What is the main purpose of medium access control?

A  Provide quality of service
B  Prevent multiple devices transmitting at the same time
C  Relay messages to the correct destination
D  Make sure no node deviates too far from the average bandwidth usage
E  Configure the devices in the network automatically
Why can't multiple devices transmit at once in a wireless network?
In the beginning, there was ALOHA...

- Earliest protocol for wireless LANs
- Pure random access: when you have a packet to send, you send it
  - Relies on positive acknowledgements: if your transmission failed, you find out because you do not receive an acknowledgement
- ALOHA is the baseline protocol for wireless networks: we tend to compare all other protocols to this
Reservation schemes

- Basic idea: reserve some resources (time, frequency, etc) for each node so that no collisions can occur
- No loss of capacity due to collision
- But we waste resources when reservations are not fully utilised
Reservation Schemes: 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
## Comparison

<table>
<thead>
<tr>
<th>Approach</th>
<th>SDMA</th>
<th>TDMA</th>
<th>FDMA</th>
<th>CDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Idea</strong></td>
<td>segment space into cells/sectors</td>
<td>segment sending time into disjoint time-slots, demand driven or fixed patterns</td>
<td>segment the frequency band into disjoint sub-bands</td>
<td>spread the spectrum using orthogonal codes</td>
</tr>
<tr>
<td><strong>Terminals</strong></td>
<td>only one terminal can be active in one cell/one sector</td>
<td>all terminals are active for short periods of time on the same frequency</td>
<td>every terminal has its own frequency, uninterrupted</td>
<td>all terminals can be active at the same place at the same moment, uninterrupted</td>
</tr>
<tr>
<td><strong>Signal separation</strong></td>
<td>cell structure, directed antennas</td>
<td>synchronization in the time domain</td>
<td>filtering in the frequency domain</td>
<td>code plus special receivers</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>very simple, increases capacity per km²</td>
<td>established, fully digital, flexible</td>
<td>simple, established, robust</td>
<td>flexible, less frequency planning needed, soft handover</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>inflexible, antennas typically fixed</td>
<td>guard space needed (multipath propagation), synchronization difficult</td>
<td>inflexible, frequencies are a scarce resource</td>
<td>complex receivers, needs more complicated power control for senders</td>
</tr>
<tr>
<td><strong>Comment</strong></td>
<td>only in combination with TDMA, FDMA or CDMA useful</td>
<td>standard in fixed networks, together with FDMA/SDMA used in many mobile networks</td>
<td>typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)</td>
<td>still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA</td>
</tr>
</tbody>
</table>
FDD/FDMA - general scheme, example GSM

- 960 MHz
- 935.2 MHz
- 915 MHz
- 890.2 MHz

f

200 kHz

20 MHz

12

1

12

1
TDD/TDMA - general scheme, example DECT

downlink

uplink

417 µs
FDMA / TDMA Utilisation

c.f. circuit switching

- $\nu = \text{achievable bit/Hz/s}$
  - includes resources in guard bands, signaling overheads etc.
- $\rho = \text{utilised rate, bit/Hz/s}$
- $\eta = \text{Rate of work}$

$$\eta = \frac{1}{n \times \nu} \sum_{i=1}^{i=n} \rho_i$$
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 time-slot
- sending within this reserved time-slot 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)*
- *Reservation-TDMA*
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: Reservation-TDMA

Reservation Time Division Multiple Access

- 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. \( x = N \times k \)).
- other stations can send data in unused data-slots according to a round-robin sending scheme (best-effort traffic)

![Diagram of Reservation-TDMA](image-url)

- N mini-slots
- N * k data-slots
- e.g. N=6, k=2

reservations for data-slots

other stations can use free data-slots based on a round-robin scheme
OFDM

OFDM stands for **orthogonal frequency division multiplexing**. As the name suggests, it is a form of FDM, but using orthogonal subcarriers.
What is meant by saying the subcarriers in OFDM are orthogonal?
• Orthogonal subcarriers: each subcarrier has its peak at a point where all other subcarriers are zero

• This is achieved by ensuring that the sub-carrier spacing is $\Delta f = \frac{k}{T_U}$ Hz, where $T_U$ is the useful symbol duration and $k \in \mathbb{N}$. 
OFDM

- Since subcarriers are orthogonal, we do not need guard bands between them.
  - More efficient spectrum usage
- Each symbol is spread over a wider frequency range: many slowly-modulated narrowband signals instead of one rapidly-modulated wideband signal.
  - Coupled with error detection and correction, the transmission is more robust to narrowband interference or frequency-selective fading (e.g. from multipath effects)
OFDM and media access control

All these advantages make OFDM a useful physical layer technology, but how can we use it for media access control?
OFDM and media access control

All these advantages make OFDM a useful physical layer technology, but how can we use it for media access control?

We can use OFDM to separate transmissions from multiple users by

- Subcarrier allocation (FDMA)
- Transmission power control (SDMA)
- Both at once!
Subcarrier allocation

Sometimes nodes do not require the full bandwidth available on a channel. Then we can share the channel between multiple nodes by allocating sets of OFDM subcarriers to nodes.
Subcarrier allocation

This is quite a flexible reservation scheme:

- Can allocate different numbers of subcarriers to nodes depending on throughput requirements
- Can adjust which subcarriers are allocated to account for adverse channel conditions
OFDM allows for different data rates depending on the modulation scheme used for each subcarrier.

<table>
<thead>
<tr>
<th>Data rate (Mb/s)</th>
<th>Modulation</th>
<th>Coding rate</th>
<th>Coded bits per subcarrier</th>
<th>Coded bits per OFDM symbol</th>
<th>Data bits per OFDM symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
Transmission power control

- If a node does not require the highest rate possible for the current SINR, it can reduce transmission power.
- SINR is lowered but the node changes to a different modulation scheme to compensate.
- This reduces the data rate, so the transmission power should be chosen to match the required rate.
Transmission power control

Adjusting nodes’ transmission power creates a form of SDMA: nodes will cause interference to other nodes in a larger area the higher their transmission power.

We can also do this without OFDM, but with OFDM we have greater flexibility to set different data rates (and therefore transmission power levels).
OFDM Conclusion

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Why not both?
Joint subcarrier allocation and transmission power control

We can do subcarrier allocation and transmission power control at the same time.

- **Advantage:** lots of flexibility
- **Disadvantage:** difficult optimisation problem, especially if we want to do it in real time
CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
  - each sender has a unique random number, the sender XORs the signal with this pseudo random number
  - the receiver can “tune” into this signal if it knows the pseudo random number, tuning is done via a correlation function
CDMA, an example

Ms I sends: 0 1

Generate the chip Stream

00011011

110010000011011

Base station

Ms II sends: 1 1

Generate the chip Stream

11010001

1101000111010001

Base station
Spreading and scrambling of user data

- Constant chip rate of 3.84 Mchip/s
- Different user data rates supported via different spreading factors
  - higher data rate: less chips per bit and vice versa
- User separation via unique, quasi orthogonal scrambling codes
  - users are not separated via orthogonal spreading codes
  - much simpler management of codes: each mobile can use the same orthogonal spreading codes
DS-CDMA Spreading

Channel coding \[ \rightarrow \]

B \[ \rightarrow \]

C \[ \rightarrow \]

D \[ \rightarrow \]

Modulator

Code generator

“bit” Length \( \frac{1}{R_i} \)

“chip” Length \( \frac{1}{R_c} \)

\[ \frac{1}{R_i} = \frac{R_c}{R_i} \]

SPREADING FACTOR
Frequency Diversity

- Radio-channels suffer from frequency-selective fading
- Narrow-band carriers: A few users may suffer severely
- Wideband carrier: All users suffer a small amount
CDMA Principle

User \(\#N\) (rate = \(R_N\))
User \(\#2\) (rate = \(R_2\))
User \(\#1\) (rate = \(R_1\))

rate = \(R_c\)
rate = \(R_c\)
rate = \(R_c\)

\(C_N\)
\(C_2\)
\(C_1\)

\(R_i\): symbol rate for user \(i\)
\(C_i\): code for user \(i\)

\(R_c\): chip rate (same for all users)

3.84 Mchip/s
CDMA in theory

senders

data bits
\[ d_i^1 = -1 \]
\[ d_i^2 = 1 \]

channel, \( Z_{i,m}^* \)

\[ Z_{i,m}^1 = d_i^1 \cdot c_m^1 \]
\[ Z_{i,m}^2 = d_i^2 \cdot c_m^2 \]

receiver 1

\[ d_i^1 = \sum_{m=1}^{M} Z_{i,m}^* \cdot c_m^1 \]
\[ d_i^1 = -1 \]
\[ d_i^1 = 1 \]
CDMA in theory

- **Sender A**
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0“ = -1, „1“ = +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“ = -1, „1“ = +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)
    
    $A_e = (-2, 0, 0, -2, +2, 0) \cdot A_k$
    
    $(-2, 0, 0, -2, +2, 0) \cdot (-1, +1, -1, -1, +1, +1) = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    
    • result greater than 0, therefore, original bit was „1“

  - receiving B
    
    $B_e = (-2, 0, 0, -2, 2, 0) \cdot B_k$
    
    $(-2, 0, 0, -2, 2, 0) \cdot (1, 1, -1, +1, -1, +1) = -6$, i.e. „0“
Here the binary "0" is assigned a positive value,

The binary "1" a negative value!

Real systems use much longer keys resulting in a larger distance between single code words in code space.
CDMA on signal level II

signal A

+1

-1

data B

1

0

0

key B

key sequence B

0 0 0 1 1 0 1 0 1 0 0 0 0 0 1 0 1 1 1

1 1 1 0 0 1 1 0 1 0 0 0 0 0 1 0 1 1 1

data key

+1

signal B

-1

+2

+0

A_s + B_s

-2
CDMA on signal level III

Data A:

- $A_d$
- $A_s + B_s$
- $A_d$
- $(A_s + B_s) \times A_d$

Integrator output:

Comparator output:

1 0 1
CDMA on signal level IV

- data B
  - 1 0 0

- \(A_s + B_s\)
  - \(\sim\) \(\sim\)

- \(B_k\)
  - \(\sim\) \(\sim\)

- \((A_s + B_s) \ast B_k\)
  - \(\sim\) \(\sim\)

- integrator output
  - \(\sim\) \(\sim\)

- comparator output
  - 1 0 0
CDMA on signal level V
OSVF coding
Orthogonal Variable Spreading Factor Codes

Recursive rule
Transmission Power Control

Near-far problem

Node B

Power control

Transmit Power Control

Minimize the Tx power

More secure detection

Increase the system capacity
# How to use the codes - UMTS

## Summary

<table>
<thead>
<tr>
<th></th>
<th><strong>Down Link</strong></th>
<th><strong>Up Link</strong></th>
</tr>
</thead>
</table>
| **Scrambling Code**       | - To identify cells.  
- Code shall be assigned to each cell.  
- Number of Code ; 512  
- Assignment work by System Designer is required.                                                                                          | - To identify Users.  
- Code shall be assigned to each user.  
- Number of Code ; $2^{24}$  
- Assignment work by System Designer is not required.                                                                                       |
| **Spreading Code**        | - To identify the channels to be used in a cell.  
- Code shall be assigned to each user.                                                                                                          | - To identify the channels to be used in a user.  
- Code shall be assigned to each channel.                                                                                                       |
CDMA performance characteristics

• Codes not perfectly orthogonal, each node causes some interference
• Approx. Gaussian
• Soft performance degradation with increased users/load
Polling mechanisms

If one terminal can be heard by all others, this “central” terminal (for eg. 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)
- 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
Polling performance

• Simple models in general

• Effective performance depends on load and overhead as:

\[ E = \frac{T_t}{T_t + T_{idle} + T_{poll}} \]

• Where \( T_t \) is transmit time, \( T_{idle} \) is time waiting to detect no transmission and \( T_{poll} \) is time to send poll message
Resource reservations in unlicensed spectrum

- 802.11 pure random access, no traffic separation, QoS management
- There are some extensions in the standards though:
  - First attempt, Point Coordination Function (PCF)
    - Centralised polling mechanism, AP coordinator

[Diagram showing CFP, PCF, DCF, and polling sequence with SIFS and PIFS intervals.]
PCF Shortcomings

• Performance quite poor, especially for voice (Kanjanavapastit & Landfeldt 2003)
  – Null packets incur cost
  – If Voice Activity Decoder (VAD) applied:
    – Talk spurt less than 50%, poll likely in silent period
    – Resulting Null packet
• No QoS signaling
• No Tx time limit
  – if polled, transmit until done
What is a disadvantage all reservation schemes have in common? i.e. Why shouldn’t we just use them all the time?