

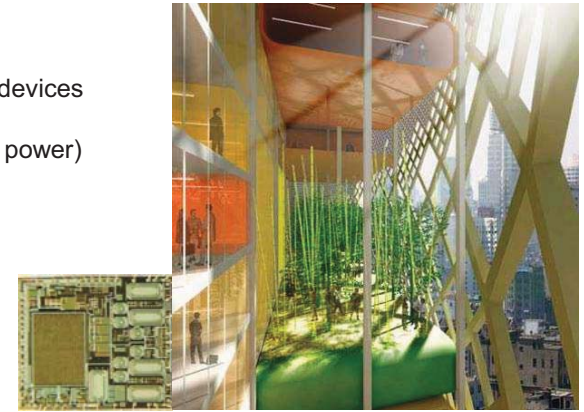
Media Access Control

Chapter 6



Home Automation

- Cooperative Lights, Blinds, Fans
- Energy Monitoring
- Security
 - Intrusion Detection
 - Fire Alarm
- Digitalstrom
 - EU: 10 billion electrical devices
 - 95% are not networked
 - cheap networking (over power)
 - true standby
 - remote control
 - universal ID
 - ...



Rating

- Area maturity

First steps

Text book

- Practical importance

No apps

Mission critical

- Theory appeal

Booooooring

Exciting

Overview

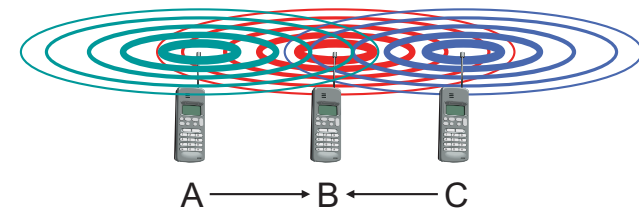
- Motivation
- Classification
- MAC layer techniques
- Case study: 802.11

Motivation

- Can we apply media access methods from fixed networks?
- Example CSMA/CD
 - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
 - send as soon as the medium is free, listen into the medium if a collision occurs (original method in IEEE 802.3)
- Problems in wireless networks
 - signal strength decreases quickly with distance
 - senders apply CS and CD, but the collisions happen at receivers
 - **E**nergy **e**fficiency: having the radio turned on costs almost as much energy as transmitting, so to seriously save energy one needs to turn the radio off!

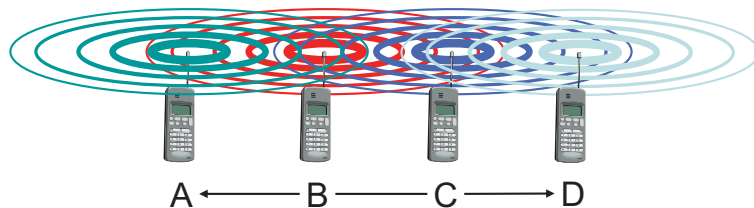
Motivation – Hidden Terminal Problem

- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- collision at B, A cannot receive the collision (CD fails)
- A is “hidden” for C



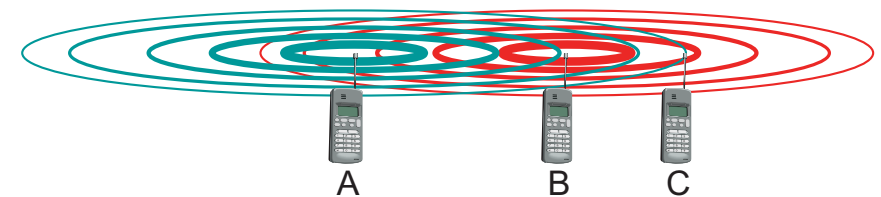
Motivation – Exposed Terminal Problem

- B sends to A, C wants to send to D
- C has to wait, CS signals a medium in use
- since A is outside the radio range of C waiting is not necessary
- C is “exposed” to B



Motivation - Near and Far Terminals

- Terminals A and B send, C receives
 - the signal of terminal B hides A's signal
 - C cannot receive A



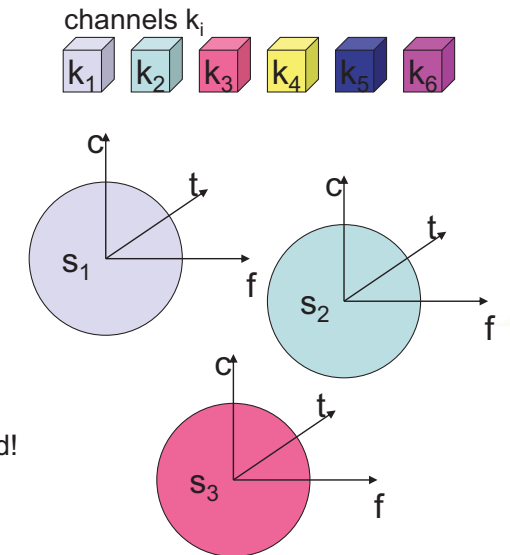
- This is also a severe problem for CDMA networks
- precise power control required

Access Methods

- **SDMA** (Space Division Multiple Access)
 - segment space into sectors, use directed antennas
 - Use cells to reuse frequencies
- **FDMA** (Frequency Division Multiple Access)
 - assign a certain frequency to a transmission channel
 - permanent (radio broadcast), slow hopping (GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- **TDMA** (Time Division Multiple Access)
 - assign a fixed sending frequency for a certain amount of time
- **CDMA** (Code Division Multiple Access)
- Combinations!

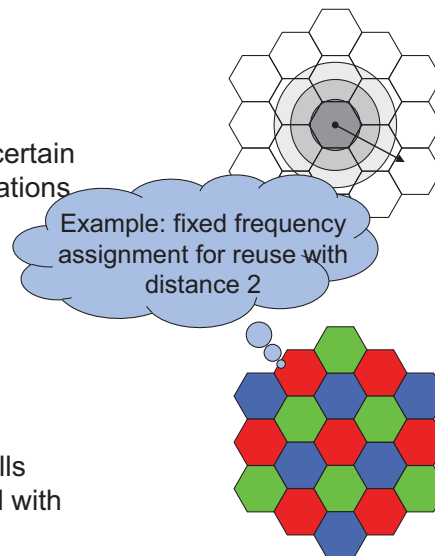
Multiplexing: Space Multiplexing

- Multiplex channels (k) in four dimensions
 - space (s)
 - time (t)
 - frequency (f)
 - code (c)
- Goal: multiple use of a shared medium
- Important: guard spaces needed!
- Example: radio broadcast



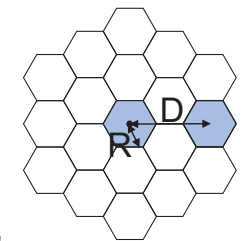
Example: Cellular network

- Simplified hexagonal model
- Signal propagation ranges: Frequency reuse only with a certain distance between the base stations
- Can you reuse frequencies in distance 2 or 3 (or more)?
- Graph coloring problem
- Interference from neighbor cells (other color) can be controlled with transmit and receive filters



Signal-to-Noise

- Digital techniques can withstand a signal to noise ratio (S/N) of approximately 9 dB, depending on the techniques...



- Assume the path loss exponent $\alpha = 3$. Then,

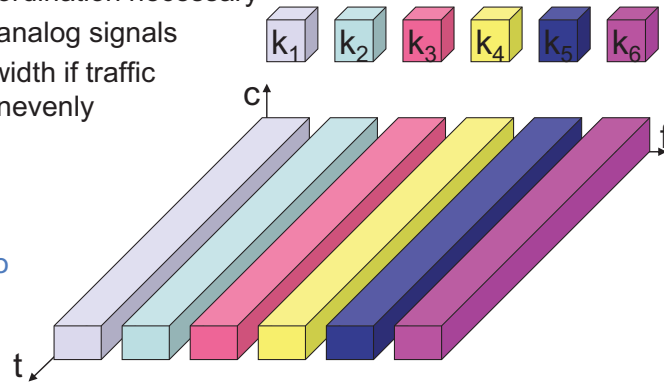
$$\frac{S}{N} = \frac{(D - R)^\alpha}{R^\alpha} = \left(\frac{D}{R} - 1\right)^\alpha$$

which gives $D/R = 3$. Reuse distance of 2 might just work...

- Remark: Signal-to-noise is also known as, e.g. carrier-to-interference ratio C/I .

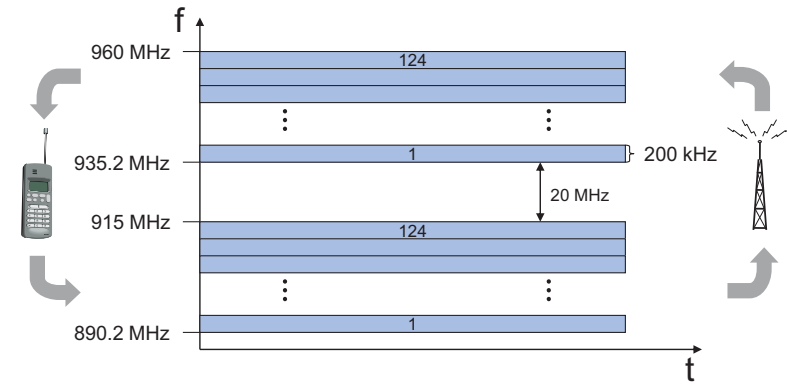
Frequency Division Multiplex (FDM)

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- + no dynamic coordination necessary
- + works also for analog signals
- waste of bandwidth if traffic is distributed unevenly
- inflexible



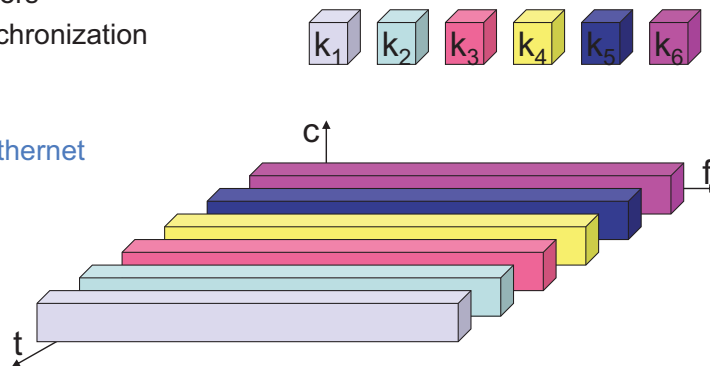
- Example: [broadcast radio](#)

FDD/FDMA - general scheme, example GSM @ 900Mhz



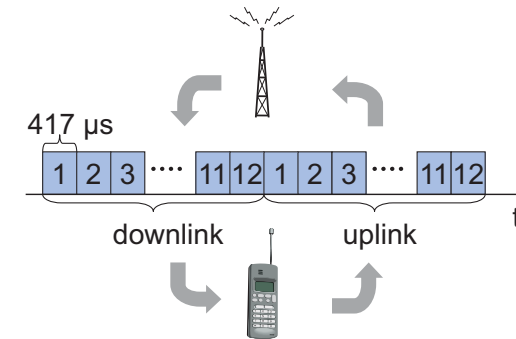
Time Division Multiplex (TDM)

- A channel gets the whole spectrum for a certain amount of time
- + only one carrier in the medium at any time
- + throughput high even for many users
- precise synchronization necessary



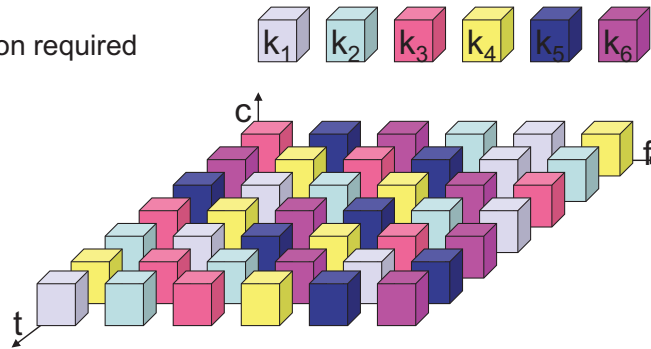
- Example: [Ethernet](#)

TDD/TDMA - general scheme, example DECT



Time and Frequency Division Multiplex

- Combination of both methods
- A channel gets a certain frequency band for some time
- + protection against frequency selective interference
- + protection against tapping
- + adaptive
- precise coordination required

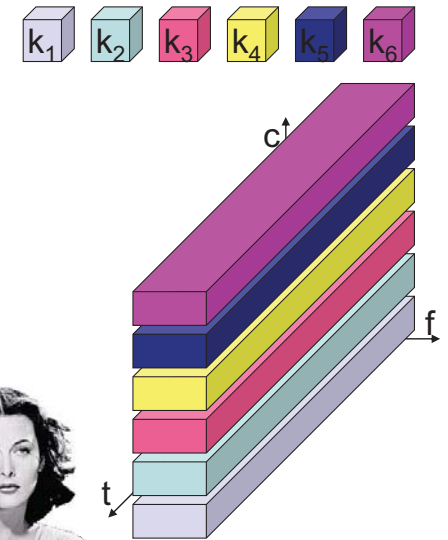


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- Example: GSM

Code Division Multiplex (CDM)

- Each channel has a unique code
- All channels use the same spectrum at the same time
- + bandwidth efficient
- + no coordination or synchronization
- + hard to tap
- + almost impossible to jam
- lower user data rates
- more complex signal regeneration
- Example: UMTS
- Spread spectrum
- U. S. Patent 2'292'387, Hedy K. Markey (a.k.a. Lamarr or Kiesler) and George Antheil (1942)



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Code Division Multiple Access (CDMA)

- CDMA is a novel **Physical/MAC** concept.
- Example: Direct Sequence Spread Spectrum (DSSS)
- Each station is assigned an m -bit code (or chip sequence)
- Typically $m = 64, 128, \dots$ (in our examples $m = 4, 8, \dots$)
- To send 1 bit, station sends chip sequence
- To send 0 bit, station sends complement of chip sequence
- Instead of splitting a 1 MHz band shared between 100 channels into 100 x 10kHz bands, every station can use the whole band, with 100 chips.
 - CDMA does not increase the total bandwidth, but it may simplify the MAC layer at the expense of complicating the physical layer.

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CDMA Basics

Each station s has unique m -bit chipping code S or complement \bar{S}
 Bipolar notation: binary 0 is represented by -1 (or short: $-$)
 Two chips S, T are orthogonal iff $S \cdot T = 0$

$S \cdot T$ is the inner (scalar) product: $S \cdot T = \frac{1}{m} \sum_{i=1}^m S_i T_i$

Note: $S \cdot S = 1, S \cdot \bar{S} = -1$

Note: $S \cdot T = 0 \Rightarrow S \cdot \bar{T} = 0$

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CDMA Example

- Assume that all stations are perfectly synchronous
- Assume that all codes are pair wise orthogonal
- Assume that if two or more stations transmit simultaneously, the bipolar signals add up linearly
- Example
- $S = (+ - + - + - + -)$
- $T = (+ + - - - + + -)$
- $U = (+ - - + - - + +)$
- Check that codes are pair wise orthogonal
- E.g., if S, T, U transmit simultaneously, a receiver receives $R = S+T+U = (+3, -1, -1, -1, -1, -1, +3, -1)$

CDMA Example (2)

- To decode a received signal R for sender s , one needs to calculate the normalized inner product $R \cdot S$.
- $R \cdot S = (+3, -1, -1, -1, -1, -1, +3, -1) \cdot (+ - + - + - + -) / 8$
 $= (+3+1-1+1-1+1+3+1) / 8$
 $= 8 / 8 = 1 \dots$ by accident?
- $R \cdot S = (S+T+U) \cdot S = S \cdot S + T \cdot S + U \cdot S = 1 + 0 + 0 = 1$
- With orthogonal codes we can safely decode the original signals

CDMA: Construction of orthogonal codes with m chips

- Note that we cannot have more than m orthogonal codes with m chips because each code can be represented by a vector in the m -dimensional space, and there are not more than m orthogonal vectors in the m -dimensional space.
- Walsh-Hadamard codes can be constructed recursively (for $m = 2^k$):
The set of codes of length 1 is $C_0 = \{(+)\}$.
For each code $(c) \in C_k$ we have two codes $(c \ c)$ and $(c \ \bar{c})$ in C_{k+1}
- Code tree:
 $C_0 = \{(+)\}$
 $C_1 = \{(+ +), (+ -)\}$
 $C_2 = \{(+ + + +), (+ + - -), (+ - + -), (+ - - +)\}$
- Note: **Random codes** are also quite balanced and pretty orthogonal.

CDMA: How much noise can we tolerate?

- We now add random noise:
- $R' = R + N$, where N is an m -digit noise vector.
- Assume that chipping codes are balanced (as many “+” as “-”)
- If $N = (\alpha, \alpha, \dots, \alpha)$ for any (positive or negative) α , then the noise N will not matter when we decode the received signal.
- $R' \cdot S = (R+N) \cdot S = S \cdot S + (\text{orthogonal codes}) \cdot S + N \cdot S = 1 + 0 + 0 = 1$
- How much random (white) noise can we tolerate?

CDMA: Problems

Some of our assumptions are problematic:

- A) It is not possible to synchronize chips perfectly. What can be done is that the sender first transmits a long enough known chip sequence on which the receiver can lock onto.
- B) Not all stations are received with the same power level. CDMA is typically used for systems with fixed base stations. Then mobile stations can send with the reciprocal power they receive from the base station. (Alternatively: First decode the best station, and then subtract its signal to decode the second best station...)
- C) We didn't discuss how to transmit bits with electromagnetic waves.

CDMA: Summary

- + all terminals can use the same frequency, no planning needed
- + reduces frequency selective fading and interference
- + base stations can use the same frequency range
- + several base stations can detect and recover the signal
- + soft handover between base stations
- + forward error correction and encryption can be easily integrated
- precise power control necessary
- higher complexity of receiver and sender

Example: UMTS

Cocktail party as analogy for multiplexing

- Space multiplex: Communicate in different rooms
- Frequency multiplex: Use soprano, alto, tenor, or bass voices to define the communication channels
- Time multiplex: Let other speaker finish
- Code multiplex: Use different languages and hone in on your language. The “farther apart” the languages the better you can filter the “noise”: German/Japanese better than German/Dutch. Can we have orthogonal languages?



Comparison SDMA/TDMA/FDMA/CDMA

| Approach | SDMA | TDMA | FDMA | CDMA |
|-------------------|--|--|--|---|
| Idea | segment space into cells/sectors | segment sending time into disjoint time-slots, demand driven or fixed patterns | segment the frequency band into disjoint sub-bands | spread the spectrum using orthogonal codes |
| Terminals | only one terminal can be active in one cell/one sector | all terminals are active for short periods of time on the same frequency | every terminal has its own frequency, uninterrupted | all terminals can be active at the same place at the same moment, uninterrupted |
| Signal separation | cell structure, directed antennas | synchronization in the time domain | filtering in the frequency domain | code plus special receivers |
| Advantages | very simple, increases capacity per km ² | established, fully digital, flexible | simple, established, robust | flexible, less frequency planning needed, soft handover |
| Dis-advantages | inflexible, antennas typically fixed | guard space needed (multipath propagation), synchronization difficult | inflexible, frequencies are a scarce resource | complex receivers, needs more complicated power control for senders |
| Comment | only in combination with TDMA, FDMA or CDMA useful | standard in fixed networks, together with FDMA/SDMA used in many mobile networks | typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse) | still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA |

MAC Alphabet Soup

[TU Delft]

| | | | |
|------------|---------------|-------------------|---------|
| μ -MAC | f-MAC | PicoRadio | SMACS |
| Aloha | FLAMA | PMAC | SCP-MAC |
| AI-LMAC | Funneling-MAC | PMAC' | SEESAW |
| B-MAC | G-MAC | Preamble sampling | Sift |
| BitMAC | HMAC | Q-MAC | SS-TDMA |
| BMA | LMAC | Q-MAC' | STEM |
| CMAC | LPL | QMAC | T-MAC |
| Crankshaft | MMAC | RATE EST | TA-MAC |
| CSMA-MPS | nanoMAC | RL-MAC | TRAMA |
| CSMA/ARC | O-MAC | RMAC | U-MAC |
| DMAC | PACT | RMAC' | WiseMAC |
| E2-MAC | PCM | S-MAC | X-MAC |
| EMACs | PEDAMACS | S-MAC/AL | Z-MAC |

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Traditional MAC Protocol Classification

- Centralized/Single-Hop Protocols
 - A base station coordinates all traffic
- Contention Protocols (CSMA)
 - Transmit when you feel like transmitting
 - Retry if collision, try to minimize collisions, additional reservation modes
 - Problem: Receiver must be awake as well
- Scheduling Protocols (TDMA)
 - Use a “pre-computed” schedule to transmit messages
 - Distributed, adaptive solutions are difficult
- Hybrid protocols
 - E.g. contention with reservation → scheduling
 - Specific (“cross-layer”) solutions, e.g. Dozer for data gathering

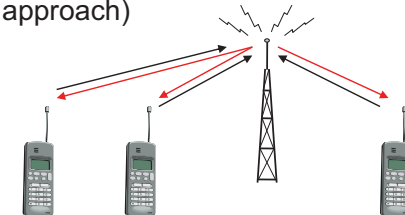
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Polling mechanisms

- If one terminal can be heard by all others, this “central” terminal (a.k.a. base station) can poll all other terminals according to a certain scheme
 - Use a scheme known from fixed networks
 - The base station chooses one address for polling from the list of all stations
 - The base station acknowledges correct packets and continues polling the next terminal
 - The cycle starts again after polling all terminals of the list

Example: Inhibit Sense Multiple Access (ISMA)

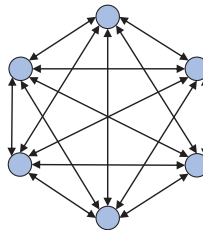
- Current state of the medium is signaled via a “busy tone”
- the base station signals on the downlink (base station to terminals) whether the medium is free
- terminals must not send if the medium is busy
- terminals can access the medium as soon as the busy tone stops
- the base station signals collisions and successful transmissions via the busy tone and acknowledgements, respectively (media access is not coordinated within this approach)
- Example: for CDPD (USA, integrated into AMPS)



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TDMA – Motivation

- System with n stations $(0,1,2,\dots,n-1)$ and one shared channel
- The channel is a perfect broadcast channel
 - Single transmissions are received by every other station.
 - No hidden or exposed terminal problem.
 - Interference if more than one station transmits.



- **Round robin** algorithm: station k sends after station $k-1 \pmod n$
 - If a station does not need to transmit data, then it sends “ ϵ ”
 - There is a maximum message size m that can be transmitted
- How efficient is round robin? What if a station breaks or leaves?



All deterministic TDMA protocols have these (or worse) problems

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TDMA – Slotted Aloha

- We assume that the stations are perfectly synchronous
- In each time slot each station transmits with probability p .



$$P_1 = \Pr[\text{Station 1 succeeds}] = p(1-p)^{n-1}$$

$$P = \Pr[\text{any Station succeeds}] = nP_1$$

$$\text{maximize } P : \frac{dP}{dp} = n(1-p)^{n-2}(1-pn) \stackrel{!}{=} 0 \Rightarrow pn = 1$$

$$\text{then, } P = \left(1 - \frac{1}{n}\right)^{n-1} \geq \frac{1}{e}$$

- In **Slotted Aloha**, a station can transmit successfully with probability at least $1/e$, or about 36% of the time.

Backoff Protocols

- **Backoff protocols** rely on acknowledgements only.
- Binary exponential backoff
 - If a packet has collided k times, we set $p = 2^{-k}$
 - Or alternatively: wait from random number of slots in $[1..2^k]$
- It has been shown that binary exponential backoff is not stable for any arrival rate $\lambda > 0$ (if there are infinitely many potential stations)

[Proof sketch: with very small but positive probability you go to a bad situation with many waiting stations, and from there you get even worse with a potential function argument – sadly the proof is too intricate to be shown in this course ☺]
- Interestingly when there are only finite stations, binary exponential backoff becomes unstable with $\lambda > 0.568$; Polynomial backoff however, remains stable for any $\lambda < 1$.

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Demand Assigned Multiple Access (DAMA)

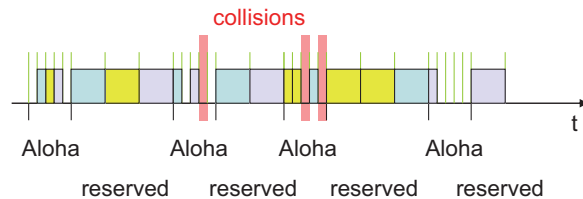
- Channel efficiency is only 36% for Slotted Aloha, and even worse for backoff protocols.
- Practical systems therefore use reservation whenever possible.
 - But: Every scalable system needs an Aloha style component.
- Reservation:
 - a sender *reserves* a future time-slot
 - sending within this reserved time-slot is possible without collision
 - reservation also causes higher delays
- Examples for reservation algorithms on the following slides

typical scheme for satellite systems

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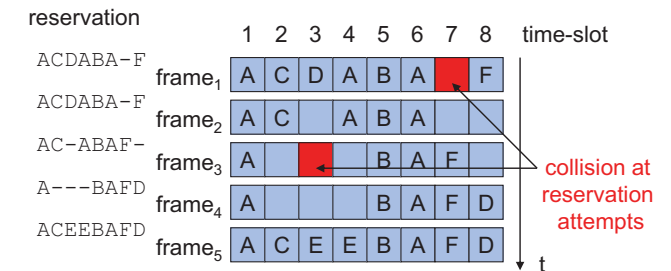
DAMA: Explicit Reservation

- *Aloha mode* for reservation: competition for small reservation slots, collisions possible.
- *Reserved mode* for data transmission within successful reserved slots (no collisions possible).
- It is important for all stations to keep the reservation list consistent at any point in time and, therefore, all stations have to synchronize from time to time.



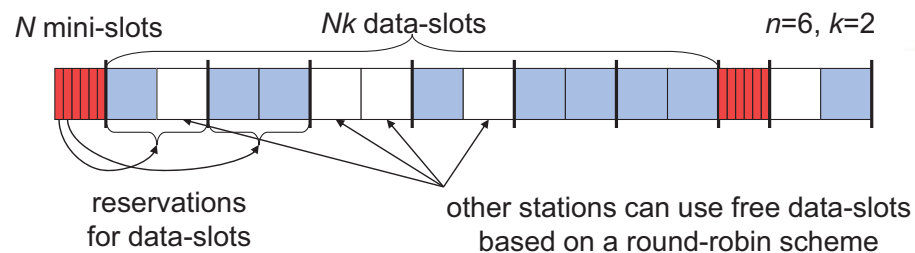
DAMA: Implicit Reservation

- A certain number of slots form a frame, frames are repeated.
- Stations compete for empty slots according to the slotted aloha principle.
- Once a station reserves a slot successfully, this slot is automatically assigned to this station in all following frames.
- Competition for this slots starts again as soon as the slot was empty in the last frame .



DAMA: Reservation TDMA

- Every frame consists of n mini-slots and x data-slots
- Every station has its own mini-slot and can reserve up to k data-slots using this mini-slot (i.e. $x = nk$).
- Other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)



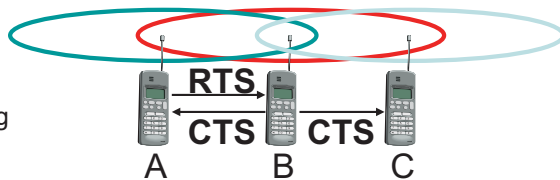
Multiple Access with Collision Avoidance (MACA)

- Use short signaling packets for collision avoidance
 - Request (or ready) to send **RTS**: a sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
 - Clear to send **CTS**: the receiver grants the right to send as soon as it is ready to receive
- Signaling packets contain
 - sender address
 - receiver address
 - packet size
- Example: [Wireless LAN \(802.11\) as DFWMAC](#)

MACA examples

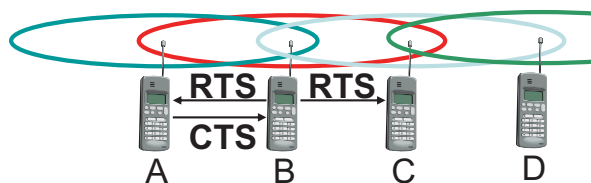
- MACA avoids the problem of hidden terminals

- A and C want to send to B
- A sends RTS first
- C waits after receiving CTS from B



- MACA avoids the problem of exposed terminals

- B wants to send to A, and C to D
- now C does not have to wait as C cannot receive CTS from A

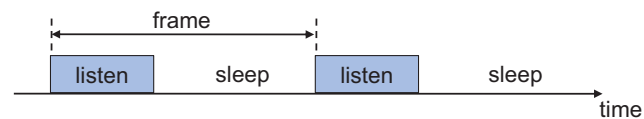


Energy Efficient MAC Protocols

- In sensor networks energy is often more critical than throughput.
 - The radio component should be turned off as much as possible.
- Energy management considerations have a big impact on MAC protocols.
 - Idle listening costs about as much energy as transmitting
- In the following we present a few ideas, stolen from some known protocols that try to balance throughput and energy consumption.
 - S-MAC, T-MAC, B-MAC, or WiseMAC
- Many of the hundreds of MAC protocols that were proposed have similar ideas...

Sensor MAC (S-MAC)

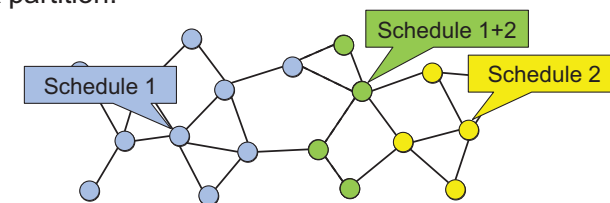
- Coarse-grained TDMA-like sleep/awake cycles.



- All nodes choose and announce awake schedules.
 - synchronize to awake schedules of neighboring nodes.
- Uses RTS/CTS to resolve contention during listen intervals.
 - And allows interfering nodes to go to sleep during data exchange.

Sensor MAC (S-MAC)

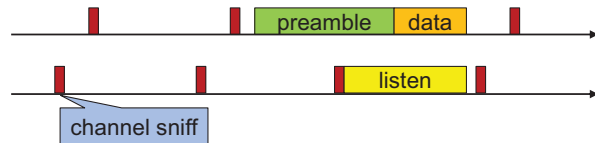
- Problem: Nodes may have to follow multiple schedules to avoid network partition.



- A fixed sleep/awake ratio is not always optimal.
 - Variable load in the network.
- Idea: Adapt listen interval dependent on the current network load.
 - T-MAC

Low Power Listening (B-MAC)

- Nodes wake up for a short period and check for channel activity.
 - Return to sleep if no activity detected.
- If a sender wants to transmit a message, it sends a long preamble to make sure that the receiver is listening for the packet.
 - preamble has the size of a sleep interval



- Very robust
 - No synchronization required
 - Instant recovery after channel disruption

Low Power Listening (B-MAC)

overhearing problem

- Problem: All nodes in the vicinity of a sender wake-up and wait for the packet.
 - Solution 1: Send wake-up packets instead of preamble, wake-up packets tell when data is starting so that receiver can go back to sleep as soon as it received one wake-up packet.
 - Solution 2: Just send data several times such that receiver can tune in at any time and get tail of data first, then head.



- Communication costs are mostly paid by the sender.
 - The preamble length can be much longer than the actual data length.

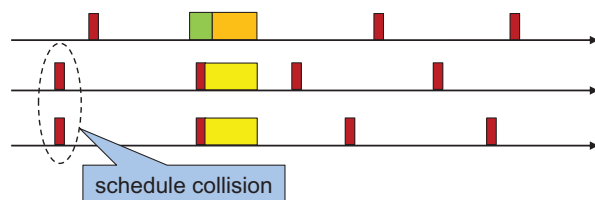
- Idea: Learn wake-up schedules from neighboring nodes.
 - Start sending preamble just before intended receiver wakes up.
 - WiseMAC

encode wake-up pattern in ACK message

Hybrid Protocols

- Protocols may use information from upper layers to further improve their performance.
 - Information about neighborhood
 - Routing policies
- Minimize costly overhearing of neighboring nodes
 - Inform them to change their channel sniff patterns

optimization for WiseMAC



like in Dozer

- Use randomization to resolve schedule collisions

Standards

- IEEE 802.15.4
 - physical & MAC layer
 - star, clique (peer-to-peer), and cluster tree topology
 - Full function (with coordinator) and reduced function nodes
 - Unslotted mode (nonbeacon)
 - CSMA/CA: Send when medium is free
 - Slotted mode (beacon)
 - Similar to beacons in Dozer: Coordinator sends beacon to indicate period when nodes can send
- Protocols on higher layers using 802.15.4
 - ZigBee
 - Goals: low cost, low power (not really), plug-in and short range
 - TSMP (Time Synchronized Mesh Protocol)
 - Goals: reliability and low power

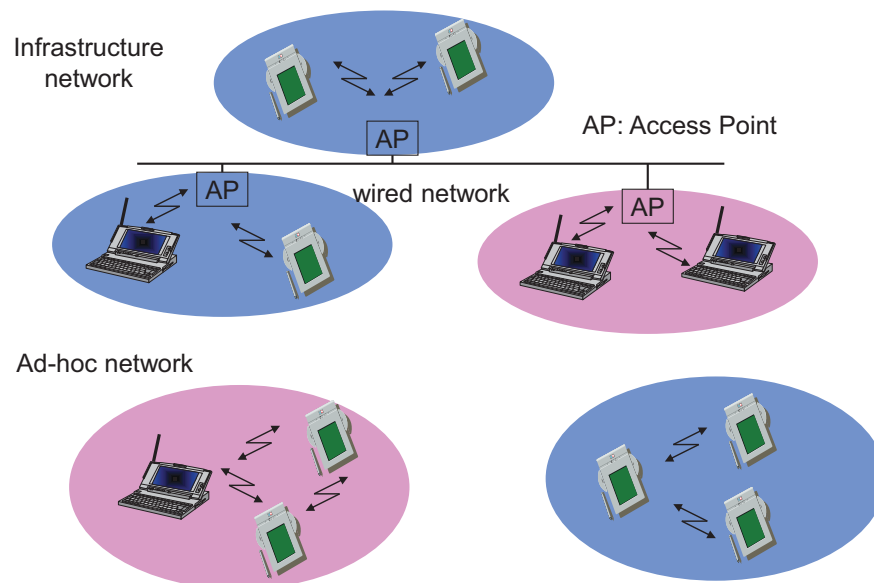
Case Study: 802.11 – Design Goals

- Global, seamless operation
- Low power consumption for battery use
- No special permissions or licenses required
- Robust transmission technology
- Simplified spontaneous cooperation at meetings
- Easy to use for everyone, simple management
- Interoperable with wired networks
- Security (no one should be able to read my data), privacy (no one should be able to collect user profiles), safety (low radiation)
- Transparency concerning applications and higher layer protocols, but also location awareness if necessary

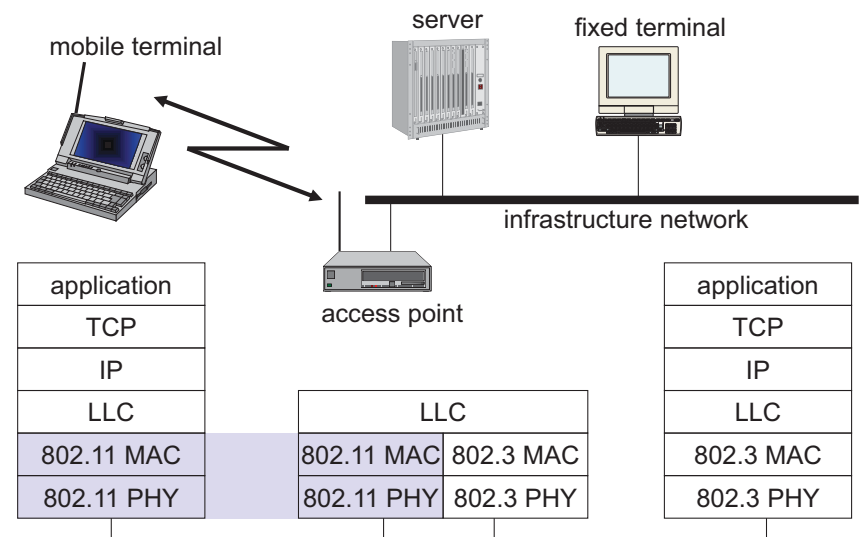
802.11 Characteristics

- + Very flexible (economical to scale)
- + Ad-hoc networks without planning possible
- + (Almost) no wiring difficulties (e.g. historic buildings, firewalls)
- + More robust against disasters or users pulling a plug
- Low bandwidth compared to wired networks (20 vs. 1000 Mbit/s)
- Many proprietary solutions, especially for higher bit-rates, standards take their time
- Products have to follow many national restrictions if working wireless, it takes a long time to establish global solutions (IMT-2000)
- Security
- Economy

802.11 Infrastructure vs. ad hoc mode

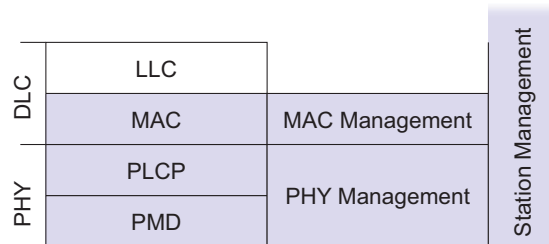


802.11 – Protocol architecture



802.11 – The lower layers in detail

- PMD (Physical Medium Dependent)
 - modulation, coding
- PLCP (Physical Layer Convergence Protocol)
 - clear channel assessment signal (carrier sense)
- PHY Management
 - channel selection, PHY-MIB
- Station Management
 - coordination of all management functions
- MAC
 - access mechanisms
 - fragmentation
 - encryption
- MAC Management
 - Synchronization
 - roaming
 - power management
 - MIB (management information base)

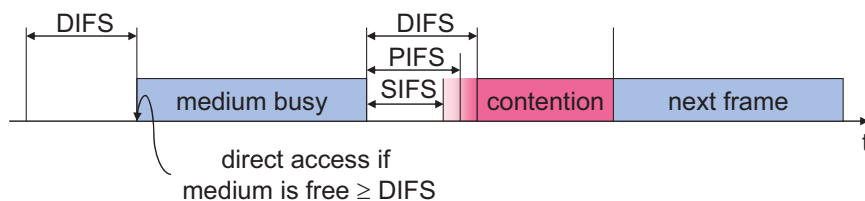


MAC layer: DFWMAC

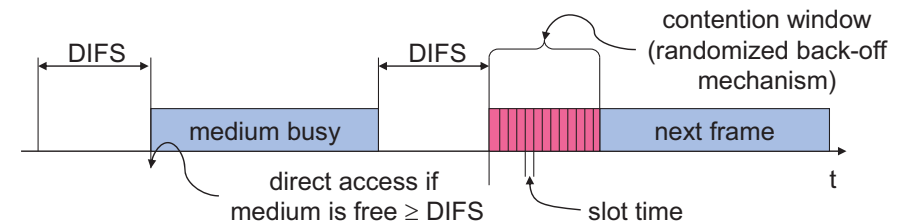
- Traffic services
 - Asynchronous Data Service (mandatory)
 - exchange of data packets based on “best-effort”
 - support of broadcast and multicast
 - Time-Bounded Service (optional)
 - implemented using PCF (Point Coordination Function)
- Access methods
 - DFWMAC-DCF CSMA/CA (mandatory)
 - collision avoidance via binary exponential back-off mechanism
 - minimum distance between consecutive packets
 - ACK packet for acknowledgements (not used for broadcasts)
 - DFWMAC-DCF w/ RTS/CTS (optional)
 - avoids hidden terminal problem
 - DFWMAC-PCF (optional)
 - access point polls terminals according to a list

MAC layer

- defined through different inter frame spaces
- no guaranteed, 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

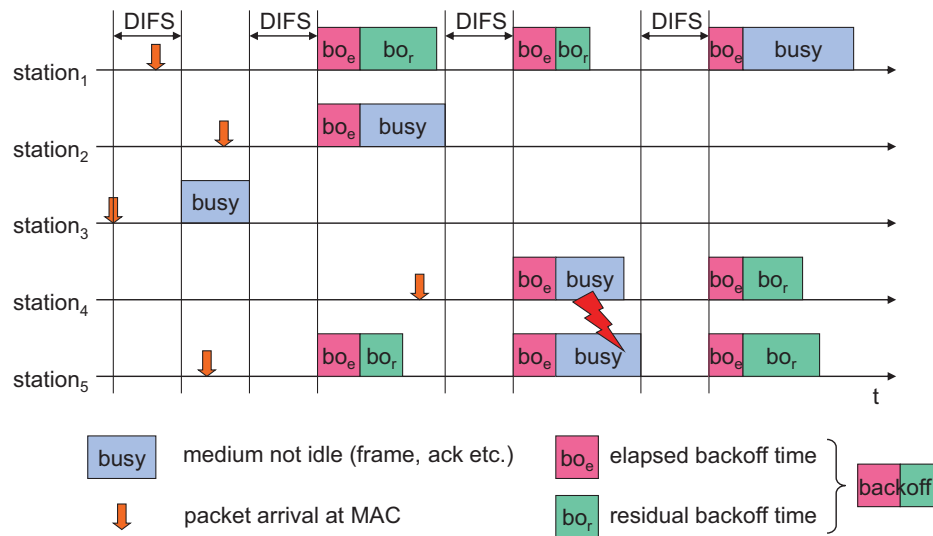


CSMA/CA



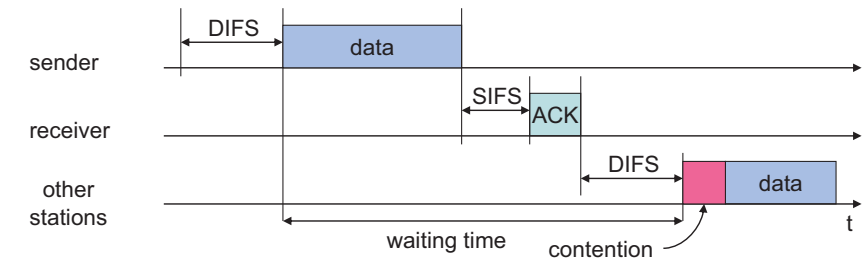
- station ready to send starts sensing the medium (Carrier Sense based on CCA, Clear Channel Assessment)
- if the medium is free for the duration of an Inter-Frame Space (IFS), the station can start sending (IFS depends on service type)
- if the medium is busy, the station has to wait for a free IFS, then the station must additionally wait a random back-off time (collision avoidance, multiple of slot-time)
- if another station occupies the medium during the back-off time of the station, the back-off timer stops (fairness)

Competing stations - simple example



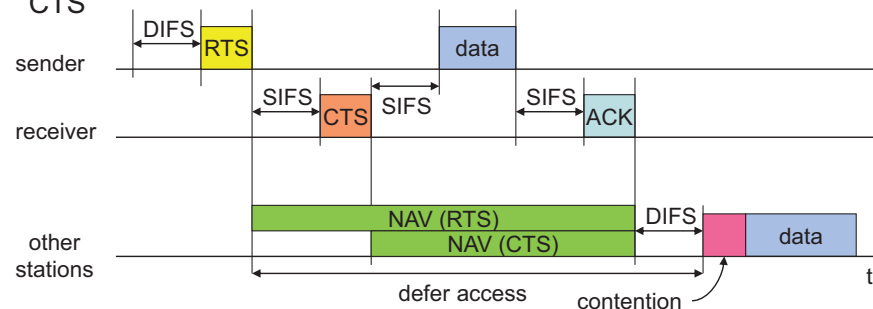
CSMA/CA 2

- Sending unicast packets
 - station has to wait for DIFS before sending data
 - receivers acknowledge at once (after waiting for SIFS) if the packet was received correctly (CRC)
 - automatic retransmission of data packets in case of transmission errors



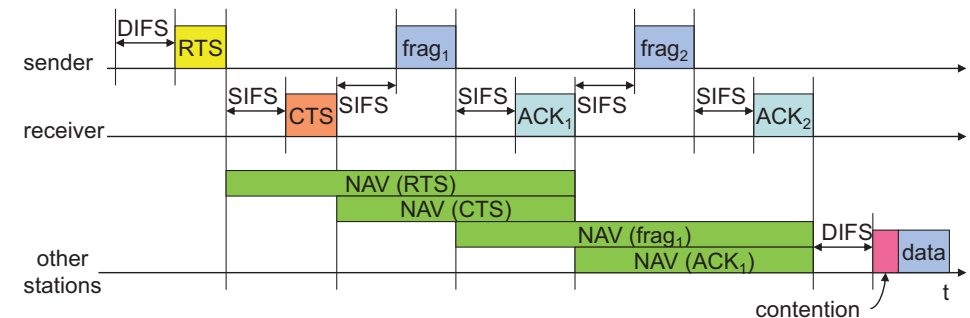
DFWMAC

- station can send RTS with reservation parameter after waiting for DIFS (reservation determines amount of time the data packet needs the medium)
- acknowledgement via CTS after SIFS by receiver (if ready to receive)
- sender can now send data at once, acknowledgement via ACK
- other stations store medium reservations distributed via RTS and CTS



Fragmentation

- If packet gets too long transmission error probability grows
- A simple back of the envelope calculation determines the optimal fragment size



Fragmentation: What fragment size is optimal?

- Total data size: D bits
- Overhead per packet (header): h bits
- Overhead between two packets (acknowledgement): a "bits"
- We want f fragments, then each fragment has $k = D/f + h$ data + header bits
- Channel has bit error probability $q = 1-p$
- Probability to transmit a packet of k bits correctly: $P := p^k$
- Expected number of transmissions until packet is success: $1/P$
- Expected total cost for all D bits: $f \cdot (k/P + a)$
- Goal: Find a $k > h$ that minimizes the expected cost

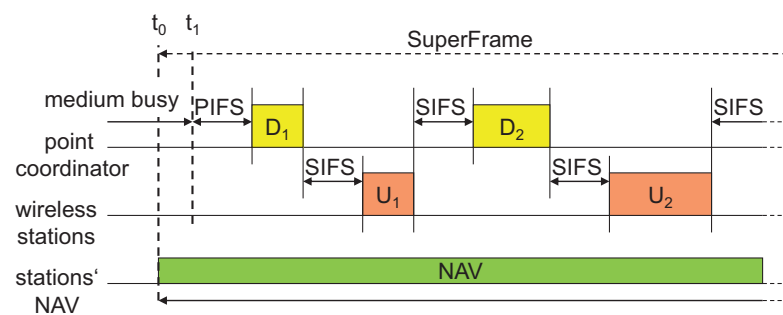
Fragmentation: What fragment size is optimal?

- For the sake of a simplified analysis we assume $a = O(h)$
- If we further assume that a header can be transmitted with constant probability c , that is, $p^h = c$.
- We choose $k = 2h$; Then clearly $D = f \cdot h$, and therefore expected cost

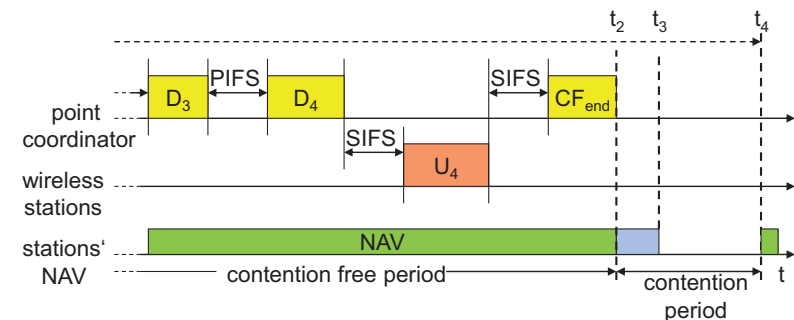
$$f \cdot \left(\frac{k}{P} + a \right) = \frac{D}{h} \left(\frac{2h}{p^{2h}} + O(h) \right) = O\left(\frac{D}{p^{h^2}} \right) = O\left(\frac{D}{c^2} \right) = O(D).$$
- If already a header cannot be transmitted with high enough probability, then you might keep the message very small, for example $k = h + 1/q$

DFWMAC-PCF

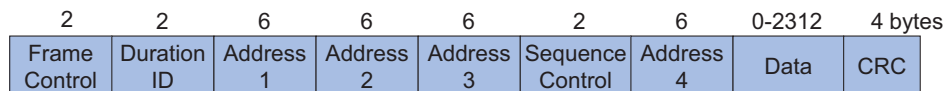
- An access point can poll stations



DFWMAC-PCF 2



Frame format



Byte 1: version, type, subtype

Byte 2: two DS-bits, fragm., retry, power man., more data, WEP, order

- Type
 - control frame, management frame, data frame
- Sequence control
 - important against duplicated frames due to lost ACKs
- Addresses
 - receiver, transmitter (physical), BSS identifier, sender (logical)
- Miscellaneous
 - sending time, checksum, frame control, data

MAC address format

| scenario | to DS | from DS | address 1 | address 2 | address 3 | address 4 |
|-----------------------------------|-------|---------|-----------|-----------|-----------|-----------|
| ad-hoc network | 0 | 0 | DA | SA | BSSID | - |
| infrastructure network, from AP | 0 | 1 | DA | BSSID | SA | - |
| infrastructure network, to AP | 1 | 0 | BSSID | SA | DA | - |
| infrastructure network, within DS | 1 | 1 | RA | TA | DA | SA |

DS: Distribution System

AP: Access Point

DA: Destination Address

SA: Source Address

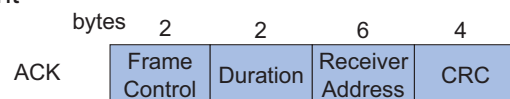
BSSID: Basic Service Set Identifier

RA: Receiver Address

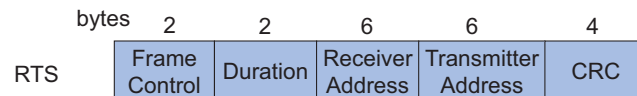
TA: Transmitter Address

Special Frames: ACK, RTS, CTS

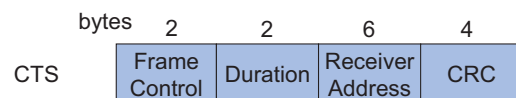
- Acknowledgement



- Request To Send



- Clear To Send

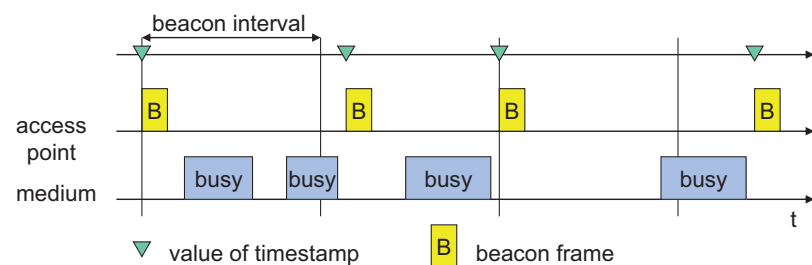


MAC management

- Synchronization
 - try to find a LAN, try to stay within a LAN
 - timer etc.
- Power management
 - sleep-mode without missing a message
 - periodic sleep, frame buffering, traffic measurements
- Association/Reassociation
 - integration into a LAN
 - roaming, i.e. change networks by changing access points
 - scanning, i.e. active search for a network
- MIB - Management Information Base
 - managing, read, write

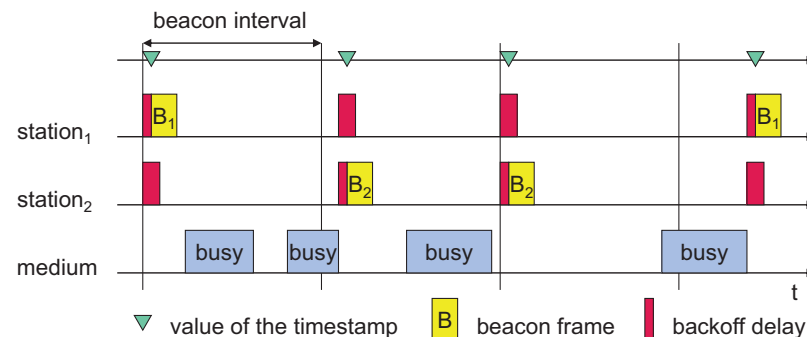
Synchronization

- In an infrastructure network, the access point can send a beacon



Synchronization

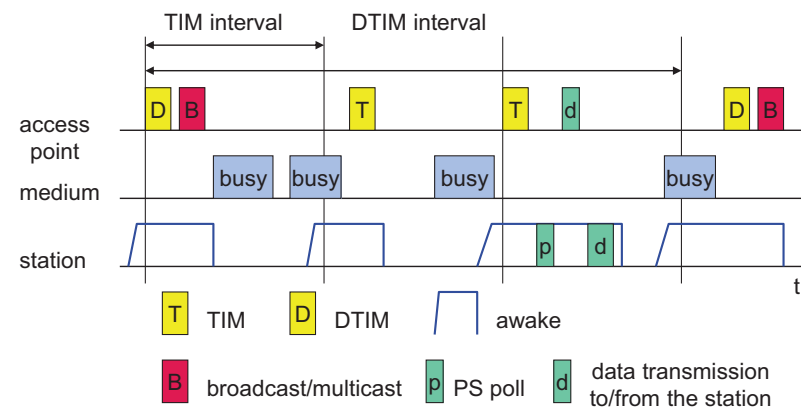
- In an ad-hoc network, the beacon has to be sent by any station



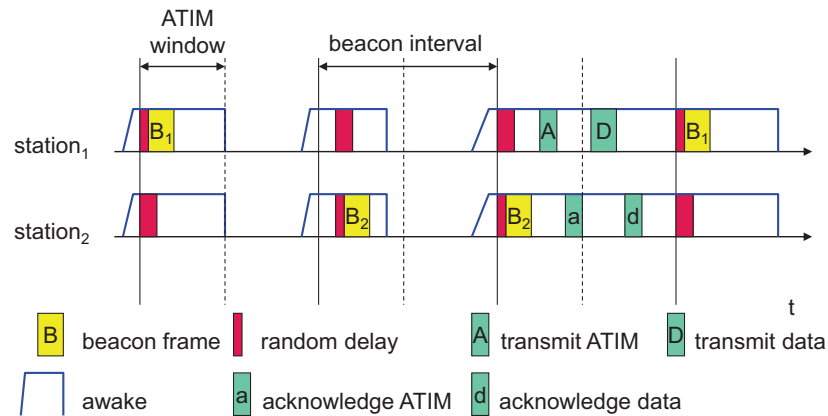
Power management

- Idea: if not needed turn off the transceiver
- 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
 - collision of ATIMs possible (scalability?)

Power saving with wake-up patterns (infrastructure)



Power saving with wake-up patterns (ad-hoc)



WLAN: IEEE 802.11b

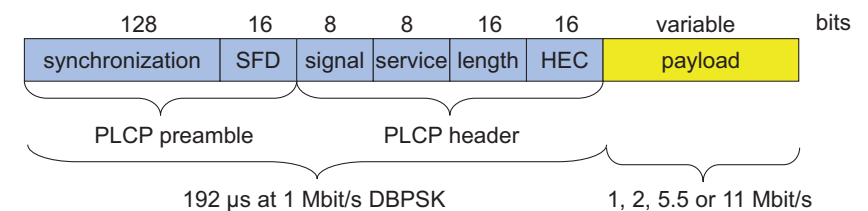
- Data rate
 - 1, 2, 5.5, 11 Mbit/s, depending on SNR
 - User data rate max. approx. 6 Mbit/s
- Transmission range
 - 300m outdoor, 30m indoor
 - Max. data rate <10m indoor
- Frequency
 - Free 2.4 GHz ISM-band
- Security
 - Limited, WEP insecure, SSID
- Cost
 - Low
- Availability
 - Declining

WLAN: IEEE 802.11b

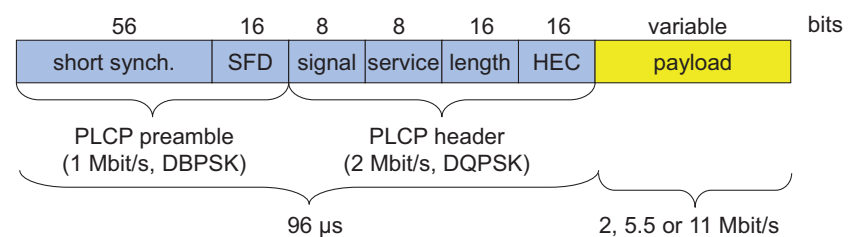
- Connection set-up time
 - Connectionless/always on
- Quality of Service
 - Typically best effort, no guarantees
 - unless polling is used, limited support in products
- Manageability
 - Limited (no automated key distribution, sym. encryption)
- + Advantages: many installed systems, lot of experience, available worldwide, free ISM-band, many vendors, integrated in laptops, simple system
- Disadvantages: heavy interference on ISM-band, no service guarantees, slow relative speed only

IEEE 802.11b – PHY frame formats

Long PLCP PPDU format

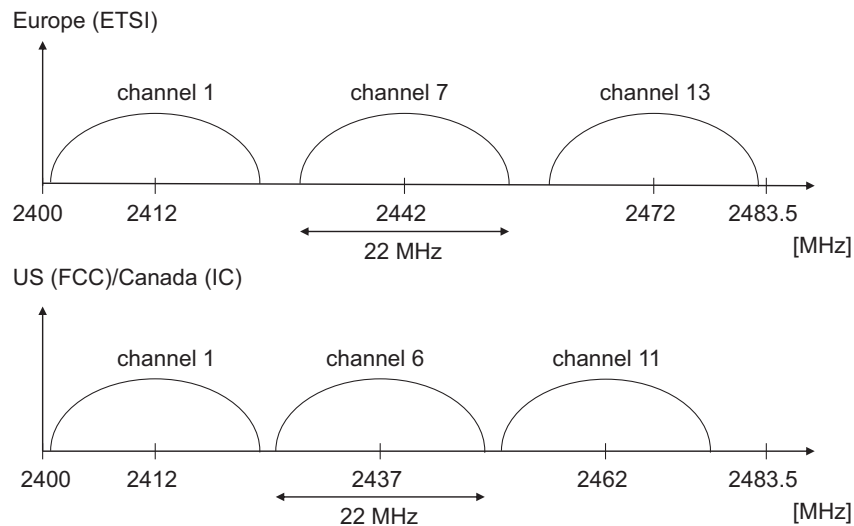


Short PLCP PPDU format (optional)



2, 5.5 or 11 Mbit/s

Channel selection (non-overlapping)



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 30m, 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
- Security
 - Limited, WEP insecure, SSID
- Cost
 - \$50 adapter, \$100 base station, dropping
- Availability
 - Some products, some vendors
 - Not really deployed in Europe (regulations!)

WLAN: IEEE 802.11a

- Connection set-up time
 - Connectionless/always on
- Quality of Service
 - Typically best effort, no guarantees (same as all 802.11 products)
- Manageability
 - Limited (no automated key distribution, sym. Encryption)
- + Advantages: fits into 802.x standards, free ISM-band, available, simple system, uses less crowded 5 GHz band
- Disadvantages: stronger shading due to higher frequency, no QoS

Quiz: Which 802.11 standard?



Open Problem

- Although the MAC alphabet soup is constantly growing, the tradeoffs delay, throughput, energy-efficiency, locality, dynamics, fairness, ... are still not understood. In particular there is no Swiss Army Knife of MAC protocols, with good guarantees in delay and throughput, even in dynamic situations.