Motivation

- Can we apply media access methods from fixed networks?
- Example CSMA/CD
  - Carrier Sense Multiple Access with Collision Detection
  - 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 proportional to the square of the distance
  - the sender would apply CS and CD, but the collisions happen at the receiver
  - it might be the case that a sender cannot “hear” the collision, i.e., CD does not work
  - furthermore, CS might not work if, e.g., a terminal is “hidden”

Motivation - hidden and exposed terminals

- Hidden terminals
  - 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
- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is “exposed” to B

Motivation - near and far terminals

- Terminals A and B send, C receives
  - signal strength decreases proportional to the square of the distance
  - the signal of terminal B therefore drowns out A’s signal
  - C cannot receive A
- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Also severe problem for CDMA-networks - precise power control needed!
Access methods
SDMA/FDMA/TDMA

- **SDMA (Space Division Multiple Access)**
  - segment space into sectors, use directed antennas
  - cell structure
- **FDMA (Frequency Division Multiple Access)**
  - assign a certain frequency to a transmission channel between a sender and a receiver
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
- **TDMA (Time Division Multiple Access)**
  - assign the fixed sending frequency to a transmission channel between a sender and a receiver for a certain amount of time

- The multiplexing schemes are now used to control medium access!

---

**FDD/FDMA - general scheme, example GSM**

---

**TDD/TDMA - general scheme, example DECT**

---

**Frequency Division Multiple Access**

- **Concept:**
  - assign different frequency bands to different users
  - no-sharing of a frequency band between two users
  - user separation using band-pass filters
  - continuous flow
  - two-way: two frequency bands or Time Division Duplex (TDD)

- **Advantages:** simple receivers
  - longer symbol duration: no need for equalization
    - e.g., 50kb/s QPSK >> 40μs >> 1-10μs delay spread

- **Drawbacks:**
  - frequency guard bands, costly tight RF band-filters,
  - long fading duration: need slow frequency hopping
  - may need spatial diversity (multiple antennas/beam forming) Rx/Tx
Frequency Selection

- Frequency management:
  - Fixed (cellular phones-base stations): reuse factor
  - On-demand (cellular phones-mobile terminals)
  - Dynamic (cordless/WLAN): based on sensing interference levels
- Problems: congestion management, dynamic load, ...

- Antenna implications:
  - High antennas (e.g., 50m): higher coverage but higher interference between base stations (need for synchronization)
  - Low antennas: higher attenuation, lower coverage, better reuse

- Conclusion:
  - Pure FDMA is only interesting for simple cordless systems (CT-2)

Time Division Multiple Access

- Concept:
  - use the same frequency over non-overlapping periods of time

- Advantages:
  - simple filters (window)
  - transmit and receive over the same frequency channel

- Drawbacks:
  - users must be synchronized with BS (master clock over a BCH)
  - guard times: common 30-50µs, may be less in recent systems
  - short symbol duration: need for equalization, training sequences...
    - high inter-symbol interference
      - e.g., 50Kbps, QPSK, 8 users:
        - 5µs symbol duration
        - delay spread: 1µs (cordless), up to 20µs for cellular

FDMA/TDMA

- First channel allocation:
  - random access channel (RACH) to send short requests
  - ALOHA type protocol over the RACH

- One can use both FDMA and TDMA
  - examples: GSM system, D-AMPS

Access method CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency simultaneously and use the whole bandwidth of the transmission channel
  - codes generate signals with "good-correlation" properties
  - signals from another user appear as "noise" (use spread spectrum technology)
  - signals are spread over a wideband using pseudo-noise sequences
    - each sender has a unique random number, the sender XORs the signal with this random number
    - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function

- Disadvantages:
  - higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have the same strength at a receiver (near-far effect)

- Advantages:
  - all terminals can use the same frequency => no planning needed, macrodiversity
  - huge code space (e.g., 2^31) compared to frequency space
  - interferers (e.g., white noise) is not coded
  - forward error correction and encryption can be easily integrated
CDMA in theory

- Sender A
  - sends $A_d = 1$, key $A_k = 010011$ (assign: $0^\prime = -1$, $1^\prime = +1$)
  - sending signal $A_s = A_d \cdot A_k = (-1, +1, -1, +1, +1, +1)$
- Sender B
  - sends $B_d = 0$, key $B_k = 110101$ (assign: $0^\prime = -1$, $1^\prime = +1$)
  - sending signal $B_s = B_d \cdot B_k = (-1, -1, +1, -1, -1, -1)$
- Both signals superimpose in space
  - interference neglected (noise etc.)
    - $A_s + B_s = (-2, 0, 0, -2, +2, 0)$
- Receiver wants to receive signal from sender A
  - apply key $A_k$ bitwise (inner product)
    - $A_e = (-2, 0, 0, -2, +2, 0)$
    - $A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was "1"
- receiving B
  - $B_e = (-2, 0, 0, -2, +2, 0)$
    - $B_k = -2 + 0 + 0 - 2 - 2 = -6$, i.e. "0"

CDMA on signal level I

- data $A$
- key $A_k$
- key sequence $A_k$
- data @ level 2
- signal $A$

Real systems use much longer keys resulting in a larger distance between single code words in code space.

CDMA on signal level II

- data $A$
- data $B$
- key $B_k$
- key sequence $B_k$
- data @ key
- signal $B$
- $A_s + B_s$

CDMA on signal level III

- data $A$
- $A_s$
- $B_s$
- $(A_s + B_s)$
- integrator
- output
- comparator
- output
CDMA on signal level IV

\[
\begin{align*}
A_s &+ B_s \\
&\times B_k \\
& \text{integrator output} \\
& \text{comparator output}
\end{align*}
\]

CDMA on signal level V

\[
\begin{align*}
A_s + B_s \\
\times K \\
& \text{integrator output} \\
& \text{comparator output}
\end{align*}
\]

CDMA: Direct Sequence

- Each mobile is allocated a PN sequence:
- The elements of the PN-sequence are called chips
- To transmit one bit 1/0 send the PN-seq/inv-PN-seq
- Example Hadamard Matrix:
  - Each mobile uses one row
  - The rows are orthogonal

\[
H_4 = \begin{bmatrix}
+1 & +1 & +1 & +1 \\
+1 & -1 & +1 & -1 \\
+1 & +1 & -1 & -1 \\
+1 & -1 & -1 & +1
\end{bmatrix}
\]

Aloha/slotted aloha

- Mechanism
  - random, distributed (no central arbiter), time-multiplex
  - Slotted Aloha additionally uses timeslots, sending must always start at slot boundaries

- Aloha
- Slotted Aloha

\[
\begin{align*}
sender A \\
sender B \\
sender C
\end{align*}
\]

\[
\begin{align*}
sender A \\
sender B \\
sender C
\end{align*}
\]
### Carrier Sense Protocols

Use the fact that in some networks you can sense the medium to check whether it is currently free:
- 1-persistent CSMA
- non-persistent CSMA
- p-persistent protocol
- CSMA with collision Detection (CSMA/CD): not applicable to wireless systems

**1-persistent CSMA**
- when a station has a packet:
  - it waits until the medium is free to transmit the packet
  - if a collision occurs, the station waits a random amount of time
  - first transmission results in a collision if several stations are waiting for the channel

**non-persistent CSMA**
- when a station has a packet:
  - if the medium is free, transmit the packet
  - otherwise wait for a random period of time and repeat the algorithm
  - higher delays, but better performance than pure ALOHA

**p-persistent protocol**
- when a station has a packet wait until the medium is free:
  - transmit the packet with probability $p$
  - wait for next slot with probability $1-p$
  - better throughput than other schemes but higher delay

**CSMA with collision Detection (CSMA/CD)**
- stations abort their transmission when they detect a collision
- e.g., Ethernet, IEEE802.3 but not applicable to wireless systems

### DAMA - Demand Assigned Multiple Access

- Channel efficiency only 18% for Aloha, 36% for Slotted Aloha (assuming Poisson distribution for packet arrival and packet length)
- Reservation can increase efficiency to 80%
  - a sender reserves a future timeslot
  - sending within this reserved timeslot is possible without collision
  - reservation also causes higher delays
  - typical scheme for satellite links
- Examples for reservation algorithms:
  - Explicit Reservation according to Roberts (Reservation ALOHA)
  - Implicit Reservation (PRMA)
  - Reservation TDMA
- Reservation can increase efficiency to 80%

### Access method DAMA: Explicit Reservation

- Explicit Reservation (Reservation ALOHA):
  - two modes:
    - 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
Access method DAMA: PRMA

• Implicit reservation (PRMA - Packet Reservation MA):
  - 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 as long as the station has data to send
  - competition for this slot starts again as soon as the slot was empty in the last frame

reservation

<table>
<thead>
<tr>
<th>reservation</th>
<th>NCDABAF</th>
<th>NCDABAF</th>
<th>NCDABAF</th>
<th>NCDABAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>frame</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>frames</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>collision at reservation attempts</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>B</td>
</tr>
</tbody>
</table>

MACA - collision avoidance

• MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - RTS (request to send): a sender requests the right to send from a receiver with a short RTS packet before it sends a data packet
  - CTS (clear to send): the receiver grants the right to send as soon as it is ready to receive

• Signaling packets contain
  - sender address
  - receiver address
  - packet size

• Variants of this method can be found in IEEE802.11 as DFWMAC (Distributed Foundation Wireless MAC)

MACA examples

• MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits RTS first
  - C cannot receive CTS from A

• MACA avoids the problem of exposed terminals
  - B wants to send to A, C to another terminal
  - now C does not have to wait for it cannot receive CTS from A

N mini-slots N * k data-slots
reservations for data-slots other stations can use free data-slots based on a round robin scheme

e.g. N=6, k=2
MACA variant: DFWMAC in IEEE802.11

- ACK (positive acknowledgement)
- NAK (negative acknowledgement)
- RxBusy (receiver busy)
- RTS; CTS
- RTS; data
- wait for ACK
- packet ready to send; RTS
- time-out; ACK
- time-out; NAK
- RxBusy: receiver busy
- sender
- idle
- wait for the right to send
- wait for ACK
- receiver
- idle
- data: ACK
- RTS: CTS
- RTS; data
- wait for data
- ISMA (Inhibit Sense Multiple Access)

- Current state of the medium is signaled via a “busy tone”
  - the base station signals on the downlink (base station to terminals) if the medium is free or not
  - 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 in the busy tone and acknowledgements, respectively (media access is not coordinated within this approach)
  - mechanism used, e.g., for CDPD (USA, integrated into AMPS)
- 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
  - now all schemes known from fixed networks can be used (typical mainframe - terminal scenario)
- Example: Randomly Addressed Polling
  - base station signals readiness to all mobile terminals
  - terminals ready to send can now transmit a random number without collision with the help of CDMA or FDMA (the random number can be seen as dynamic address) or with collisions (over the Random Access Channel)
  - the base station now chooses one address for polling from the list of all random numbers (collision if two terminals choose the same address)
  - the base station acknowledges correct packets and continues polling the next terminal
  - this cycle starts again after polling all terminals of the list
- SAMA - Spread Aloha Multiple Access

- Aloha has only a very low efficiency, CDMA needs complex receivers to be able to receive different senders with individual codes at the same time
- Idea: use spread spectrum with only one single code (chipping sequence) for spreading for all senders accessing according to aloha

- Problem: find a chipping sequence with good characteristics
Comparison SDMA/TDMA/FDMA/CDMA

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure ALOHA</td>
<td>$S_a - 2G_a$</td>
</tr>
<tr>
<td>Slotted ALOHA</td>
<td>$S_a - G_a$</td>
</tr>
<tr>
<td>Non-persistent non-slotted CSMA</td>
<td>$S_a$</td>
</tr>
<tr>
<td>Non-persistent slotted CSMA</td>
<td>$S_a$</td>
</tr>
<tr>
<td>Slotted CSMA</td>
<td>$S_a$</td>
</tr>
</tbody>
</table>

Where:
- $G_a$: load includes both successful transmission attempts and retransmissions
- $S$: successful transmission attempts
- $a$: ratio of propagation delay to the packet transmission delay
- $G$: load

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

Throughputs of Some Random Access Protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure ALOHA</td>
<td>$S_a - 2G_a$</td>
</tr>
<tr>
<td>Slotted ALOHA</td>
<td>$S_a - G_a$</td>
</tr>
<tr>
<td>Non-persistent non-slotted CSMA</td>
<td>$S_a$</td>
</tr>
<tr>
<td>Non-persistent slotted CSMA</td>
<td>$S_a$</td>
</tr>
<tr>
<td>Slotted CSMA</td>
<td>$S_a$</td>
</tr>
</tbody>
</table>

Where:
- $G_a$: load includes both successful transmission attempts and retransmissions
- $S$: successful transmission attempts
- $a$: ratio of propagation delay to the packet transmission delay
- $G$: load

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