Access Methods and Spectral Efficiency

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Mobile Communications

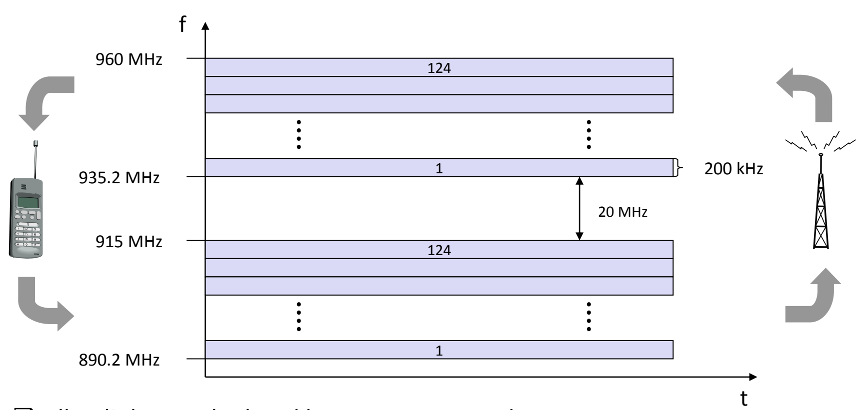
Access methods SDMA/FDMA/TDMA

- 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 presented earlier are now used to control medium access!

- **FDMA** comprises all algorithms allocating frequencies to transmission channels according to the **FDM**
- Channels can be assigned to the same frequency at all times, i.e., pure FDMA, or change frequencies according to a certain pattern, i.e., FDMA combined with TDMA

FDD/FDMA - general scheme, example GSM



- All uplinks use the band between 890.2 and 915 MHz.
- All downlinks use 935.2 to 960 MHz.
- Up- and downlink have a fixed relation

If the uplink frequency for a certain channel n is

$$f_u = 890\ MHz + n \times 0.2\ MHz$$

the downlink frequency is

$$f_d = f_u + 45\ MHz$$

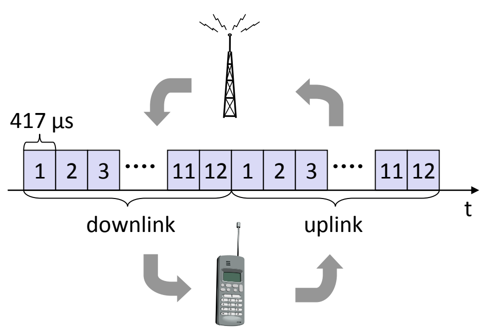
i.e.,

$$f_d = 935\ MHz + n \times 0.2\ MHz$$

- The base station selects the channel.
- Each channel (uplink and downlink) has a bandwidth of 200 kHz.
- 124 channels per direction are available at 900 MHz

Time division multiple access (TDMA)

- Comprises all technologies that allocate certain time slots for communication.
- The receiver can stay at the same frequency the whole time.
- Using only one frequency, and thus very simple receivers and transmitters.
- synchronization between sender and receiver has to be achieved in the time domain.
  - Fixed pattern
  - Dynamic allocation



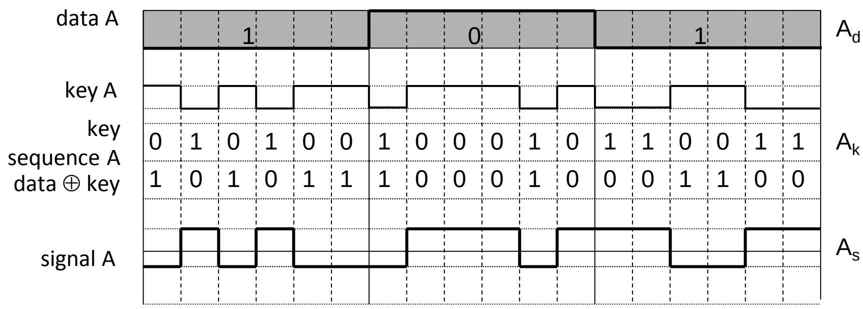
Access method CDMA

- 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 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
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g. 2^{32}) compared to frequency space
  - interferences (e.g. white noise) is not coded
  - forward error correction and encryption can be easily integrated

CDMA in theory

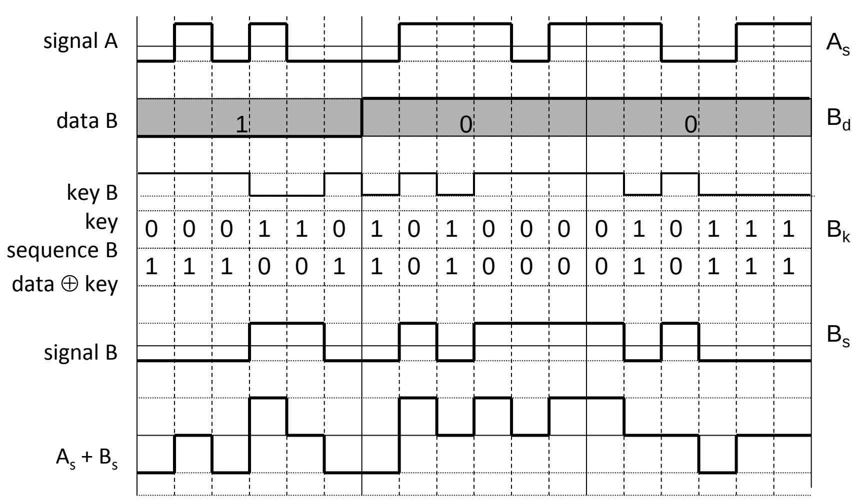
- Sender A
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0“= -1, „1“= +1)
  - sending signal $A_s = A_d * A_k = (-1, +1, -1, -1, +1, +1)$
- Sender B
  - sends $B_d = 0$, key $B_k = 110101$ (assign: „0“= -1, „1“= +1)
  - sending signal $B_s = B_d * B_k = (-1, -1, +1, -1, +1, -1)$
- Both signals superimpose 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)
    - $A_e = (-2, 0, 0, -2, +2, 0) \bullet A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was „1“
  - receiving B
    - $B_e = (-2, 0, 0, -2, +2, 0) \bullet B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6$, i.e. „0“

CDMA on signal level I

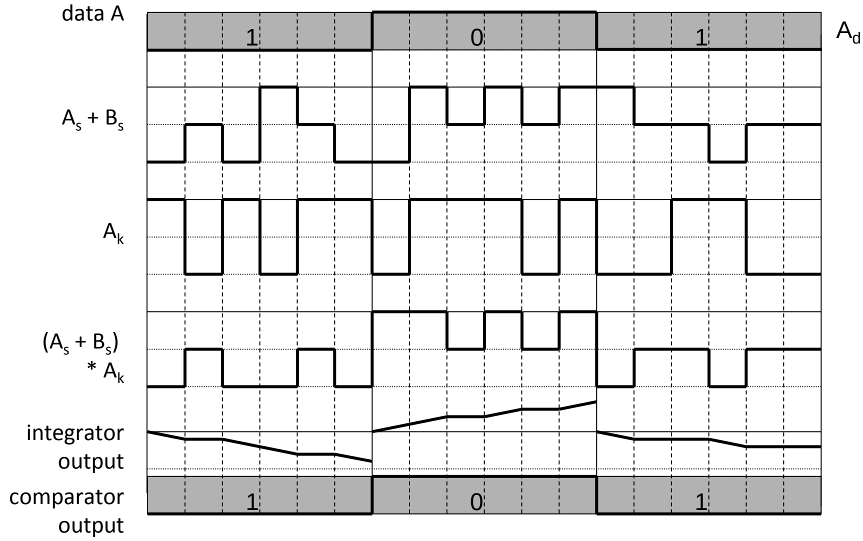


Real systems use much longer keys resulting in a larger distance between single code words in code space.

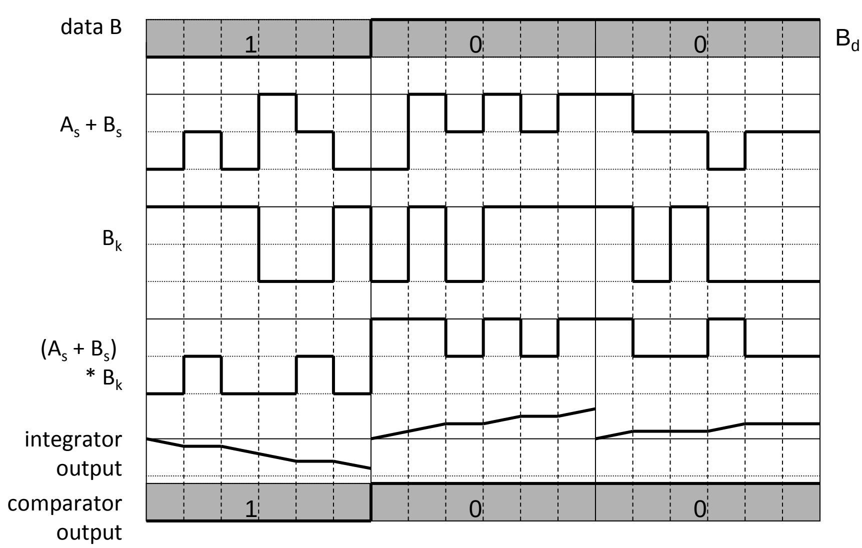
CDMA on signal level II



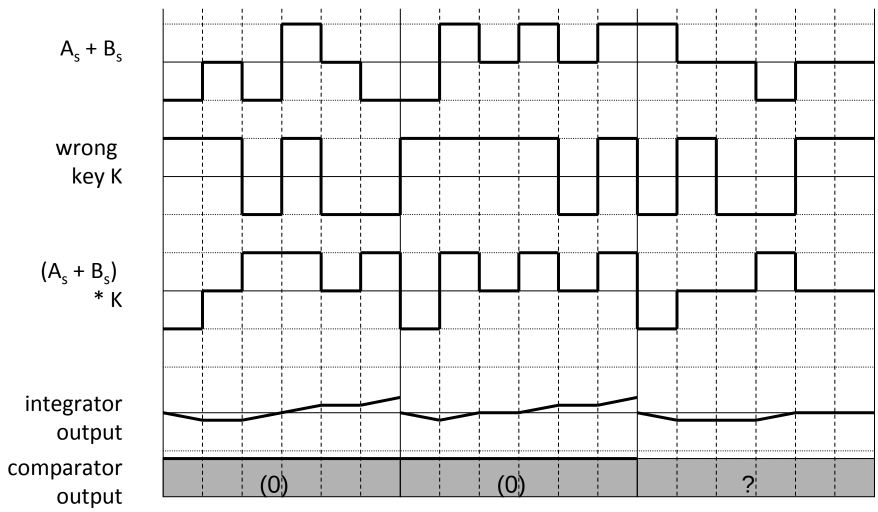
CDMA on signal level III



CDMA on signal level IV



CDMA on signal level V



Spectral Efficiency

- An efficient use of the spectrum is the most desirable feature of a mobile communications system.
- The overall spectral efficiency of a mobile communications system can be estimated by knowing the *modulation* and the *multiple access* spectral efficiencies separately.
- **The modulation spectral efficiency is defined as,**

$$\eta_m = \frac{(Total\ Number\ of\ Cannels\ Available\ in\ the\ System)}{(Bandwidth)(Total\ Coverage\ Area)}$$

$$\eta_m = \frac{1}{B_c \times N \times A_c}\ Channles/MHz/km^2$$

Where,

η_m: modulation efficiency ($Channles/MHz/km^2$)
B_c: channel spacing (MHz)
N: frequency reuse factor of the system (or cluster size)
A_c: area covered by a cell (km^2)

- Spectral efficiency of modulation does not depend on the bandwidth of the system.
- It only depends on the channel spacing, the cell area, and the frequency reuse factor, *N*.
- By reducing the channel spacing, the spectral efficiency of modulation for the system is increased, provided the cell area (A_c) and reuse factor (*N*) remain unchanged.
- If a modulation scheme can be designed to reduce *N* then more channels are available in a cell and efficiency is improved.

The digital modulation schemes differ in many issues

- **Spectral efficiency : how efficiently the modulation** scheme utilizes the available frequency spectrum.
- **Power efficiency: how** much power is needed to transfer bits – which is very important for portable devices that are battery dependent.
- **Robustness: to multi-path propagation**

Multiple Access Spectral Efficiency

- Multiple access spectral efficiency is defined **as the ratio of the total time or frequency dedicated for traffic transmission to the total time or frequency available to the system.**
- Thus, the multiple access spectral efficiency is a dimensionless number with an upper limit of unity.

FDMA Spectral Efficiency

$$\eta_a = \frac{B_c N_T}{B_\omega} \leq 1$$

η_a: multiple access spectral efficiency
N_T: total number of traffic channels in the covered area
B_c: channel spacing
$B\omega$: system bandwidth

Example

In a first-generation AMP system where there are 395 channels of 30 kHz each in a bandwidth of 12.5 MHz, what is the multiple access spectral efficiency for FDMA?

Solution:

$$\eta_a = \frac{30 \times 395}{12.5 \times 1000} = 0.948$$

TDMA Spectral Efficiency

- For the **wideband TDMA**, i.e. the entire spectrum is used by each individual user,

$$\eta_a = \frac{\tau M_t}{T_f}$$

τ:duration of a time slot that carries data
M_t: number of time slots per frame
T_f: frame duration

- Note: in the above equation it is assumed that the total available bandwidth is shared by all users.

- For the narrowband TDMA schemes, the total band is divided into a number of sub-bands, each using the TDMA technique

- The multiple access spectral efficiency of the **narrowband TDMA system** is given as,

$$\eta_a = \left(\frac{(\tau M_t)}{T_t}\right)\left(\frac{(B_u N_u)}{B_\omega}\right)$$

B_u: bandwidth of an individual user during his or her time slot
N_u: number of users sharing the same time slot in the system, but having access to different frequency sub-bands

Overall Spectral Efficiency of FDMA and TDMA Systems

$$\eta = \eta_m \eta_a$$

Example

In the North American Narrowband TDMA cellular system, the one-way bandwidth of the system is 12.5 MHz. The channel spacing is 30 kHz and the total number of voice channels in the system is 395. The frame duration is 40 ms, with six time slots per frame. The system has an individual user data rate of 16.2 kbps in which the speech with error protection has a rate of 13 kbps. Calculate the multiple access spectral efficiency of the TDMA system.

Solution

The time slot duration that carries data

$$\tau = \left(\frac{13}{16.3}\right)\left(\frac{40}{6}\right) = 5.35\ ms$$

$$T_f = 40\ ms, M_t = 6, N_u = 395, B_u = 30KHz\ and\ B_\omega = 12.5\ MHz$$

$$\eta_a = \frac{5.35 \times 6}{40} \times \frac{30 \times 395}{12500} = 0.76$$

Capacity and Frame Efficiency of a TDMA System

➢ Cell Capacity

The cell capacity is defined as the maximum number of users that can be supported simultaneously in each cell.

The **capacity of a TDMA system** is given by,

$$N_u = \frac{\eta_b \mu}{v_f} \times \frac{B_\omega}{RN}$$

Where,

N_u:number of channels (mobile users) per cell
η_b: bandwidth efficiency factor (<1.0)
μ: bit efficiency (2 bit/symbol for QPSK, 1 bit/symbol for GMSK as used in GSM)
v_f: voice activity factor (equal to one for TDMA)
B_ω: one-way bandwidth of the system.
R: information (bit rate plus overhead) per user
N: frequency reuse factor

$$Spectral\ efficiency\ \eta = \frac{N_u \times R}{B_\omega}\ \ bit/sec/Hz$$

Example

Calculate the capacity and spectral efficiency of a TDMA system using the following parameters: bandwidth efficiency factor $\eta_b = 0.9$, bit efficiency (with QPSK) $\mu = 2$, voice activity factor $v_f = 1.0$, one-way system bandwidth $B_\omega = 12.5\ mHz$, information bit rate *R* = 16.2 kbps, and frequency reuse factor *N* = 19.

Solution

$$N_u = \frac{0.9 \times 2}{1.0} \times \frac{12.5 \times 10^6}{16.2 \times 10^3 \times 19}$$

$$N_\mu = 73.1\ (say\ 73\ mobile\ users\ per\ cell)$$

$$Spectral\ efficiency\ \eta = \frac{73 \times 16.2}{12.5 \times 1000} = 0.094\ bit/sec/Hz$$

Further reading:
John Schiller, “Mobile Communications”, sections 3.2, 3.3, 3.4, 3.4.1 and 3.5.