Mobilkommunikation - Mobile Communications

Lecture 4: Multiple Access

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Previous lectures

Characteristics of the radio channel

- radio propagation
- channel capacity

Space division multiplexing

- cell geometry
- cochannel interference

Physical layer (layer 1)

- encoding and modulation
- multiplexing

The wireless medium is scarce and not trivial!

Outline

Challenges of wireless medium access

Duplexing

Multiple access
- Reservation-based access
- Random access

Data link layer (layer 2)

- medium access control (MAC)
  - radio channel is shared by an a priori unknown number of stations
  - target is to achieve
    - high throughput
    - fair resource allocation
  - difficulties due to different ranges
    - transmission range
    - detection range
    - interference range
- logical link control (LLC)
  - reliable service uses automatic repeat request
  - actual implementations may differ significantly

Solutions from the wired domain?

Why not use known MAC protocols from the wired domain?

Ethernet uses 1-persistent CSMA/CD

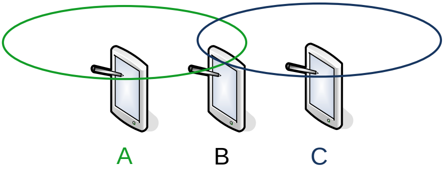
- carrier sense multiple access with collision detection
  - sense if the medium is free and start sending as soon as it becomes free
  - while sending listen to the medium to detect other senders
  - in case of a collision immediately stop sending and wait for a random amount of time

Difficulties in wireless networks

- inverse square law: signal strength drops with the square of the distance or even faster
- the sender can generally not detect a collision while sending; it would need a second antenna and moreover it would mainly hear its own signal
- even if the sender could detect a collision this does not imply that there is also a collision at the receiver
- similarly, a collision at the receiver does not imply a collision at other locations, e.g. at the sender

Hidden terminals

transmission and detection ranges

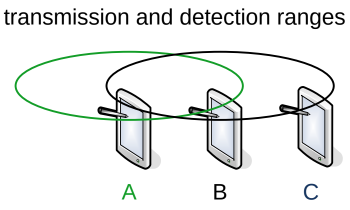


A is hidden from C and C is hidden from A

- A senses free medium and starts sending to B
- C cannot hear A
- C senses free medium and starts sending to B
- A cannot hear C

collision at B

Hidden terminals (2)



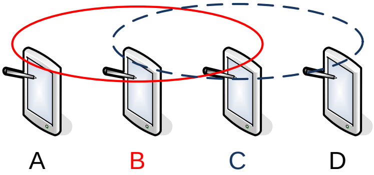
A is hidden from C and C is hidden from A

Solution

- once A starts transmitting, B (the receiver) sends a busy tone to notify stations that are possibly hidden from A
- C hears the busy tone and does not start sending
- need a separate channel for the busy tone

Exposed terminals

transmission and detection ranges

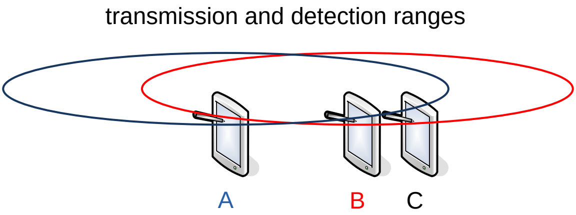


C is exposed to the transmission of B

- B senses free medium and starts sending to A
- C wants to transmit data to D
- C could transmit data to D without causing a collision
  - neither at receiver A nor at receiver D
  - but seemingly at sender B and sender C

C senses busy medium and does not start sending to D

Near and far terminals



- signal strength decreases with the square of the distance or even faster
- A can transmit to C, however, B's signal effectively drowns A's signal
- C would only see B but not A
- need power control

Outline

Challenges of wireless medium access

Duplexing

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Duplexing

Usually two communicating parties, e.g. mobile and base station

- downlink aka forward channel from base to mobile station
- uplink aka reverse channel from mobile to base station

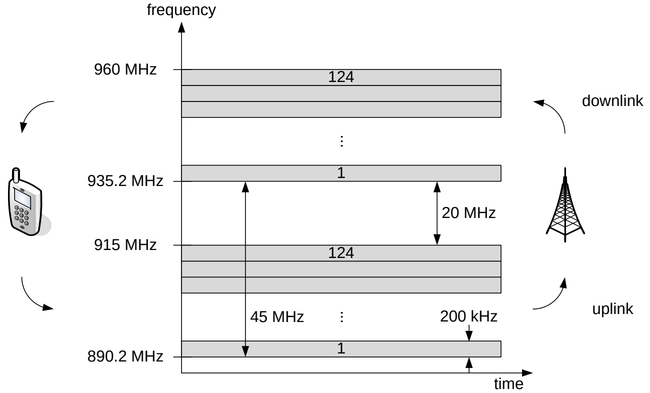
Sharing the medium

- simplex: one way communication from sender to receiver
- duplex: two way communication between two parties
  - frequency division duplex (FDD)
    combination of two simplex channels with different carrier frequencies
  - time division duplex (TDD)
    time sharing of a single channel achieves quasi-simultaneous duplex transmission

Frequency division duplex (FDD)

FDD duplex channel: two simplex channels in different freq. bands

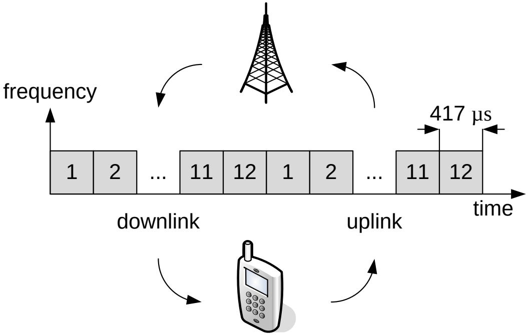
- the frequency separation is important to avoid interference
- example: GSM where $f_{\text{downlink}} = f_{\text{uplink}} + 45$ MHz



Time division duplex (TDD)

TDD duplex channel: deterministic time sharing of a freq. band

- time is slotted and certain slots are assigned to uplink and downlink only
- example: DECT



Comparison FDD vs. TDD

FDD

- requires individual, separated radio frequencies
- channels are allocated to base stations statically
- mobile stations are allocated channels dynamically
- frequently used for wide area cellular systems

TDD

- requires precise timing and synchronization
- large propagation delays require a separation of uplink and downlink in time
- can adapt uplink and downlink bandwidth dynamically
- frequently used for local area communication

Challenges of wireless medium access

Duplexing

Multiple access

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Characteristics

- shared medium: all stations share the communication channel
- broadcast medium: all stations within transmission range of a sender receive the signal

Challenge

- often no centralized control and uncoordinated channel access
- a sender cannot block access to the channel by others
- if several stations transmit collisions may occur

Need: medium access control (MAC) protocols

- centralized vs. distributed
- deterministic vs. stochastic
- difficulty: coordination among stations has to use the same communication channel

Multiple access (2)

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Static allocation of sub-channels

- the capacity of the channel is divided among the stations
- each station's share (time and frequency) is reserved
- no further control of channel access is needed
- allows providing well-defined quality of service

Dynamic assignment of the channel

- no a priori allocation; before sending stations have to obtain permission to send
- access procedure can have centralized control or it can be decentralized

Random access

- no a priori allocation; no coordination of/among stations
- collisions are inevitable; have to be detected and fixed

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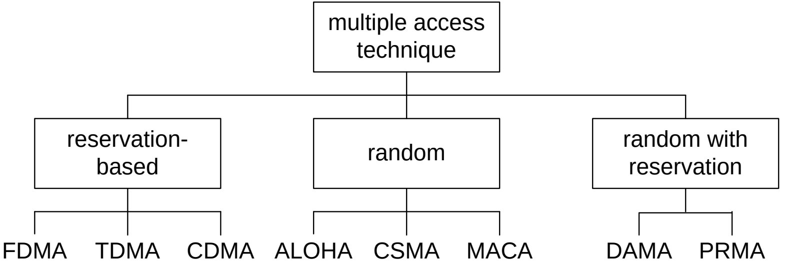
Classification of wireless MAC protocols



- reservation-based: static allocation or dynamic assignment of resources to terminals
- random access: no collision free allocation; terminals compete for the channel using randomized procedures
- random with reservation: terminals compete using random access to obtain a dynamic assignment of resources

Frequency division multiple access (FDMA)

Frequency division multiple access (FDMA)

- each sender and receiver pair is assigned a unique frequency band for transmission
- fixed frequency allocation
  - permanent, e.g. radio broadcast
  - frequency hopping, e.g. GSM, Bluetooth
    frequency hopping spread spectrum
- usually used in narrowband systems
- need guard bands between individual frequency bands
- receiver has to have a precise bandpass filter

Time division multiple access (TDMA)

- several senders share a frequency band
- time is divided into repetitive frames
- frames are divided into time slots
- each sender is allocated a certain time slot
- often combined with FDMA, e.g. GSM
- need guard times between time-slots (different terminals have different distance (propagation delay) from the base station)
- receiver has to synchronize precisely

Dynamic assignment of the channel

TDMA systems can easily assign the channel dynamically: polling

- centralized control
- stations need to obtain permission to send
- the base station gives permission to send to a station
- base station is a single point of failure
- used e.g. in the GPRS uplink

Remark: in wired (ring) networks token passing implements a similar scheme, however, with decentralized control

- a single token circulates in the ring
- the token is the permission to send
- after sending a station passes the token to the next station

Code division multiple access (CDMA)

- all terminals may transmit at the same time in the same frequency band
- each sender has a unique code
  - direct sequence spread spectrum
  - frequency hopping spread spectrum
- signal appears as noise for terminals
- receiver has to tune into the signal
- typically used in wideband systems
- huge code space
- need efficient power control; target: all signals have the same strength at the receiver/base station

Code division multiple access (CDMA) (2)

Pairs of sender and receiver use the same code, e.g.

- code of sender and receiver A: 010011
- code of sender and receiver B: 110101

Coding 1 as $+1$ and 0 as -1: multiplication is used for spreading

- code A: $- + - - ++$
- code B: $+ + - + -+$

Example

- A sends the bits 0110 i.e. $- + +-$ giving the chip sequence: $+ - + + - - - + - - + + - + - - + + + - + + --$
- B sends the bits 1010 i.e. $+ - +-$ giving the chip sequence: $+ + - + - + - - + - + - + + - + - + - - + - +-$

Autocorrelation

The receiver has to decode the pseudo noise sequence

- it has to know the code
- it has to be synchronized

Good codes have an autocorrelation function with a peak at lag $k = 0$ and small values for any other lag $k \neq 0$.

The discrete autocorrelation at lag k is defined in signal processing

$$R_{xx}(k) = \sum_n x(n)x(n+k)$$

where $x(n)$ is the chip sequence repeated periodically.

The peak of the autocorrelation function allows the receiver

- to synchronize and
- to decode the data

Autocorrelation example

Code A: $- + - - + +$ i.e. $x = (-1, +1, -1, -1, +1, +1, -1, \dots)$

- lag 0: $\sum_{n=1}^{6} x(n)x(n) = +6$
- lag 1: $\sum_{n=1}^{6} x(n+1)x(n) = -2$
- lag 2: $\sum_{n=1}^{6} x(n+2)x(n) = -2$
- lag 3: $\sum_{n=1}^{6} x(n+3)x(n) = +2$
- lag 4: $\sum_{n=1}^{6} x(n+4)x(n) = -2$
- lag 5: $\sum_{n=1}^{6} x(n+5)x(n) = -2$
- lag 6: $\sum_{n=1}^{6} x(n+6)x(n) = +6$
- $\dots$

$$R_{xx} = (+6, -2, -2, +2, -2, -2, +6, \dots)$$

Decoding example

Once synchronized the code $-+--++$ is used to decode data. The data is simply multiplied with the code.

$+-++--$	$-+--++$	$-+--++$	$+-++--$
$-+--++$	$-+--++$	$-+--++$	$-+--++$
-6	6	6	-6

The receiver assumes

- a 0 if the result is negative
- a 1 if the result is positive

i.e. the decoded bit stream is 0110

Decoding example: noise

Assume some chips are inverted due to noise on the channel

$+ + + + - -$	$- + + + + +$	$- - - - - -$	$+ - - - + +$
$- + - - + +$	$- + - - + +$	$- + - - + +$	$- + - - + +$
-4	2	0	2

The receiver decodes 0111 instead of 0110

The receiver has to decode its pseudo noise sequence

- in the presence of other codes

Codes have to be orthogonal, i.e. good codes have to have small cross-correlation.

The discrete cross-correlation at lag k is defined in signal processing

$$R_{ab}(k) = \sum_{n} a(n)b(n+k)$$

where $a(n)$ and $b(n)$ are the chip sequences of the codes that are repeated periodically.

The cross-correlation of the two codes A $-+--++$ and B $++-+-+$ at lag $k=0$ is 0.

Decoding example: two senders

Senders A and B and sum of the two signals (3 values: $+, 0, -$)

A	$+ - + + - -$	$- + - - + +$	$- + - - + +$	$+ - + + - -$
B	$+ + - + - +$	$- - + - + -$	$+ + - + - +$	$- - + - + -$
Σ	$+\ 0\ 0 + - 0$	$-\ 0\ 0 - + 0$	$0 + -\ 0\ 0 +$	$0 - +\ 0\ 0 -$

Receiver A

Σ	$+\ 0\ 0 + - 0$	$-\ 0\ 0 - + 0$	$0 + -\ 0\ 0 +$	$0 - +\ 0\ 0 -$
A	$- + - - + +$	$- + - - + +$	$- + - - + +$	$- + - - + +$
Π	-6	6	6	-6

Receiver B

Σ	$+\ 0\ 0 + - 0$	$-\ 0\ 0 - + 0$	$0 + -\ 0\ 0 +$	$0 - +\ 0\ 0 -$
B	$+ + - + - +$	$+ + - + - +$	$+ + - + - +$	$+ + - + - +$
Π	6	-6	6	-6

Comparison F/T/CDMA

	FDMA	TDMA	CDMA
Idea	frequency is segmented into subbands	time is slotted; static or dynamic time slots allocation	spread spectrum with orthogonal codes
Terminals	each terminal has its own frequency band and is not interrupted	terminals are active for short disjoint periods of time on the same frequency	all terminals can be active at the same time on the same frequency
Signal separation	bandpass filtering in frequency domain	synchronization in time domain	matched filter in code domain
Advantages	simple, robust	flexible, can assign time slots on demand	flexible, other codes only add noise
Disadvantages	inflexible, frequency is scarce	synchronization is difficult, guard times needed	complex receivers, need sophisticated power control

Random access

So far multiple access is coordinated

- F/T/CDMA
- static allocation or dynamic assignment

However, wireless communication is often much more ad-hoc

- new terminals have to register with the network
- terminals request access to the medium spontaneously
- in many cases there is no central control

Need other access methods

- distributed
- non-arbitrated

$\Rightarrow$ random access

Literature

- Jochen Schiller, Mobile Communications, Second Edition, Addison-Wesley, 2003.
- Vijay Garg, Wireless Communications & Networking, Morgan Kaufmann, 2007.
- Matthias Hollick, Mobile Networking, TU Darmstadt, 2008.