Internet Protocol Stack

- **Application**: supporting network applications
  - FTP, SMTP, HTTP
- **Transport**: data transfer between processes
  - TCP, UDP
- **Network**: routing of datagrams from source to destination
  - IP, routing protocols
- **Link**: data transfer between neighboring network elements
  - Ethernet, WiFi
- **Physical**: bits “on the wire”
  - Coaxial cable, optical fibers, radios
Introduction to Link Layer and IEEE 802.11 (WiFi)
Outline

• Introduction to MAC layer
• Introduction to IEEE 802.11
• 802.11 Physical layer
• 802.11 MAC layer
• 802.11 Management
Link Layer Services

• **Framing, link access:**
  - encapsulate datagram into frame, adding header, trailer
  - implement and coordinate channel access if shared medium (e.g., Ethernet)
  - ‘physical addresses’ used in frame headers to identify source, dest
    • different from IP address!

• **Correct and reliable delivery between two physically connected devices**

• **flow control**
Link layer: setting the context
Multiple Access protocols

- Single shared broadcast channel
- Two or more simultaneous transmissions by nodes: interference
  - Collision if node receives two or more signals at the same time

**Multiple access protocol**

- Distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- Communication about channel sharing must use channel itself!
  - no out-of-band channel for coordination
Ideal Multiple Access Protocol

Broadcast channel of rate $R$ bps

1. When one node wants to transmit, it can send at rate $R$.
2. When $M$ nodes want to transmit, each can send at average rate $R/M$.
3. Fully decentralized:
   - no special node to coordinate transmissions
   - no synchronization of clocks, slots
4. Simple
MAC Protocols: a taxonomy

• **Channel Partitioning**
  - divide channel into smaller “pieces” (time slots, frequency, code)
  - allocate piece to node for exclusive use
  - Examples
    • TDMA: partition time slots
    • FDMA: partition frequency

• **Random Access**
  - allow collisions
  - “recover” from collisions

• **“Taking turns”**
  - nodes take turns, but nodes with more to send can take longer turns
Random Access Protocols

• When a node has a packet to send
  - transmit at full channel data rate R.
  - no a priori coordination among nodes

• two or more transmitting nodes -> “collision”

• random access MAC protocol specifies:
  - how to detect collisions
  - how to recover from collisions (e.g., via delayed retransmissions)

• Examples of random access MAC protocols:
  - Pure ALOHA
  - Slotted ALOHA
  - CSMA and CSMA/CD
Slotted ALOHA

**Assumptions:**
- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

**Operation:**
- when node obtains fresh frame, transmits in next slot
  - *if no collision:* node can send new frame in next slot
  - *if collision:* node retransmits frame in each subsequent slot with prob. \( p \) until success
Pros
• single active node can continuously transmit at full rate of channel
• highly decentralized: only slots in nodes need to be in sync
• simple

Cons
• collisions, wasting slots
• idle slots
• nodes may be able to detect collision in less than time to transmit packet
• clock synchronization
Pure (unslotted) ALOHA

• unslotted Aloha: simpler, no synchronization
• when frame first arrives
  - transmit immediately
• collision probability increases:
  - frame sent at $t_0$ collides with other frames sent in $[t_0-1, t_0+1]$
Problems with Pure/Slotted ALOHA

do not listen to the channel
CSMA: Carrier Sense Multiple Access

**CSMA:** listen before transmit:
- If channel sensed idle: transmit entire pkt
- If channel sensed busy, defer transmission
  - **Persistent CSMA:** retry immediately with probability $p$ when channel becomes idle (may cause instability)
  - **Non-persistent CSMA:** retry after random interval

human analogy: don't interrupt others!
CSMA collisions

**collisions can still occur:**
propagation delay means two nodes may not hear each other’s transmission

**collision:**
entire packet transmission time wasted

**note:**
role of distance and propagation delay in determining collision prob.
CSMA/CD (Collision Detection)

**CSMA/CD:** carrier sensing, deferral as in CSMA

- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage
- persistent or non-persistent retransmission

**collision detection:**

- easy in wired LANs: measure signal strengths, compare transmitted, received signals
- *Can we do collision detection in wireless networks?*
CSMA/CD (Collision Detection)

CSMA/CD: carrier sensing, deferral as in CSMA
- collisions detected within short time
- colliding transmissions aborted, reducing channel wastage
- persistent or non-persistent retransmission

• collision detection:
  - easy in wired LANs: measure signal strengths, compare transmitted, received signals
  - difficult in wireless LANs:
    - receiver shut off while transmitting
    - receiver's channel condition is different from that of the sender
Introduction to IEEE 802.11
Characteristics of wireless LANs

• **Advantages**
  - very flexible within the reception area
  - Ad-hoc networks without previous planning possible
  - (almost) no wiring difficulties
  - more robust against disasters
    - e.g., earthquakes, fire - or users pulling a plug...

• **Disadvantages**
  - typically low bandwidth compared to wired networks (1-10 Mbit/s) due to shared medium
  - Less reliable
Design Goals for Wireless LANs

- global, seamless operation
- low power for battery use
- no special licenses needed to use the LAN
- robust transmission technology
- easy to use for everyone, simple management
- security, privacy, safety
- transparent to applications and higher layer protocols
- location aware if necessary
Infrastructure vs. ad-hoc networks

infrastructure network

wired network

ad-hoc network

AP: Access Point
802.11: Infrastructure

- **Station (STA)**
  - terminal with access mechanisms to the wireless medium and radio contact to the access point

- **Access Point**
  - station integrated into the wireless LAN and the distribution system

- **Basic Service Set (BSS)**
  - group of stations using the same AP

- **Portal**
  - bridge to other (wired) networks

- **Distribution System**
  - interconnection network to form one logical network (EES: Extended Service Set) based on several BSS
802.11: Ad hoc mode

- **Direct communication within a limited range**
  - Station (STA): terminal with access mechanisms to the wireless medium
  - Independent Basic Service Set (IBSS): group of stations using the same network
Outline

• Introduction to MAC
• Introduction to IEEE 802.11
• 802.11 Physical layer
• 802.11 MAC layer
• 802.11 Management
WLAN: IEEE 802.11b

- **Data rate**
  - 1, 2, 5.5, 11 Mbit/s, depending on SNR
  - User data rate max. approx. 6 Mbit/s

- **Transmission range**
  - 300m outdoor, 30m indoor
  - Max. data rate ~10m indoor

- **Frequency**
  - Free 2.4 GHz ISM-band

- **Availability**
  - Many products and vendors

- **Quality of Service**
  - Best effort, no guarantees (unless polling is used, limited support in products)

- **Pros**
  - Many installed systems and vendors
  - Available worldwide
  - Free ISM-band

- **Cons**
  - Heavy interference on ISM-band
  - No service guarantees
  - Relatively low data rate
WLAN: IEEE 802.11a

- **Data rate**
  - 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s, depending on SNR
  - User throughput (1500 byte packets): 5.3 (6), 18 (24), 24 (36), 32 (54)
  - 6, 12, 24 Mbit/s mandatory

- **Transmission range**
  - 100m outdoor, 10m indoor
    - E.g., 54 Mbit/s up to 5 m, 48 up to 12 m, 36 up to 25 m, 24 up to 30 m, 18 up to 40 m, 12 up to 60 m

- **Frequency**
  - Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band

- **Availability**
  - Some products, some vendors

- **Quality of Service**
  - Best effort, no guarantees (same as all 802.11 products)

- **Pros**
  - Fits into 802.x standards
  - Free ISM-band
  - Available, simple system
  - Uses less crowded 5 GHz band
  - Higher data rates

- **Cons**
  - Shorter range
WLAN: IEEE 802.11n

- **Data rate**
  - 7.2, 14.4, 21.7, 28.9, ..., 72.2 Mbit/s, depending on SNR
- **Multiple input multiple output (MIMO)**
- **20MHz and 40MHz bands**
- **Transmission range**
  - Increase range by several factors due to MIMO
- **Frequency**
  - Free 2.4GHz ISM-band
  - Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band
- **Availability**
  - Some products, some vendors

- **Quality of Service**
  - Best effort, no guarantees (same as all 802.11 products)

- **Pros**
  - Fits into 802.x standards
  - Free ISM-band
  - Available, simple system
  - Uses dual band
  - Higher data rates

- **Cons**
  - Interference on ISM-band
IEEE 802.11 further developments

- **802.11i**: Enhanced Security Mechanisms
  - Enhance the current 802.11 MAC to provide improvements in security.
  - TKIP enhances the insecure WEP, but remains compatible to older WEP systems
  - AES provides a secure encryption method and is based on new hardware
- **802.11j**: Extensions for operations in Japan
  - Changes of 802.11a for operation at 5GHz in Japan using only half the channel width at larger range
- **802.11k**: Methods for channel measurements
  - Devices and access points should be able to estimate channel quality in order to be able to choose a better access point of channel
- **802.11m**: Updates of the 802.11 standards
- **802.11n**: Higher data rates 600Mbit/s
  - Changes of PHY and MAC with the goal of 100Mbit/s at MAC SAP
  - MIMO antennas (Multiple Input Multiple Output), up to 600Mbit/s are currently feasible
  - However, still a large overhead due to protocol headers and inefficient mechanisms
- **802.11p**: Inter car communications
  - Communication between cars/road side and cars/cars
  - Planned for relative speeds of min. 200km/h and ranges over 1000m
  - Usage of 5.850-5.925GHz band in North America
IEEE 802.11 further developments

- **802.11c: Bridge Support**
  - Definition of MAC procedures to support bridges as extension to 802.1D

- **802.11d: Regulatory Domain Update**
  - Support of additional regulations related to channel selection, hopping sequences

- **802.11e: MAC Enhancements – QoS**
  - Enhance the current 802.11 MAC to expand support for applications with Quality of Service requirements, and in the capabilities and efficiency of the protocol
  - Definition of a data flow (“connection”) with parameters like rate, burst, period...
  - Additional energy saving mechanisms and more efficient retransmission

- **802.11f: Inter-Access Point Protocol**
  - Establish an Inter-Access Point Protocol for data exchange via the distribution system
  - Currently unclear to which extend manufacturers will follow this suggestion

- **802.11g: Data Rates > 20 Mbit/s at 2.4 GHz; 54 Mbit/s, OFDM**
  - Successful successor of 802.11b, performance loss during mixed operation with 11b

- **802.11h: Spectrum Managed 802.11a**
  - Extension for operation of 802.11a in Europe by mechanisms like channel measurement for dynamic channel selection (DFS, Dynamic Frequency Selection) and power control (TPC, Transmit Power Control)
IEEE 802.11 further developments

• **802.11r: Faster Handover between BSS**  
  - Secure, fast handover of a station from one AP to another within an ESS  
  - Current mechanisms (even newer standards like 802.11i) plus incompatible devices from different vendors are massive problems for the use of, e.g., VoIP in WLANs  
  - Handover should be feasible within 50ms in order to support multimedia applications efficiently

• **802.11s: Mesh Networking**  
  - Design of a self-configuring Wireless Distribution System (WDS) based on 802.11  
  - Support of point-to-point and broadcast communication across several hops

• **802.11t: Performance evaluation of 802.11 networks**  
  - Standardization of performance measurement schemes

• **802.11u: Interworking with additional external networks**

• **802.11v: Network management**  
  - Extensions of current management functions, channel measurements  
  - Definition of a unified interface

• **802.11w: Securing of network control**  
  - Classical standards like 802.11, but also 802.11i protect only data frames, not the control frames. Thus, this standard should extend 802.11i in a way that, e.g., no control frames can be forged.

• **Note:** Not all “standards” will end in products, many ideas get stuck at working group

• **Info:** www.ieee802.org/11/, 802wirelessworld.com, standards.ieee.org/getieee802/
Outline

• Introduction to MAC
• Introduction to IEEE 802.11
• 802.11 Physical layer
• 802.11 MAC layer
• 802.11 Management
IEEE 802.11 Wireless MAC

• **Distributed and centralized MAC components**
  
  - **Centralized – Point Coordination Function (PCF)**
    
    • In infrastructure mode
    
    • Contention-free access protocol with a controller (AP) called a point coordinator within the BSS
  
  - **Distributed – Distributed Coordination Function (DCF)**
    
    • In ad-hoc mode
    
    • DCF is a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol (distributed contention based protocol)

• Both the DCF and PCF can operate concurrently within the same BSS to provide alternative contention and contention-free periods
PCF in 802.11 MAC

• Its objective is to provide QoS guarantees
  - E.g. bound the max access delay, bound the minimum guaranteed txmt rate

• Centralized MAC - infrastructure mode

• Key idea
  - The AP polls the nodes in its BSS
  - A PC (point coordinator) at the AP splits the access time into super frame periods
  - A super frame period consists of alternating contention free periods (CFPs) and contention periods (CPs)
  - The PC then determines which station transmits at any point in time
DCF in 802.11 MAC

• The AP doesn’t control the medium access

• Use collision avoidance techniques, in conjunction with a (physical or virtual) carrier sense mechanism

• Carrier sense:
  - When a node wishes to transmit a packet, it first waits until the channel is idle

• Collision avoidance:
  - Once channel becomes idle, the node waits for a randomly chosen duration before attempting to transmit
  - Nodes hearing RTS or CTS stay silent for the duration of the corresponding transmission
Before a node transmits, it listens for activity on the network.
If medium is busy, node waits to transmit.
After medium is clear, don't immediately start transmitting...
Otherwise all nodes would start talking at the same time!
Instead, delay a random amount of time (random backoff).
802.11 MAC Layer

- **Distributed and centralized access methods**
  - DCF CSMA/CA (mandatory)
    - collision avoidance via randomized “back-off” mechanism
    - minimum distance between consecutive packets
    - ACK packet for acknowledgements (not for broadcasts)
  - DCF w/ RTS/CTS (optional)
    - Distributed Foundation Wireless MAC
    - avoids hidden terminal problem
  - PCF (optional)
    - access point polls terminals according to a list
How to prioritize frames?
802.11 - MAC layer II

- Priorities
  - defined through different inter frame spaces
  - no guarantee, hard priorities
  - SIFS (Short Inter Frame Spacing)
    • highest priority, for ACK, CTS, polling response
  - PIFS (PCF IFS)
    • medium priority, for time-bounded service using PCF
  - DIFS (DCF, Distributed Coordination Function IFS)
    • lowest priority, for asynchronous data service
IEEE 802.11 DCF

• DCF is **CSMA/CA** protocol
  - Why not **CSMA/CD**?
• DCF suitable for multi-hop ad hoc networking
• Optionally uses RTS-CTS exchange to avoid hidden terminal problem
  - Any node overhearing a CTS cannot transmit for the duration of the transfer
• Uses **ACK** to provide reliability
CSMA/CA

- **CSMA/CA:**
  - Wireless MAC protocols often use collision avoidance techniques, in conjunction with a (physical or virtual) carrier sense mechanism.

- **Collision avoidance**
  - Nodes hearing RTS or CTS stay silent for the duration of the corresponding transmission.
  - Once channel becomes idle, the node waits for a randomly chosen duration before attempting to transmit.
CSMA/CA

- **Carrier sense**
  - Nodes stay silent when carrier sensed (physical/virtual)
  - Physical carrier sense
    - Carrier sense threshold
  - Virtual carrier sense using Network Allocation Vector (NAV)
    - NAV is updated based on overheard RTS/CTS/DATA/ACK packets
Hidden Terminal Problem

- B can communicate with both A and C
- A and C cannot hear each other
- Problem
  - When A transmits to B, C cannot detect the transmission using the carrier sense mechanism
  - If C transmits, collision will occur at node B
- Solution
  - Hidden sender C needs to defer
Solution for Hidden Terminal Problem: MACA

- When A wants to send a packet to B, A first sends a Request-to-Send (RTS) to B

- On receiving RTS, B responds by sending Clear-to-Send (CTS), provided that A is able to receive the packet

- When C overhears a CTS, it keeps quiet for the duration of the transfer
  - Transfer duration is included in both RTS and CTS
IEEE 802.11

RTS = Request-to-Send

Pretending a circular range
IEEE 802.11

RTS = Request-to-Send

NAV = remaining duration to keep quiet
IEEE 802.11

CTS = Clear-to-Send
IEEE 802.11

CTS = Clear-to-Send

CTS

A B C D E F

NAV = 8
IEEE 802.11

• DATA packet follows CTS. Successful data reception acknowledged using ACK.
Why do we need virtual carrier sense?
Reliability

• Wireless links are prone to errors. High packet loss rate detrimental to transport-layer performance.

• Mechanisms needed to reduce packet loss rate experienced by upper layers
A Simple Solution to Improve Reliability

- When B receives a data packet from A, B sends an Acknowledgement (ACK) to A.

- If node A fails to receive an ACK, it will retransmit the packet.
Can RTS/CTS completely eliminate hidden terminals?
Outline

• Introduction to MAC layer
• Introduction to IEEE 802.11
• 802.11 Physical layer
• 802.11 MAC layer
• 802.11 Management
Question

• Is 802.11 a MAC protocol or PHY protocol?
• How does Pure Aloha access the medium?
• How does slotted Aloha access the medium?
• What are the major issues with Aloha?
• What is CSMA?
• What MAC protocol does Ethernet use?
• Why is collision detection hard in wireless networks?
• What MAC protocol does 802.11 use?
Backoff Interval

- **Collision avoidance**
  - Backoff intervals used to reduce collision probability
- **When transmitting a packet, choose a backoff interval in the range [0, CW]**
  - CW is contention window
- **Count down the backoff interval when medium is idle**
  - Count-down is suspended if medium becomes busy
- **Transmit when backoff interval reaches 0**
DCF Example

B1 and B2 are backoff intervals at nodes 1 and 2

B1 = 25
B2 = 20

B1 = 5
B2 = 15

B2 = 10

cw = 31
Backoff Interval

- The time spent counting down backoff intervals is a part of MAC overhead

- Important to choose CW appropriately
  - large CW $\Rightarrow$ large overhead
  - small CW $\Rightarrow$ may lead to many collisions (when two nodes count down to 0 simultaneously)

- How to choose an appropriate CW?
Backoff Interval (Cont.)

- Since the number of nodes attempting to transmit simultaneously may change with time, some mechanism to manage contention is needed.

- IEEE 802.11 DCF: contention window \( CW \) is chosen dynamically depending on collision occurrence.
Binary Exponential Backoff in DCF

- When a node fails to receive CTS in response to its RTS, it increases the contention window
  - $CW$ is doubled (up to an upper bound)
  - More collisions $\rightarrow$ longer waiting time to reduce collision

- When a node successfully completes a data transfer, it restores $CW$ to $CW_{\text{min}}$
MILD Algorithm in MACAW

- **MACAW** uses exponential increase linear decrease to update CW
  - When a node successfully completes a transfer, reduces CW by 1
  - In 802.11, CW is restored to CW_{min}
  - In 802.11, CW reduces much faster than it increases

- **MACAW** can avoid wild oscillations of CW when many nodes contend for the channel
802.11 Overhead

- Overhead:
  - DIFS
  - Random backoff
  - ACK/SIFS
  - Optional RTS/CTS handshake before transmission of data packet (often disabled due to its overhead)
  - Header overhead

- 802.11 has room for improvement. How?
Fragmentation
DFWMAC-PCF I

- **medium busy**
- **PIFS**
- **D1**
- **SIFS**
- **D2**
- **SIFS**
- **U1**
- **SIFS**
- **U2**
- **NAV**

SuperFrame

- **t0**
- **t1**

point coordinator
wireless stations
stations' NAV
DFWMAC-PCF II
### 802.11 - Frame format

- **Types**
  - control frames, management frames, data frames
- **Sequence numbers**
  - important against duplicated frames due to lost ACKs
- **Addresses**
  - Sender, receiver, BSS identifier
- **Miscellaneous**
  - sending time, checksum, frame control, data

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<th>6</th>
<th>6</th>
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<th>6</th>
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<th>4</th>
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<tr>
<td>Frame Control</td>
<td>Duration/ID</td>
<td>Address 1</td>
<td>Address 2</td>
<td>Address 3</td>
<td>Sequence Control</td>
<td>Address 4</td>
<td>Data</td>
<td>CRC</td>
<td></td>
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</table>

<table>
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<th>4</th>
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<tbody>
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<td>Type</td>
<td>Subtype</td>
<td>To DS</td>
<td>From DS</td>
<td>More Frag</td>
<td>Retry</td>
<td>Power Mgmt</td>
<td>More Data</td>
<td>WEP</td>
<td>Order</td>
<td></td>
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## MAC address format

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<tr>
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<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>
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<td>0</td>
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<td>SA</td>
<td>BSSID</td>
<td>-</td>
</tr>
<tr>
<td>infrastructure network, from AP</td>
<td>0</td>
<td>1</td>
<td>DA</td>
<td>BSSID</td>
<td>SA</td>
<td>-</td>
</tr>
<tr>
<td>infrastructure network, to AP</td>
<td>1</td>
<td>0</td>
<td>BSSID</td>
<td>SA</td>
<td>DA</td>
<td>-</td>
</tr>
<tr>
<td>infrastructure network, within DS</td>
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<td>1</td>
<td>RA</td>
<td>TA</td>
<td>DA</td>
<td>SA</td>
</tr>
</tbody>
</table>

DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address
BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address
Special Frames: ACK, RTS, CTS

- **Acknowledgement**
  - ACK
  - Frame Control: 2 bytes
  - Duration: 2 bytes
  - Receiver Address: 6 bytes
  - CRC: 4 bytes

- **Request To Send**
  - RTS
  - Frame Control: 2 bytes
  - Duration: 2 bytes
  - Receiver Address: 6 bytes
  - Transmitter Address: 6 bytes
  - CRC: 4 bytes

- **Clear To Send**
  - CTS
  - Frame Control: 2 bytes
  - Duration: 2 bytes
  - Receiver Address: 6 bytes
  - CRC: 4 bytes
Outline

• Introduction to MAC
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802.11 - MAC management

- **Association/Reassociation**
  - integration into a LAN
  - roaming, i.e. change networks by changing access points
  - scanning, i.e. active search for a network

- **Synchronization**
  - timing

- **Power management**
  - sleep-mode without missing a message
  - periodic sleep, frame buffering, traffic measurements

- **MIB - Management Information Base**
  - managing, read, write
Association and Reassociation

- Integration into a LAN
- Scanning: find a network to connect
- Roaming: change networks by changing access points
Scanning

- **Goal:** Find a network to connect
- **Passive scanning**
  - Not require transmission
  - Move to each channel, and listen for Beacon frames
- **Active scanning**
  - Require transmission
  - Move to each channel, and send Probe Request frames to solicit Probe Responses from a network
Association in 802.11

1: Association request
2: Association response
3: Data traffic
802.11 - Roaming

- No or bad connection? Then perform:
  - **Scanning**
    - scan the environment, i.e., listen to the medium for beacon signals or send probes to the medium and wait for an answer
  - **Reassociation Request**
    - station sends a request to one or several AP(s)
  - **Reassociation Response**
    - success: AP has answered, station can now participate
    - failure: continue scanning
  - **AP accepts Reassociation Request**
    - signal the new station to the distribution system
    - the distribution system updates its data base (i.e., location information)
    - typically, the distribution system now informs the old AP so it can release resources
Reassociation in 802.11

1: Reassociation request
3: Reassociation response
5: Send buffered frames

2: verify previous association
4: send buffered frames

Client

New AP

Old AP

6: Data traffic
Synchronization using a Beacon (infrastructure)

- **Beacon Interval**
- **Access Point**
- **Medium**
- **Busy**
- **Value of the Timestamp**
- **Beacon Frame**
Synchronization using a Beacon (ad-hoc)

- Beacon interval
- Station 1: $B_1$
- Station 2: $B_2$
- Medium: busy, busy, busy, busy
- Value of the timestamp
- Beacon frame
- Random delay
Power management

- **Idea:** switch the transceiver off if not needed
- **States of a station:** sleep and awake
- **Timing Synchronization Function (TSF)**
  - stations wake up at the same time
- **Infrastructure**
  - Traffic Indication Map (TIM)
    - list of unicast receivers transmitted by AP
  - Delivery Traffic Indication Map (DTIM)
    - list of broadcast/multicast receivers transmitted by AP
- **Ad-hoc**
  - Ad-hoc Traffic Indication Map (ATIM)
    - announcement of receivers by stations buffering frames
    - more complicated - no central AP
Power saving with wake-up patterns (infrastructure)
Power saving with wake-up patterns (ad-hoc)

station₁

ATIM window

beacon interval

station₂

B₁ beacon frame

random delay

A transmit ATIM

D transmit data

wake

a acknowledge ATIM

d acknowledge data