the frame is sent over wireless medium. Individual or Group.

- **Source Address (SA)**
  - MAC address of the station who originated the frame. Always individual address.
  - May not match TA because of the indirection performed by DS of an IEEE 802.11 WLAN. SA field is considered by higher layers.

- **Destination Address (DA)**
  - Final destination. Individual or Group.
  - May not match RA because of the indirection.

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Service Set IDentifier (SSID)

- **Name of the WLAN network**
  Plain text (ascii), up to 32 char

- **Assigned by the network administrator**
  All BSS in a same ESS have same SSID

- **Typically (but not necessarily) is transmitted in periodic management frames (beacon)**
  Typical: 1 broadcast beacon every 100 ms (configurable by sysadm)
  Beacon may transmit a LOT of other info

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Medium Access Control
Protocols: DCF
Wireless Ethernet

- **802.3 (Ethernet)**
  - CSMA/CD
    - Carrier Sense Multiple Access
    - Collision Detect

- **802.11 (wireless LAN)**
  - CSMA/CA
    - (Distributed Coordination Function)
    - Carrier Sense Multiple Access
    - Collision Avoidance

Both A and C sense the channel idle at the same time, they send at the same time.

Collision can be detected at sender in Ethernet.

Why this is not possible in 802.11?

1. Either TX or RX (no simultaneous RX/TX)
2. Large amount of power difference in Tx and Rx (even if simultaneous tx-rx, no possibility in rx while tx-ing)
3. Wireless medium = additional problems vs broadcast cable!!

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**Hidden Terminal Problem**

- Large difference in signal strength; physical channel impairments (shadowing)
  - It may result that two stations in the same area cannot communicate
- Hidden terminals
  - A and C cannot hear each other
  - A transmits to B
  - C wants to send to B; C cannot receive A; C senses "idle" medium (Carrier Sense fails)
  - Collision occurs at B.
  - A cannot detect the collision (Collision Detection fails).
  - A is "hidden" to C.

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802.11 MAC approach

Still based on Carrier Sense:
Listen before talking

But collisions can only be inferred afterwards, at the receiver
Receivers see corrupted data through a CRC error
Transmitters fail to get a response

Two-way handshaking mechanism to infer collisions
DATA-ACK packets
Channel Access details

A station can transmit only if it senses the channel IDLE for a DIFS time

\[ \text{DIFS} = \text{Distributed Inter Frame Space} \]

Packet arrival

TX \hspace{1cm} DIFS \hspace{1cm} DATA \hspace{1cm} SIFS \hspace{1cm} ACK

What about a station arriving in this frame time?

Key idea: DATA and ACK separated by a different Inter Frame Space

\[ \text{SIFS} = \text{Short Inter Frame Space} \]

Second station cannot hear a whole DIFS, as SIFS<DIFS

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DIFS & SIFS in wi-fi

- DIFS = 50 $\mu$s
- SIFS = 10 $\mu$s
**Why backoff?**

**RULE:** when the channel is initially sensed **BUSY**, station defers transmission; But when it is sensed **IDLE** for a DIFS, defer transmission of a further random time (**BACKOFF TIME**)
Slotted Backoff

Note: slot times are not physically delimited on the channel!
Rather, they are logically identified by every STA

Slot-time values: 20µs for DSSS (wi-fi)
Accounts for: 1) RX_TX turnaround time
2) busy detect time
3) propagation delay

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Backoff freezing

When STA is in backoff stage:

- It freezes the backoff counter as long as the channel is sensed BUSY.
- It restarts decrementing the backoff as the channel is sensed IDLE for a DIFS period.

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Backoff rules

- **First backoff value:**
  Extract a uniform random number in range \((0, CW_{\text{min}})\)

- **If unsuccessful TX:**
  Extract a uniform random number in range \((0, 2 \times (CW_{\text{min}} + 1) - 1)\)

- **If unsuccessful TX:**
  Extract a uniform random number in range \((0, 2^2 \times (CW_{\text{min}} + 1) - 1)\)

- **Etc up to** \(2^m \times (CW_{\text{min}} + 1) - 1\)

  Exponential Backoff!
  \(CW_{\text{min}} = 31\)
  \(CW_{\text{max}} = 1023\) (\(m=5\))

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RTS/CTS

- **Request-To-Send / Clear-To-Send**
- **4-way handshaking**
  Versus 2-way handshaking of basic access mechanism
- **Introduced for two reasons**
  Combat hidden terminal
  Improve throughput performance with long packets

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RTS/CTS and hidden terminals

RTS/CTS: carry the amount of time the channel will be BUSY. Other stations may update a Network Allocation Vector, and defer TX even if they sense the channel idle (Virtual Carrier Sensing)

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Frame formats

DATA FRAME (28 bytes excluded address 4)

<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>Data</th>
<th>FCS</th>
</tr>
</thead>
</table>

RTS (20 bytes)

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration</th>
<th>RA</th>
<th>TA</th>
<th>FCS</th>
</tr>
</thead>
</table>

CTS / ACK (14 bytes)

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration</th>
<th>RA</th>
<th>FCS</th>
</tr>
</thead>
</table>
**Fragmentation**

- Splits message (MSDU) into several frames (MPDU)
  - Same fragment size except the last one
- **Fragmentation burst**
  - Fragments separated by SIFS
  - Channel cannot be captured by someone else
  - Each fragment individually ACKed
- Each fragment reserves channel for next one
  - NAV updated fragment by fragment
- Missing ACK for fragment x
  - Release channel (automatic)
  - Backoff
  - Restart from transmission of fragment x

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Why Fragmentation?

- **High Bit Error Rate (BER)**
  - Increases with distance
  - The longer the frame, the lower the successful TX probability
  - High BER = high rts overhead & increased rtx delay
  - Backoff window increases: cannot distinguish collisions from tx error!

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**Fragment and sequence numbers**

DATA FRAME (28 bytes excluded address 4)

- **Fragment number**
  - Increasing integer value 0-15 (max 16 fragments since 4 bits available)
  - Essential for reassembly

- **More fragment bit (frame control field) set to:**
  - 1 for intermediate fragments
  - 0 for last fragment

- **Sequence Number**
  - Used to filter out duplicates
  - Unlike Ethernet, duplicates are quite frequent!
  - Retransmissions are a main feature of the MAC

- **Retry bit: helps to distinguish retransmissions**
  - Set to 0 at transmission of a new frame
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Lecture 3bis
Medium Access Control
Protocols: PCF
PCF vs DCF

PCF deployed on TOP of DCF
Backward compatibility

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PCF

- **Token-based access mechanism**
  - Polling

- **Channel arbitration enforced by a “point Coordinator” (PC)**
  - Typically the AP, but not necessarily

- **Contention-free access**
  - No collision on channel

- **PCF deployment: minimal!!**
  - Optional part of the 802.11 specification
  - As such, almost never deployed
  - But HCCA (PCF extension in 802.11e) is getting considerable attention…
PCF frame transfer

Polling strategy: very elementary!!
- send polling command to stations with increasing Association ID value…
- (regardless whether they might have or not data to transmit)
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Network Management

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Management Operations

- **Wireless is not always an advantage**
  Medium unreliable, lack of physical boundaries, power consumption

- **How to join, build, connect, move nodes, save energies, ...**
  All these issues are faced by the management procedures, which can be customized
  Different vendor offers: very simple products vs. feature-rich products
Scanning

Before joining a network, you have to find it!! The discovery operation is called scanning.

Several parameters can be specified by the user:
- BSSType (independent, infrastructure, both)
- BSSID (individual, Broadcast)
- SSID (network name)
- ScanType (active, passive)
- Channel List
- Probe Delay (to start the active scanning in each channel)
- MinChannelTime, MaxChannelTime
Passive Scanning

- Saves battery, since it requires listening only
- Scanning report based on beacon frames heard while sweeping channel to channel
Active Scanning

- **Probe Request Frames used to solicit responses from a network, when the ProbeDelay time expires**
  
  If the medium is detected busy during the MinChannelTime, wait until the MaxChanneltime expires.
  
  One station in each BSS is responsible to send Probe Responses (station which transmitted the last beacon frame).

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Joining

- A scan report is generated after each scan, reporting BSSID, SSID, BSSType,
  - Beacon Interval
  - DTIM period
  - Timing Parameters (Timestamp)
  - PHY Parameters, BSSBasicRateSet

- Joining: before associating, select a network (often it requires user action)
- and after?
  - authentication
Association

After that we choose a network and we authenticate, we can finally send an “association” message.

- The message is required for tracking the host position in the ESS.
- Not used for ad hoc networks.
- Re-association after hand-over.
And to be found?

- **It is required to periodically transmit a beacon!**
  - In infrastructure: beacon transmissions managed by the AP
  - In ad-hoc: each station contend for the beacon and leave the contention after the first observed beacon

- **The beacon frames are periodically scheduled, but contend as normal frames**
What information is carried by beacons?

- **Timestamp (8 bytes):** in Transmission Units TU (=1024 us) to synchronize stations
- **Beacon Interval (2 bytes):** beacon scheduling interval
- **Capability Info (2 bytes):** bit map to activate/deactivate some network features
- **SSID (variable size):** network name set by the operators
  - Element ID, Length, Information for every variable size field

**OPTIONAL:**
- **FH ParameterSet** (7 bytes)
- **DS ParameterSet** (2 bytes)
- **CF ParameterSet** (8 bytes)
- **IBSS ParameterSet** (4 bytes)
- **Traffic Indicator Map TIM** (variable size): to indicate which stations have buffered frames; some TIM are Delivery TIM for broadcast traffic
Why Timestamps for Synchronization?

Example: DTIM at every 3 TIM intervals

To allow power-saving modes, which are based on periodic wake-up of doze stations!

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