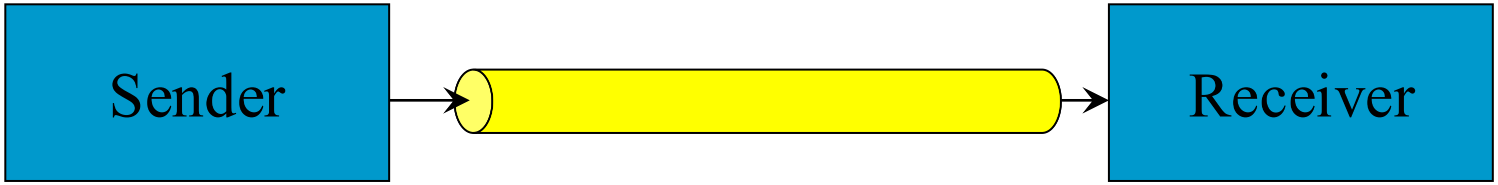
Multimedia Internet

Channels and Multiplexing

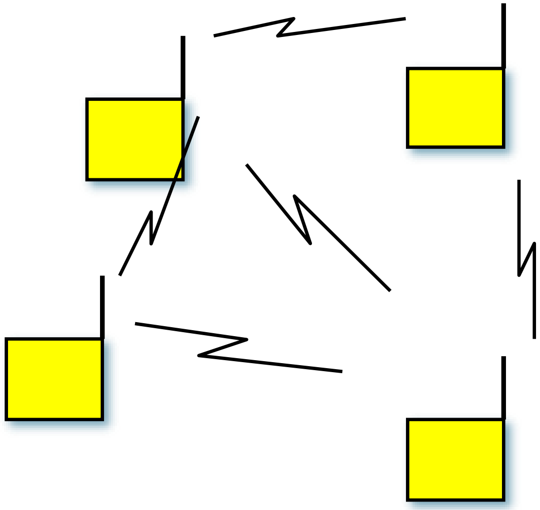
Point-to-point Channels

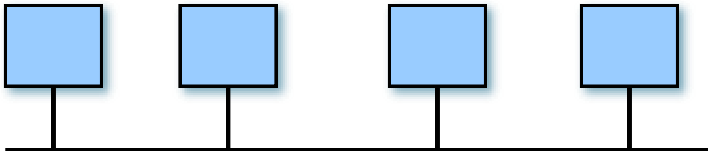
- They are permanent connections between a sender and a receiver
- The receiver can be designed and optimized based on the (only) signal it must receive
- Data transmission can be *continuous* or divided into *frames* (this raises synchronization problems)



Broadcast Channels

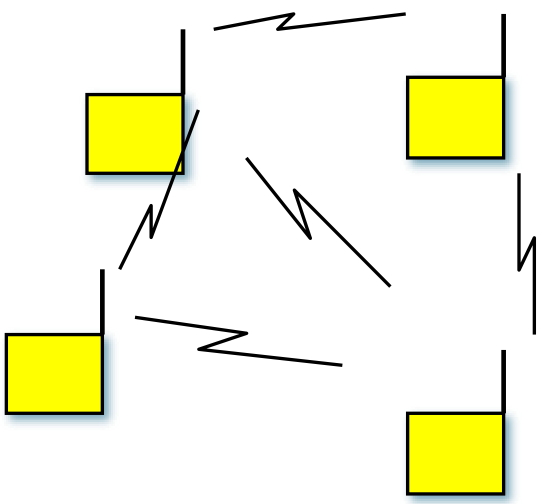
- Many stations/nodes can access a broadcast channel in parallel. The channel is «shared» among all stations
- The transmissions of a station reaches all other stations

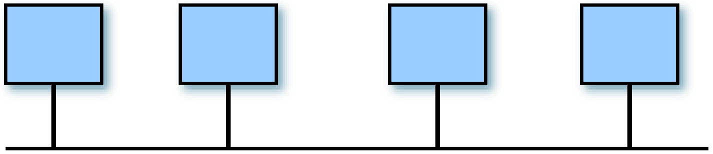




Broadcast Channels

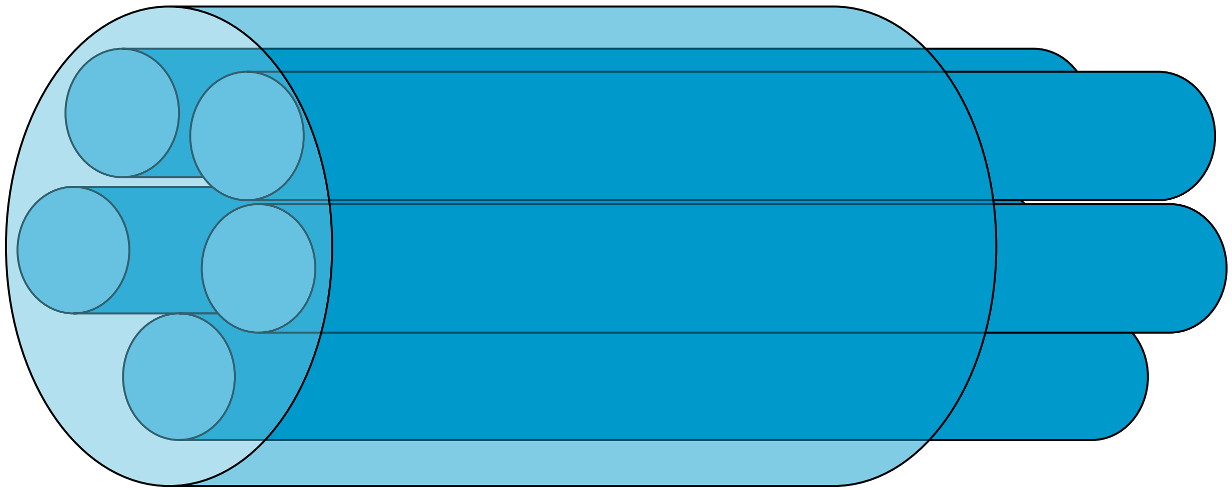
- **The receiver can receive several transmissions which differ in their *power level* and *synchronization*, and it must be able to adapt itself to such differences, and single out the right transmission**
- **Transmissions usually start with a *preamble* (*synchronization character*) to achieve synchronization**
- **Examples: local area networks/ethernet, cellular systems**





Multiplexing

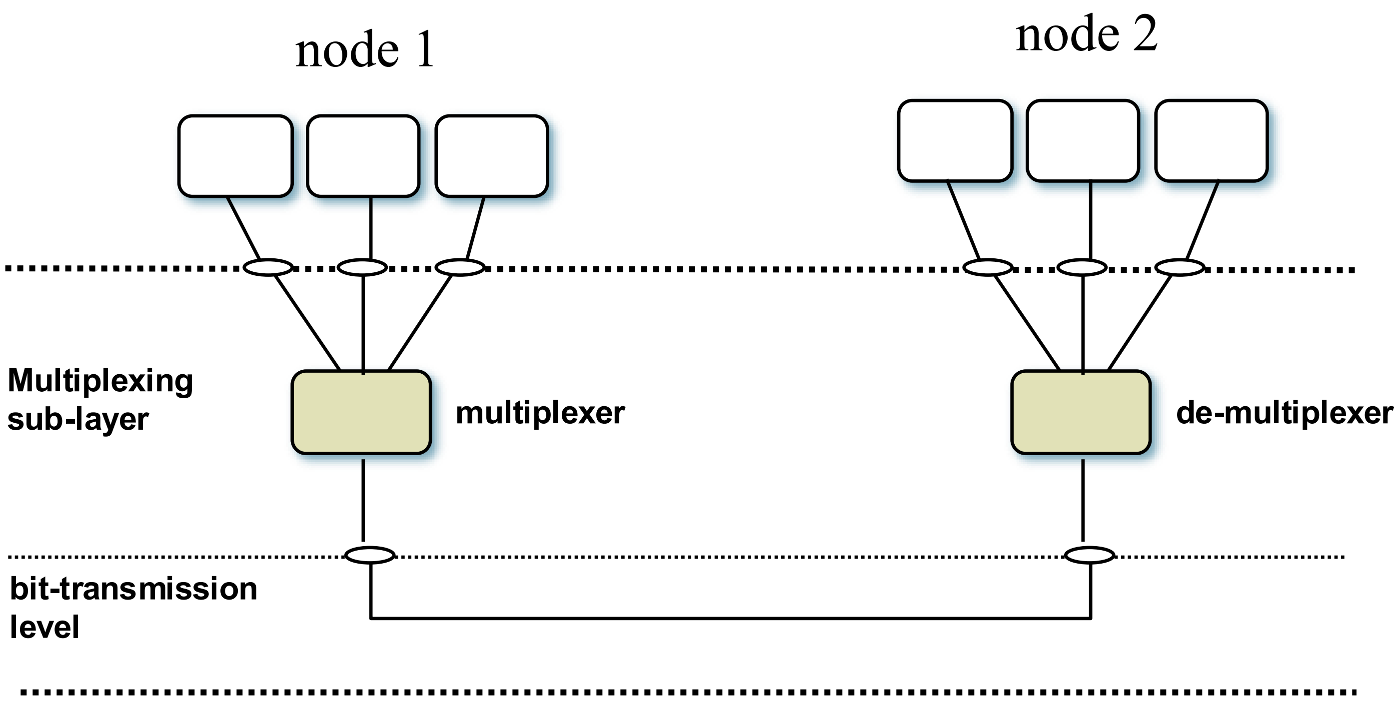
- The physical capacity of a channel can be subdivided to obtain more (sub)channels with lower speed.



Physical Multiplexing

- Each (sub)channel is defined based exclusively on physical parameters, like frequency, time, code, wavelength …

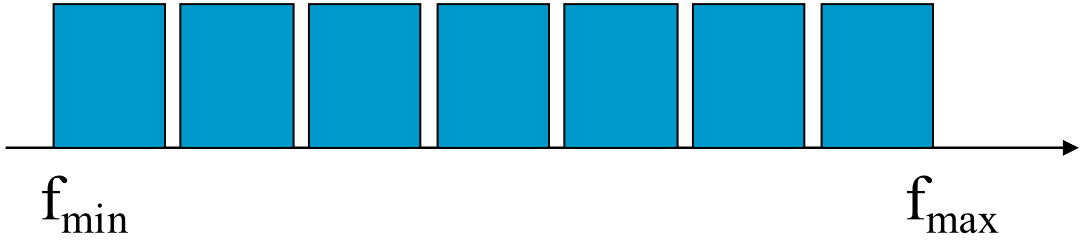
Physical layer



FDM (Frequency Division Multiplexing)

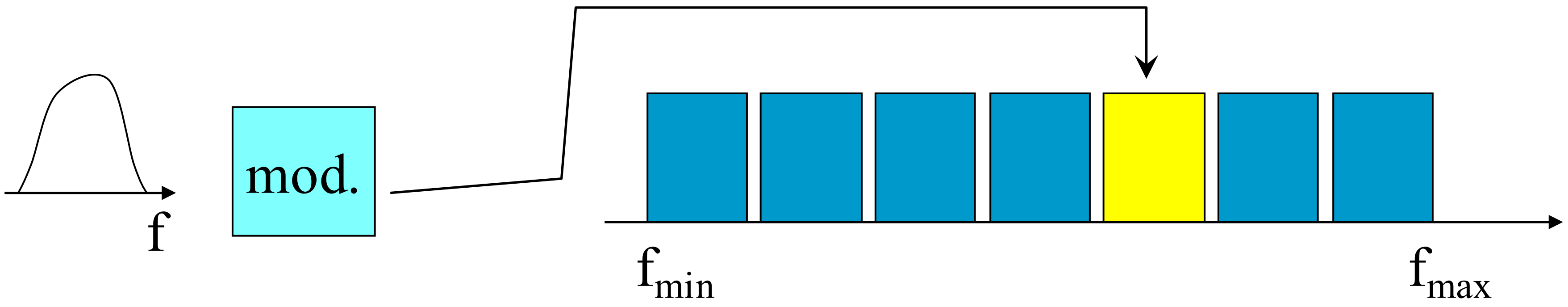
- Each physical channel can be characterized by its available bandwidth (the set of frequencies available for transmission, from f_{min} to f_{max})

- Such bandwidth can be divided into sub-channels, and we can associate a communications to each sub-channel

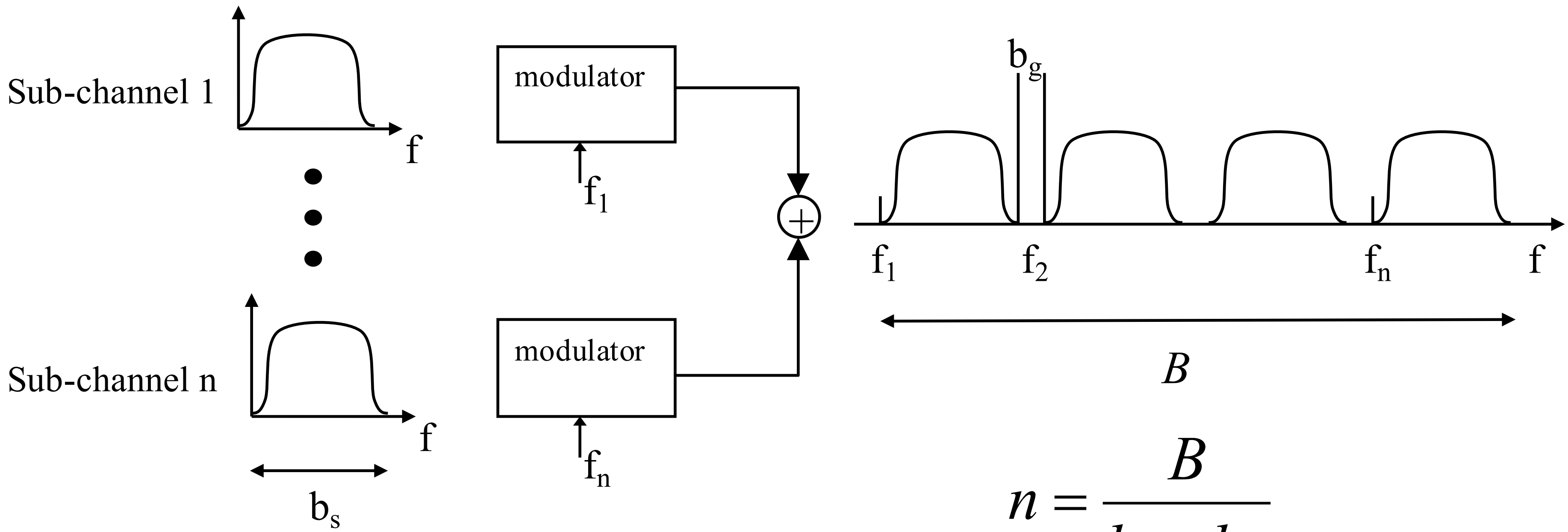


FDM (Frequency Division Multiplexing)

- The signal related to one communication is *filtered* and then *modulated* (hence, shifted in frequency) in order to fit exactly into one sub-channel



FDM (Frequency Division Multiplexing)



$$n = \frac{B}{b_s + b_g}$$

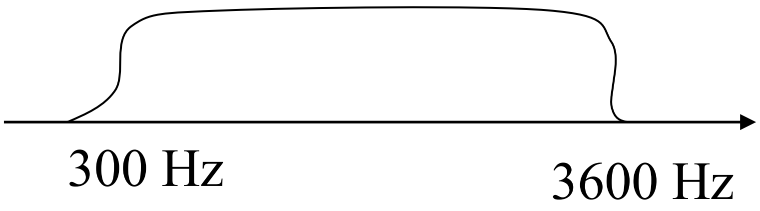
B = *total available bandwidth* $(f_{max} - f_{min})$

b_s = *signal bandwidth*

b_g = *guard band*

FDM - Telephony

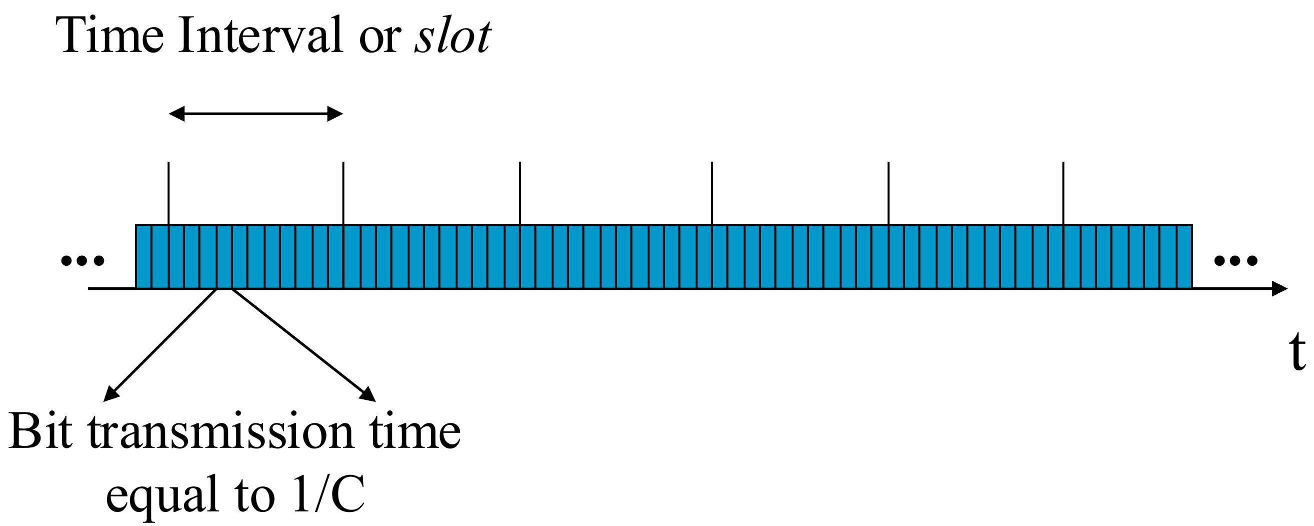
- In the past, FDM was used as a multiplexing technique to transmit voice calls between phone centrals
- Voice call bandwidth: approximately 4 kHz



- 12 channels/voice calls of 4 kHz each were multiplexed over a total bandwidth of 48 kHz (in the range between 60 and 108 kHz)
- Then, such 48 kHz aggregation was further multiplexed in even larger aggregations (in a hierarchical modulation scheme)

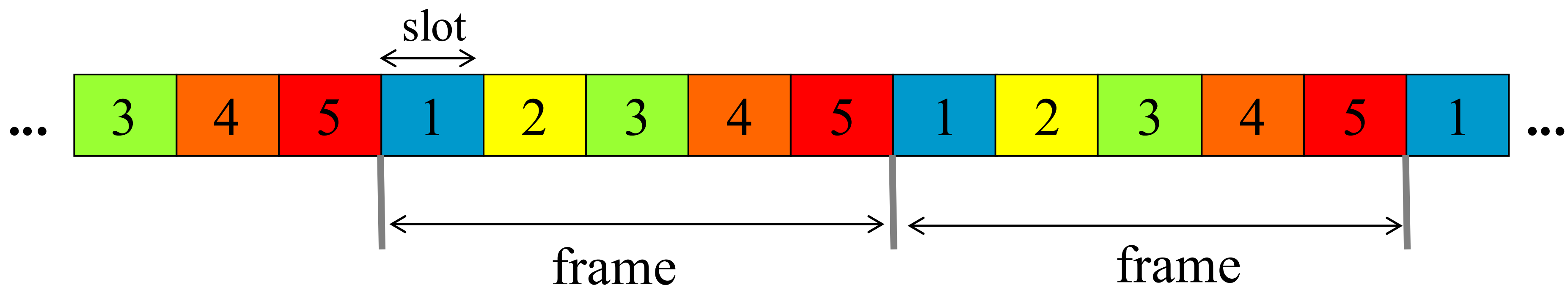
TDM (Time Division Multiplexing)

- This technique is used for digital/binary signals (sequencies of 0s - 1s)
- Given a channel with speed/capacity *C* (bit/s), we define time intervals (named *slots*), whose duration is a multiple of the bit duration $t_b=1/C$

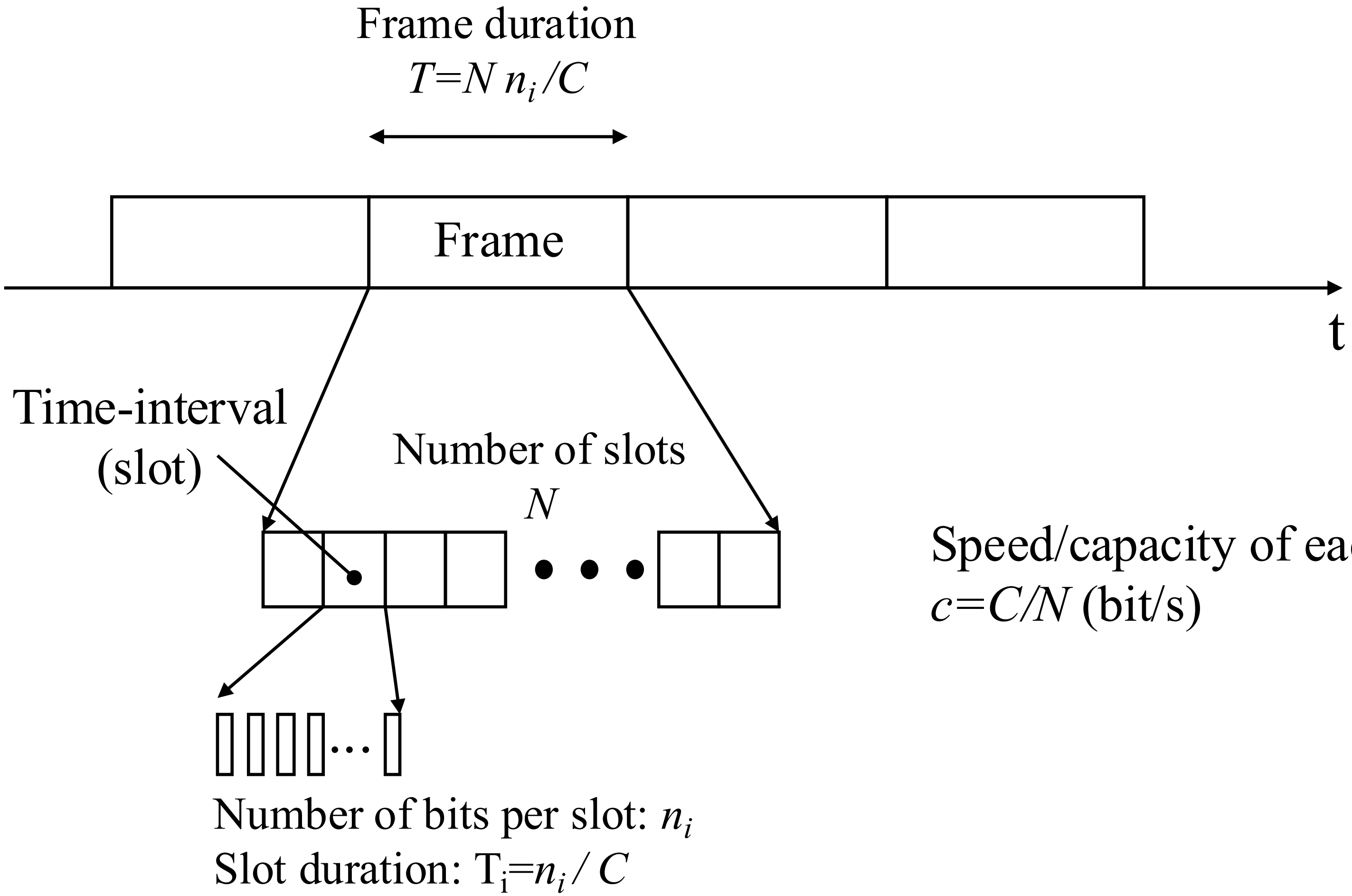


TDM (Time Division Multiplexing)

- **Each source/sender can use only a single time slot every *N***
- **Hence we define a *frame structure*, where the frame is constituted by *N* consecutive time slots**
- **If we give a number to each time slot, each source/sender is associated to a time-slot number, and it can transmit only *inside* such slot**



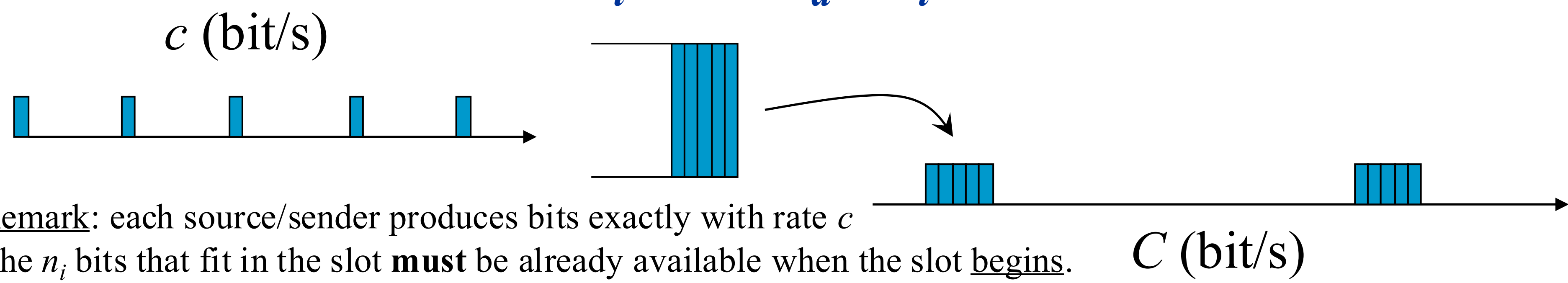
TDM (Time Division Multiplexing)



Speed/capacity of each sub-channel
$c = C/N$ (bit/s)

TDM (Time Division Multiplexing)

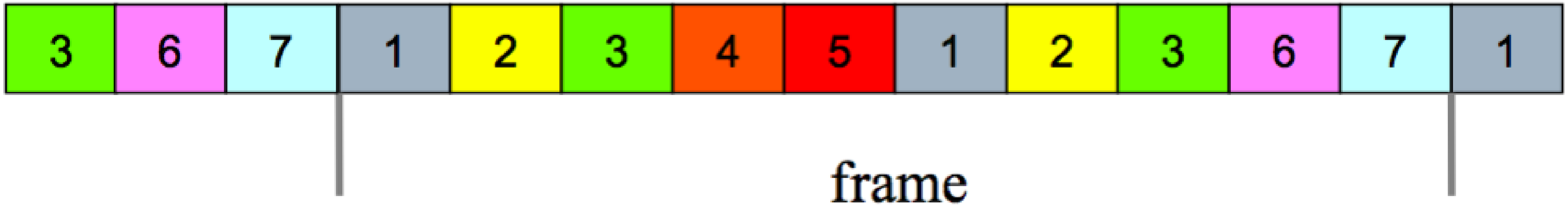
- The choice of the *slot duration* is very important (this is a parameter chosen when the slotted system is designed):
  - n_i number of bits per slot
  - T_i slot duration ($T_i = n_i / C$)
- the sub-channel capacity/speed c does not depend on T_i but only on N ($c = C/N$)
- Time to collect n_i *bits*: $T_a = n_i / c$



Remark: each source/sender produces bits exactly with rate c
The n_i bits that fit in the slot **must** be already available when the slot begins.
Clearly, the source needs n_i / c seconds to produce and accumulate the n_i bits

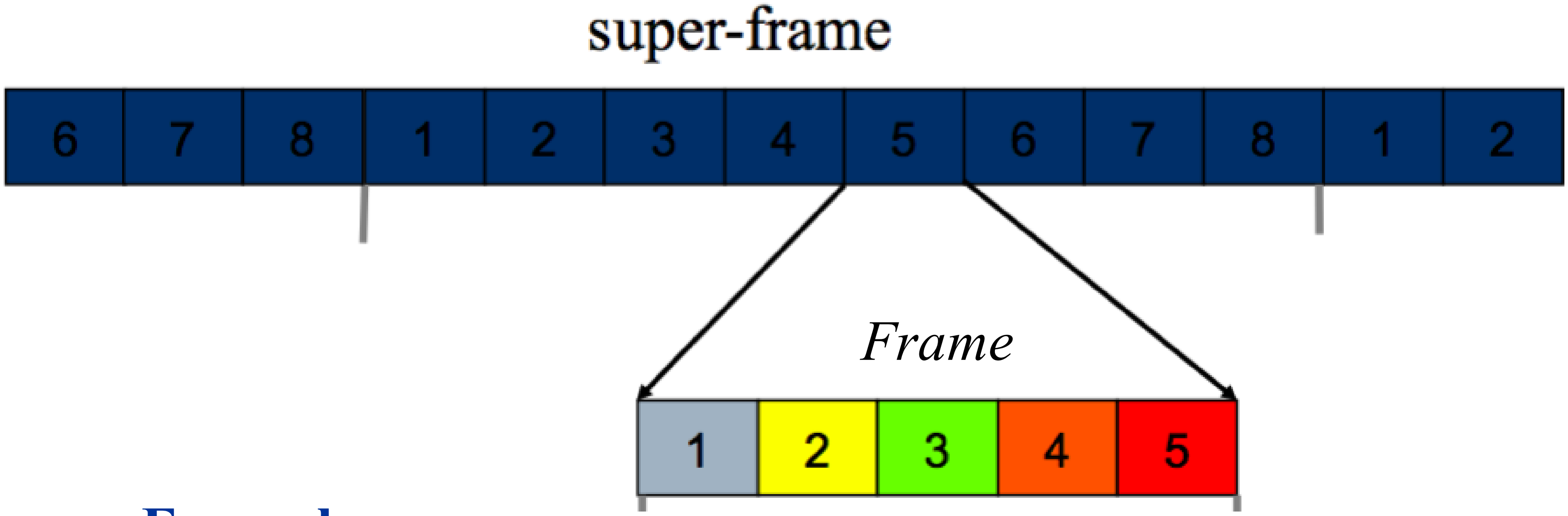
TDM/TDMA: Channels at different rates

- If at each sub channel it is assigned a single slot per frame, all transmission rates are the same
- In many cases it is necessary multiplexing channels with different rates
- To this purpose it is possible to use more complex frames where to a channel more than one slot can be assigned



TDM/TDMA: Channels at different rates

- For simplicity this is usually obtained using a hierarchy of frames, with frames and super-frames



- Example:
  - Channel A = slot 1 in every frame (C/5)
  - Channel B = slot 2 in *odd* frames only (C/10)
  - Channel C = slot 2 in frames 1 and 5 only (C/20)

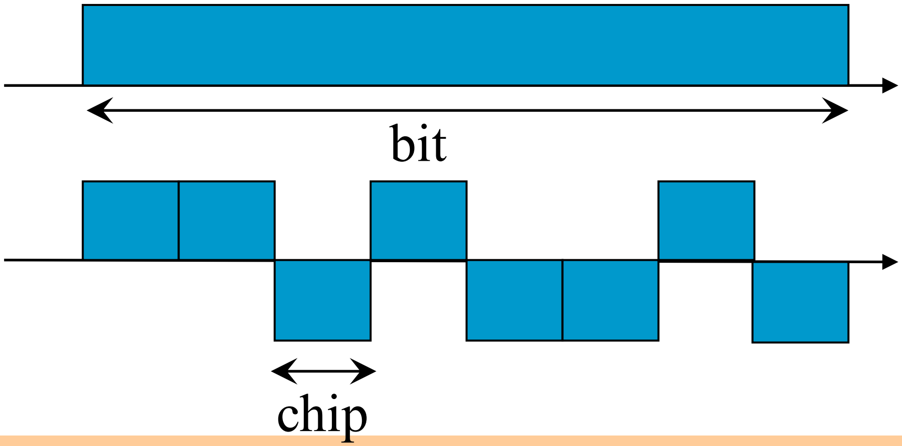
Exercise

- **Let us consider a channel with capacity C=900 kbit/s**
- **We want to create 5 sub-channels: 4 with capacity c=200 kbit/s and 1 with capacity 100 kbit/s**
- **Specify the TDM frame structure, assuming that the slot contains *at minimum* $n_i = 8$ *bits***

Homework

CDM (Code Division Multiplexing)

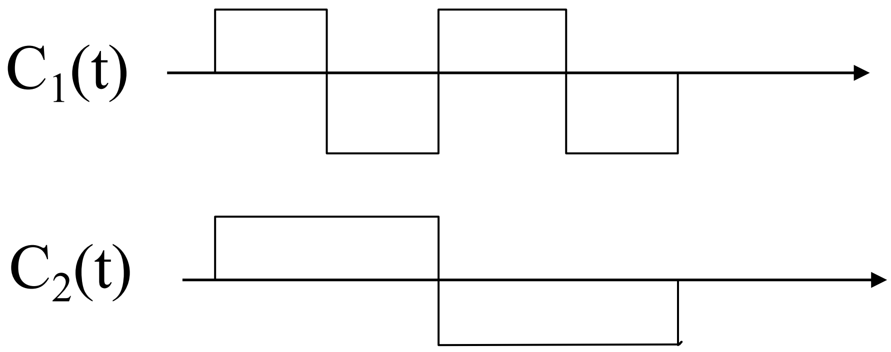
- The CDM technique consists in mixing (i.e., adding) *N* bit flows (N transmissions), just after having multiplied each one of them with a codeword C_i chosen among the *N* codewords of an orthogonal code
- Codewords are constituted by *N* binary symbols, called *chips* in order to distinguish them from *bits*, whose duration is N times shorter than a bit



Orthogonal Codes

- **Orthogonal Signals:** $\int s_1(t) \cdot s_2(t) = 0$

- **Orthogonal Sequencies:**



$$\int_0^T C_1(t) \cdot C_2(t) = 0$$

$$\sum_{i=1}^{N} c_{1i} \cdot c_{2i} = 0$$

Orthogonal Codes

Hadamard Matrix:

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & -H_n \end{bmatrix}$$

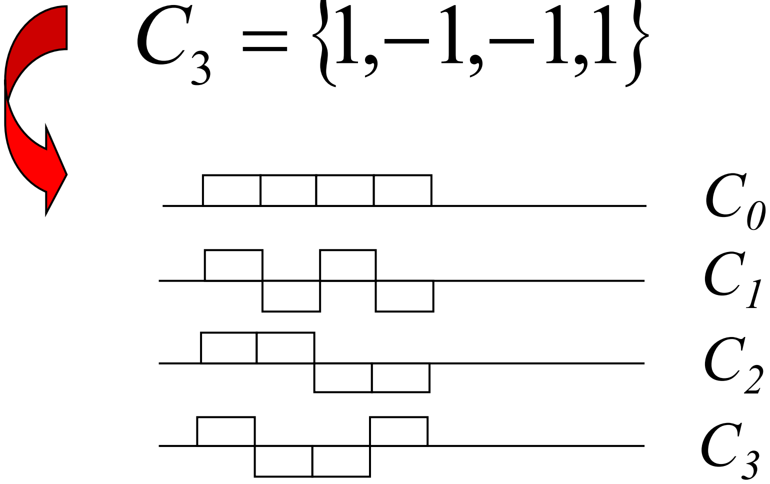
Example for N=4

$$C_0 = \{1,1,1,1\}$$

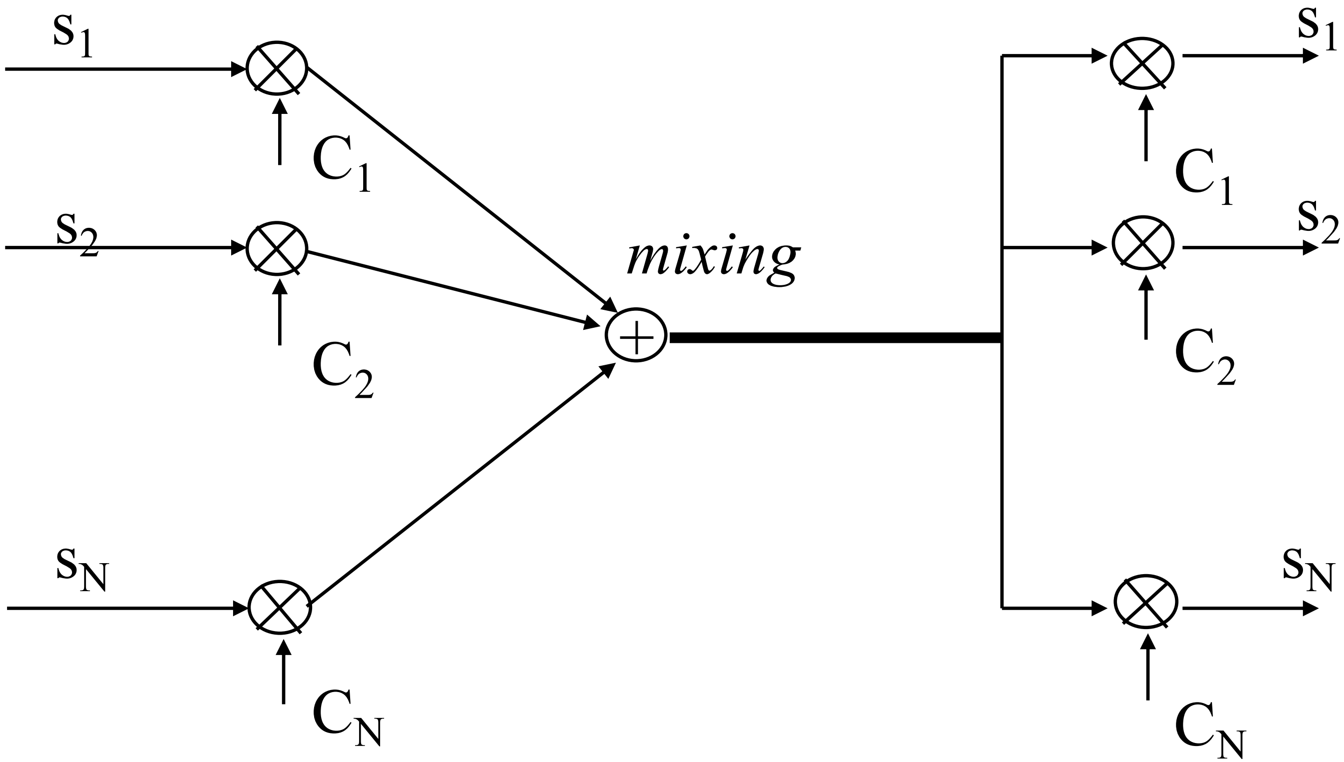
$$C_1 = \{1,-1,1,-1\}$$

$$C_2 = \{1,1,-1,-1\}$$

$$C_3 = \{1,-1,-1,1\}$$



CDM (Code Division Multiplexing)



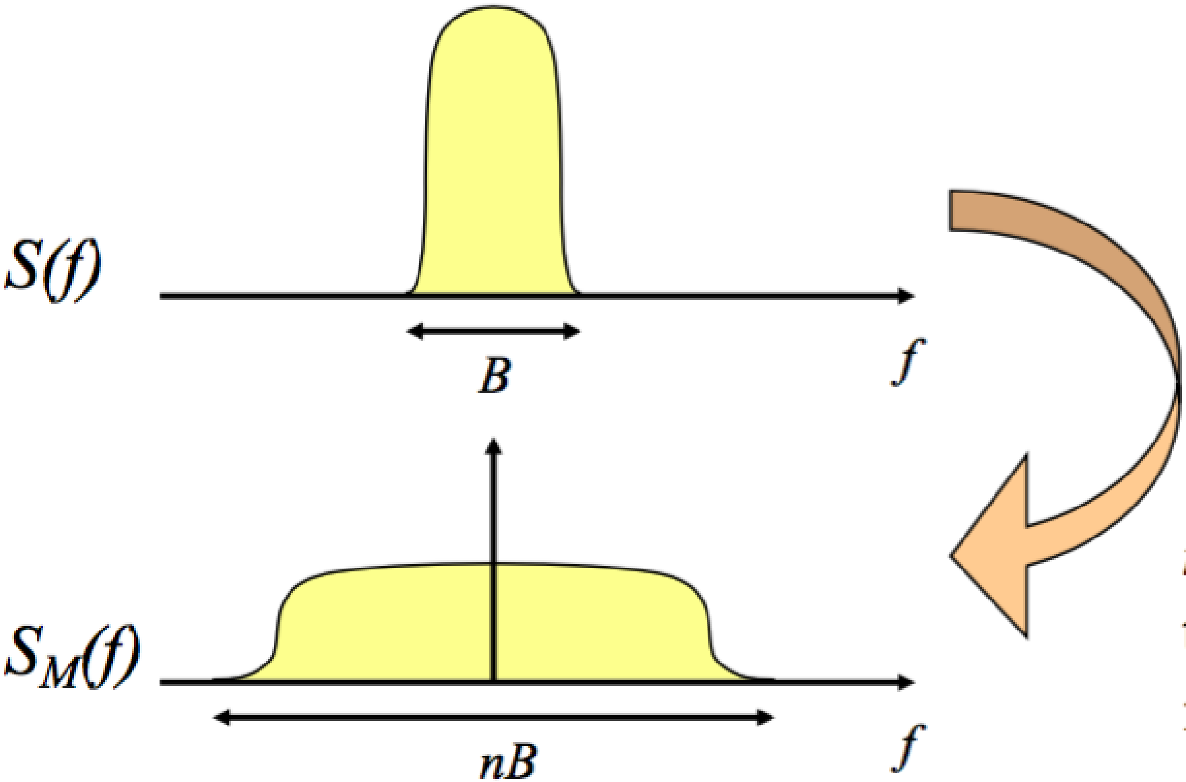
At the receiver: I can extract the k-th signal by simply multiplying by C_k

$$\int_T \left(\sum_{i=0}^{N-1} s_i C_i \right) \cdot C_k = s_k$$

T= bit time

CDMA: spreading and despreading

The code "expands" the radio bandwidth of the signal

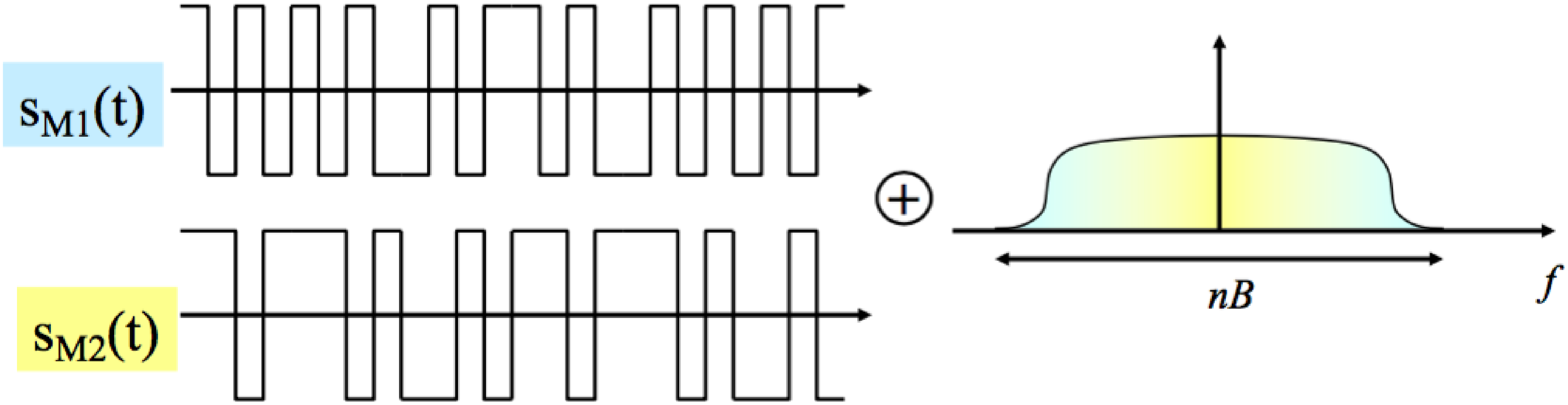


***Spreading* of the radio spectrum**

n number of chips in the code: "spreading factor" (SF)

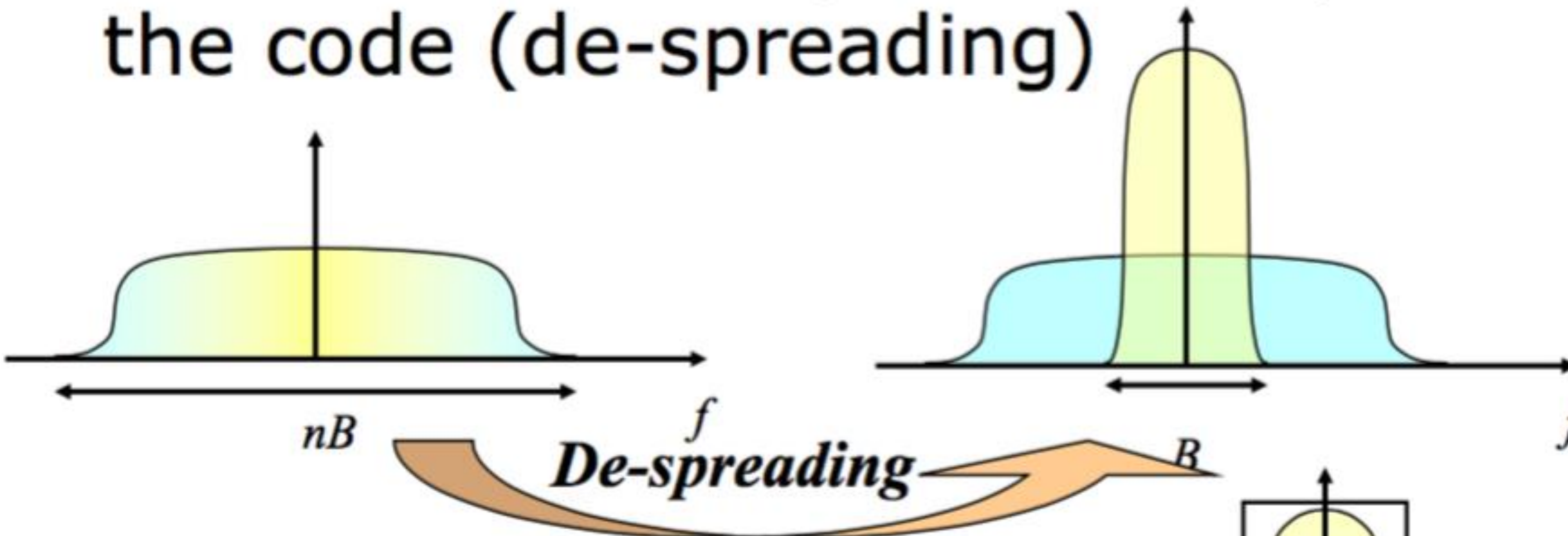
CDMA: spreading and despreading

Different signals use the same radio band

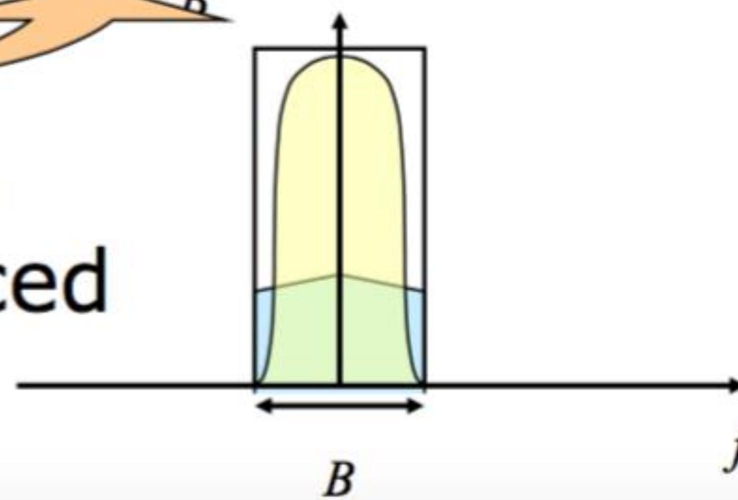


CDMA: spreading and despreading

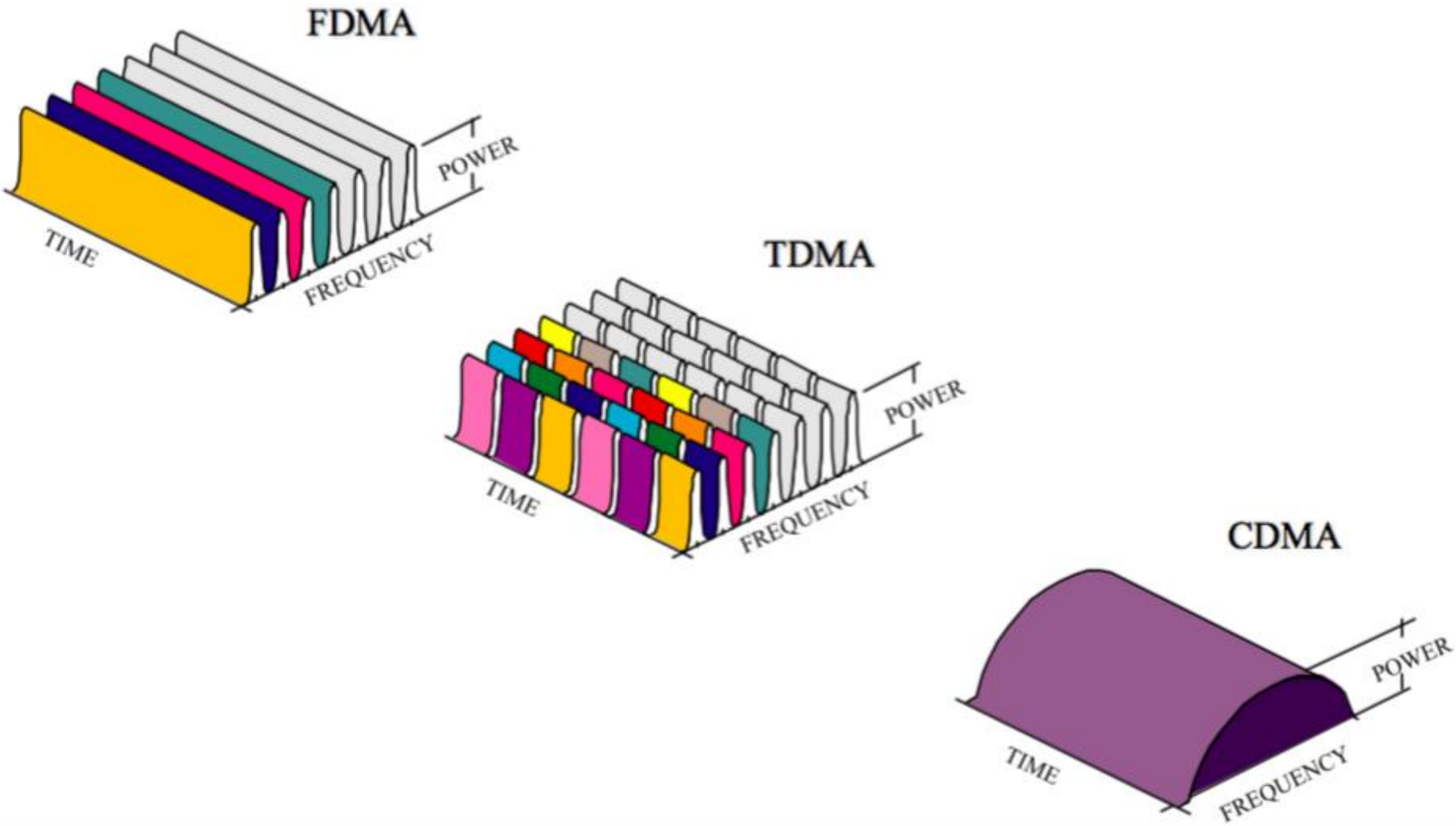
- At receiver the signal is multiplied by the code (de-spreading)



- The interfence of the other signals is reduced by *1/n*



Multiple access: comparison

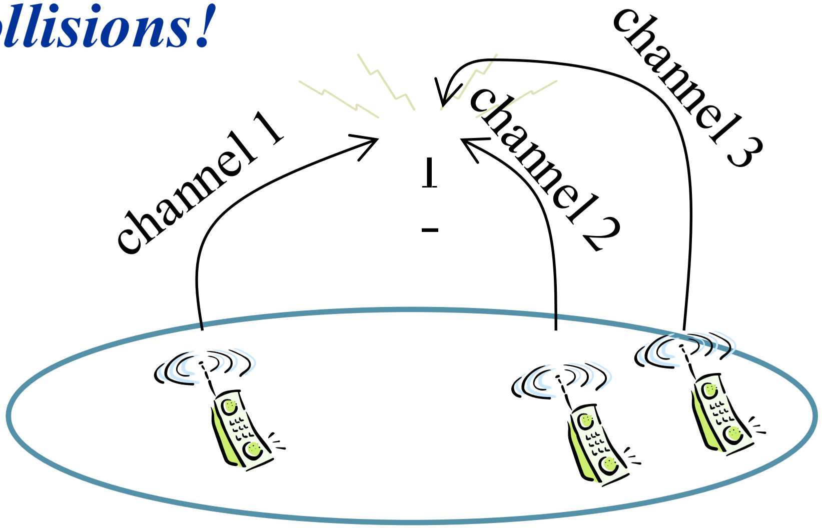


WDM (Wavelength Division Multiplexing)

- It’s the same as FDM; it is called WDM for historical reasons, related to the development of optical fibers
- Different signals are modulated using different wavelengths on optical fibers
- Each wavelength can carry huge amount of information (5-10 Gbit/s)
- Technological limit: related to the stability of LEDs/Lasers used to modulate signals, as well as by the precision of optical filters
- We have currently commercial devices with 16 – 128 wavelengths (Dense WDM, DWDM)

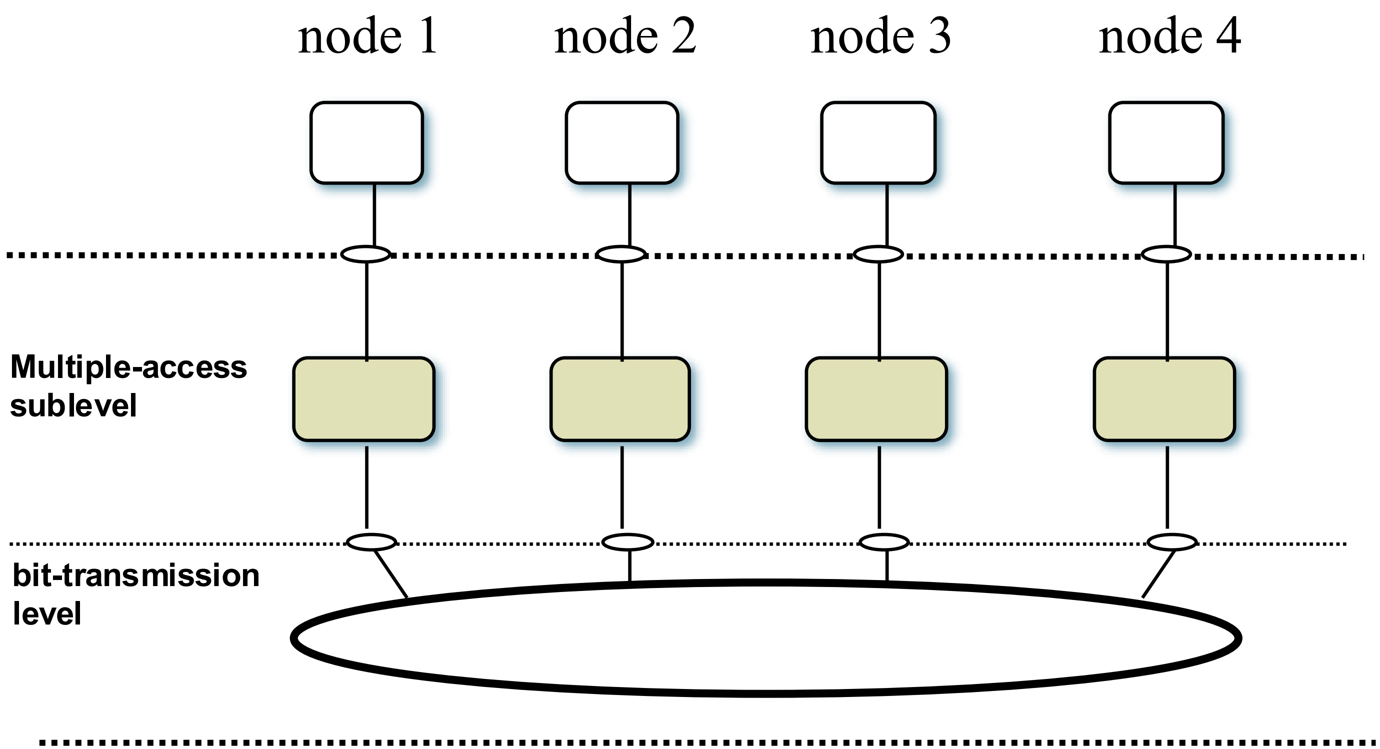
Multiple Access

- It is *similar* to multiplexing, but conceptually it is *very different.*
- In fact, multiple access is related to *broadcast channels.*
- Hence, the stations/nodes which access the broadcast channel are *distant*, hence they are physically is different places, possibly very far from each other, and so they need to *coordinate among themselves* to access the channel without *collisions!*

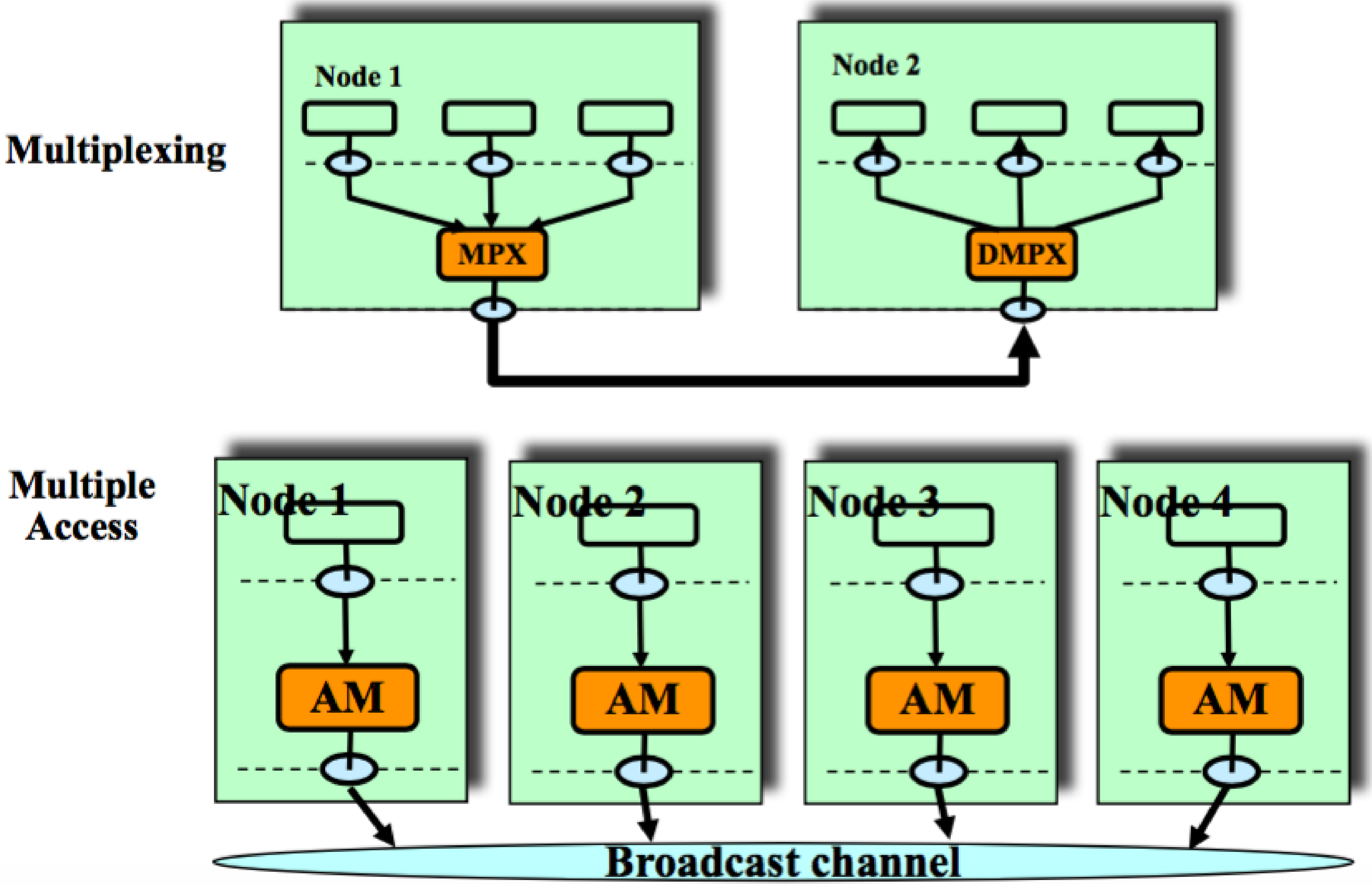


Multiple Access: logical scheme

Physical layer



Multiplexing vs Multiple Access

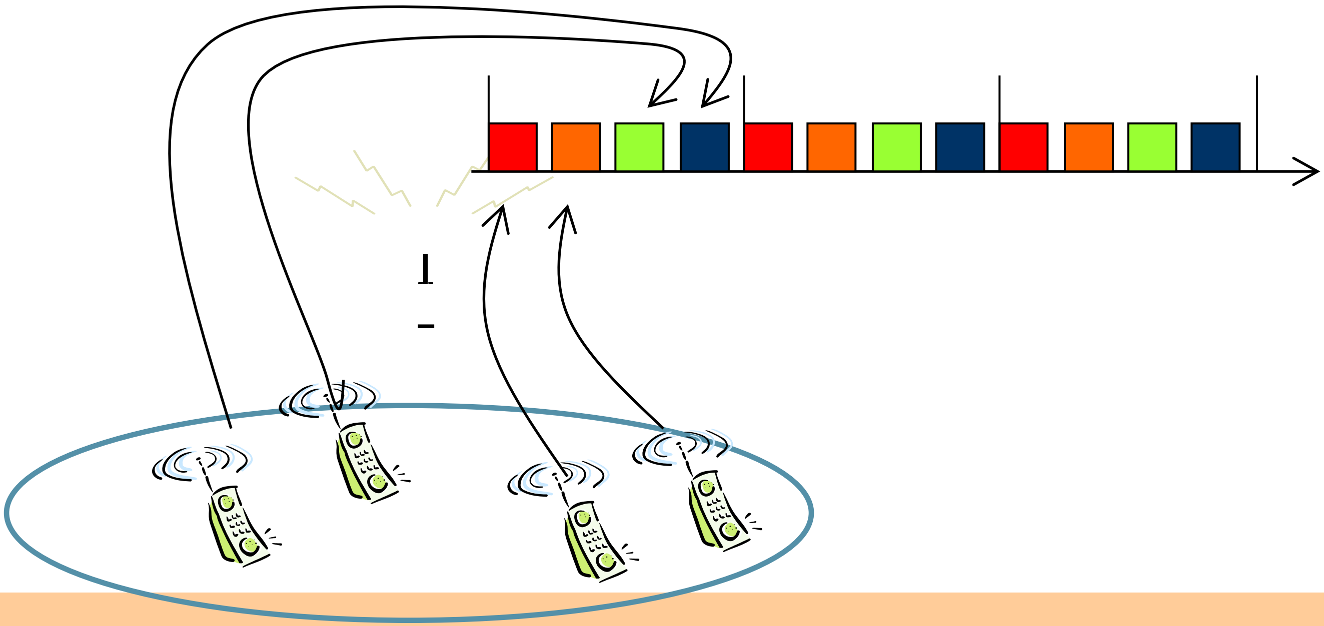


FDMA
Frequency Division Multiple Access

- **It's analogous to FDM**
- **Different nodes/stations need to coordinate to access the channel, but this is not a problem with FDMA**
- **<u>Examples</u>:**
  - **TV or Radio station broadcast**
  - **Cellular system TACS (Total Access Cellular System) which used 25 kHz subchannels for phone calls**

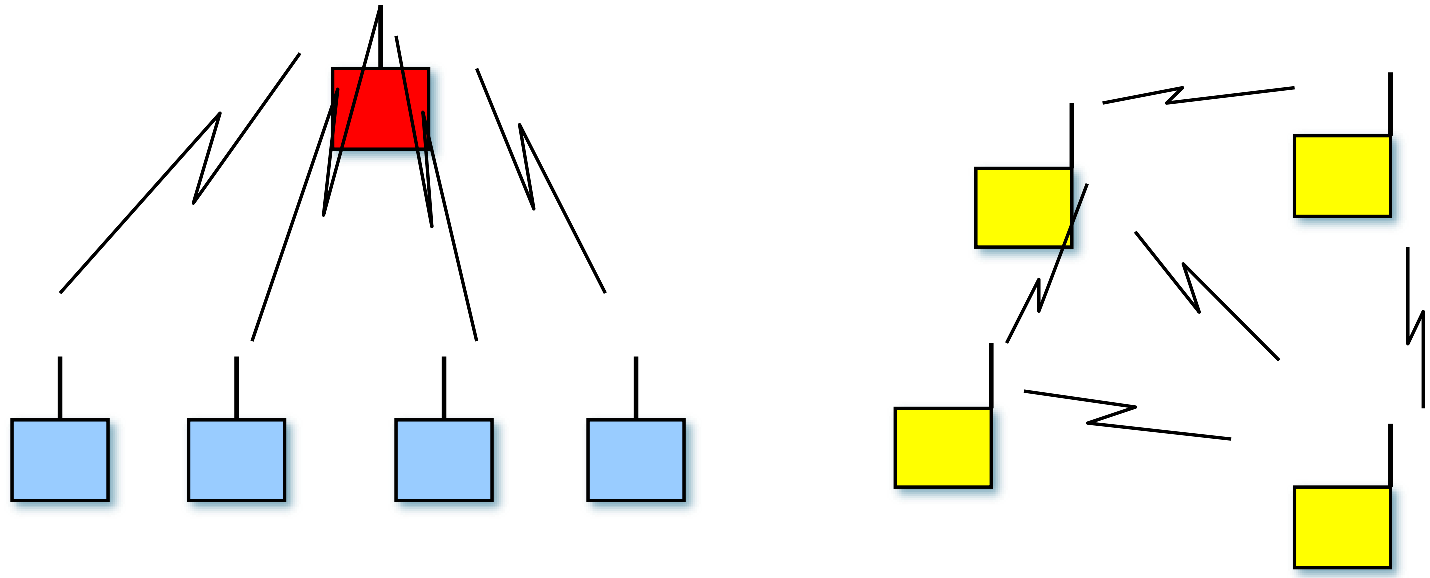
TDMA
Time Division Multiple Access

- It's similar to TDM …
- … but here it is necessary for stations to coordinate among themselves to find a common timing reference (necessary to know when slots/frames start and end)
- Synchronization cannot be perfect: *guard times* are necessary to avoid overlapping



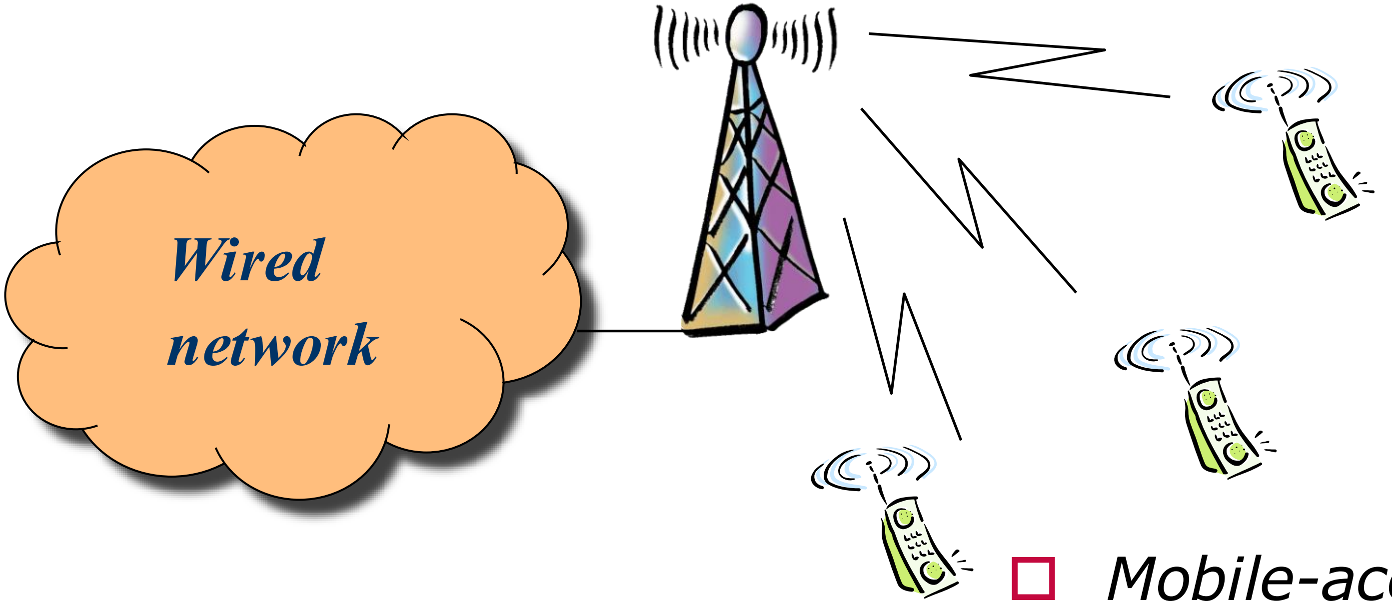
Broadcast channel

- Centralized broadcast channel
- Distributed broadcast channel



Centralized broadcast channel

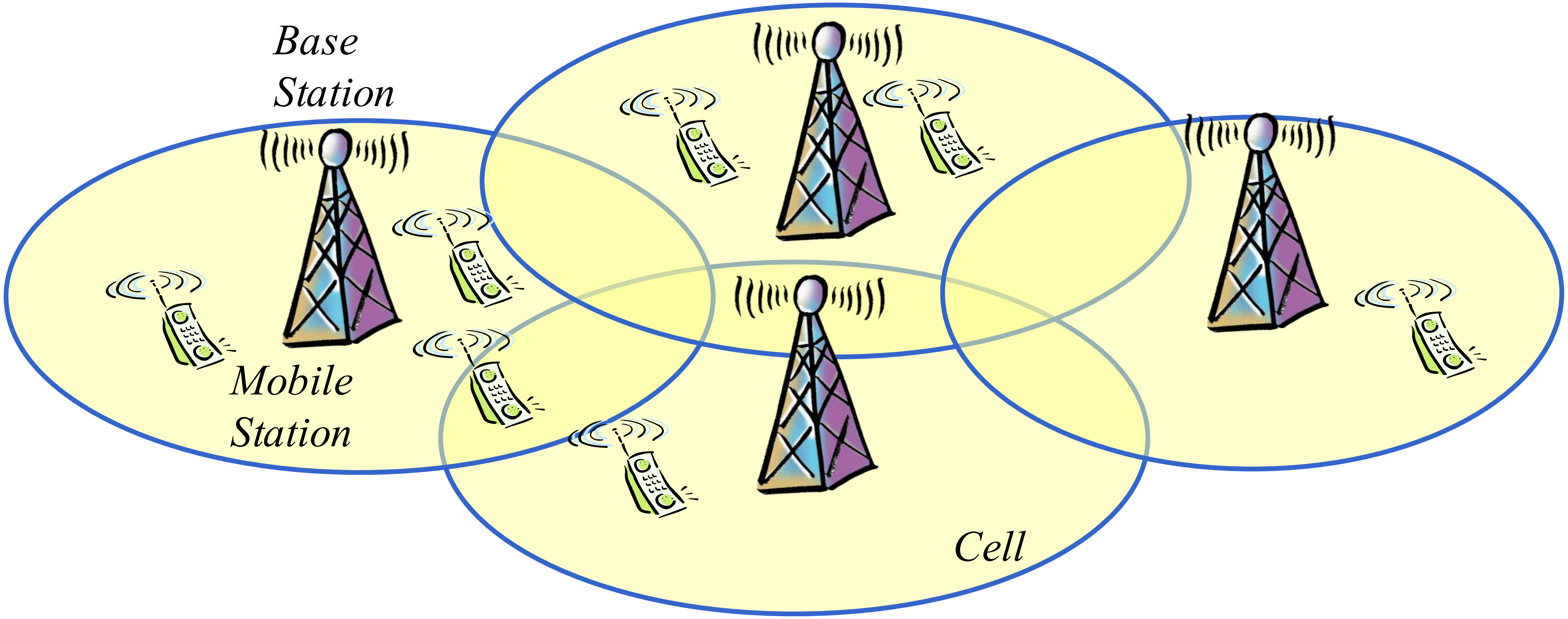
- Fixed access point (cellular systems, WLAN, WMAN)



- *Mobile-access point connection*

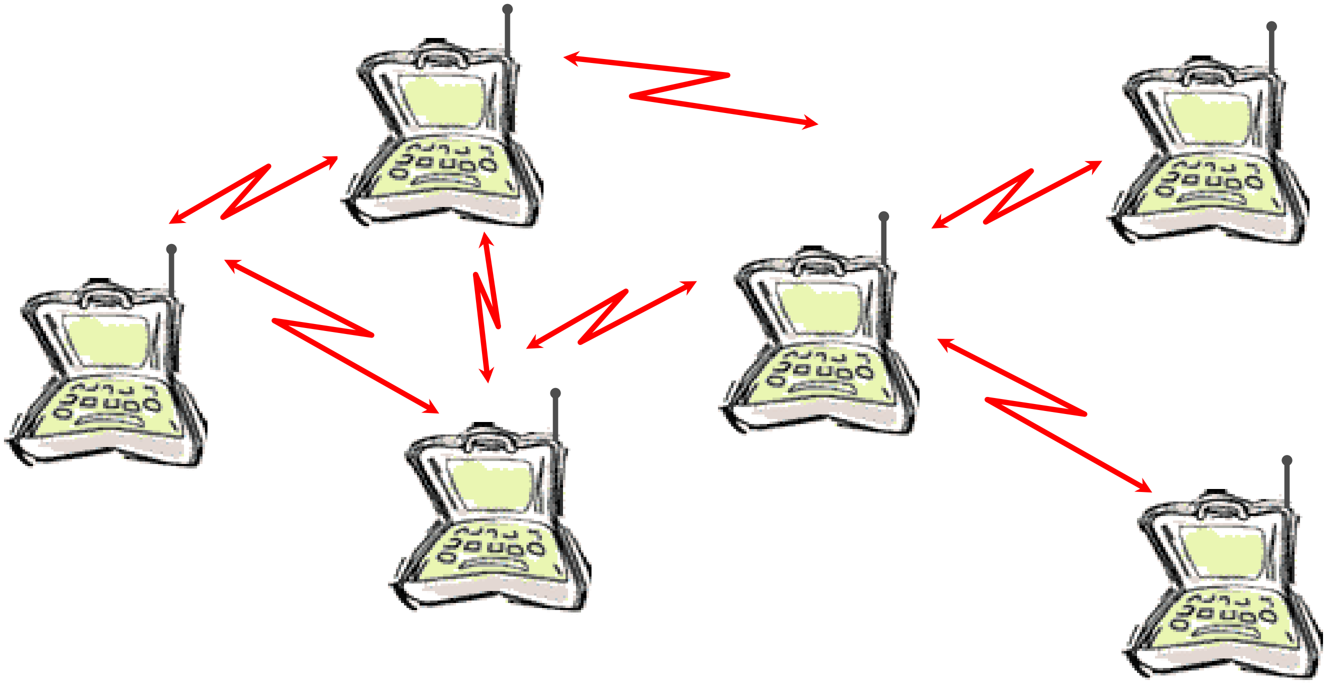
Centralized broadcast channel

- **Cellular coverage: The territory coverage is obtained by Base Stations–BS (or Access Points) that provide radio access to Mobile Stations–MS within a service area called CELL**



Distributed broadcast channel

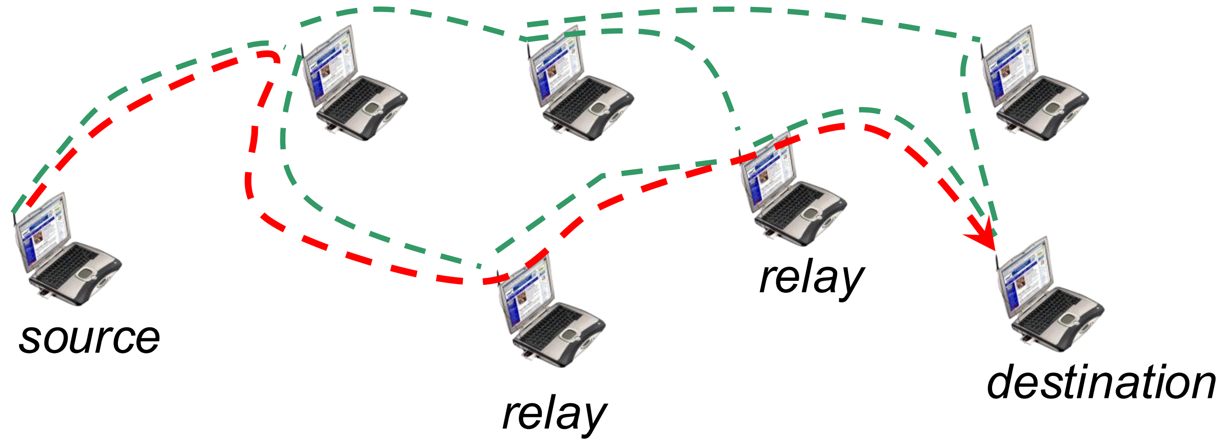
- **Ad-hoc wireless networks (mesh networks, sensor networks)**



- *mobile - mobile connections*

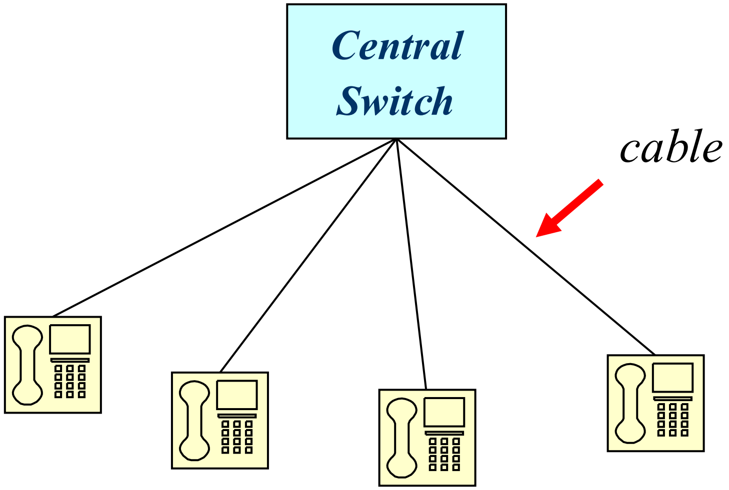
Distributed broadcast channel

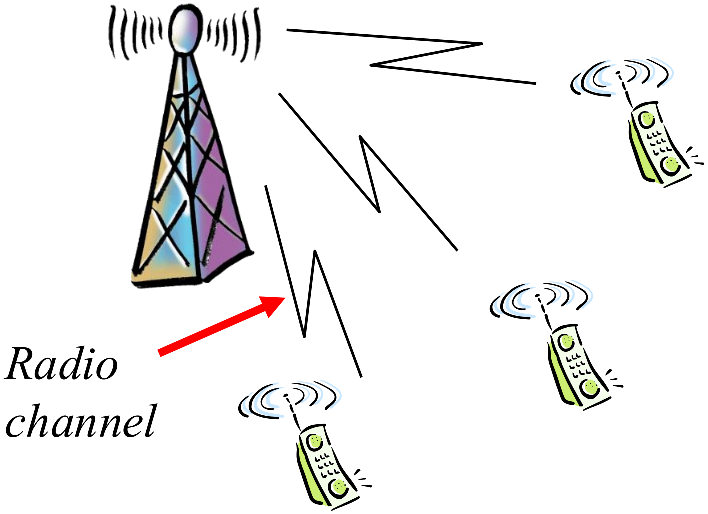
- In multi-hop operation mobile stations can forward information



Wired-Wireless networks: Main differences

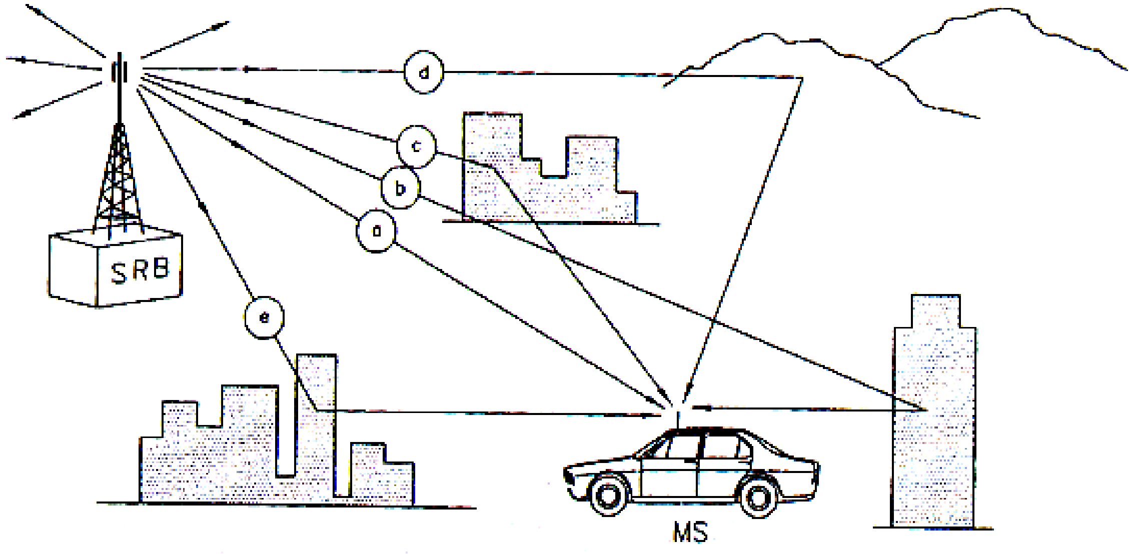
- Shared transmission medium
  - Multiple access mechanisms
  - Radio resource reuse





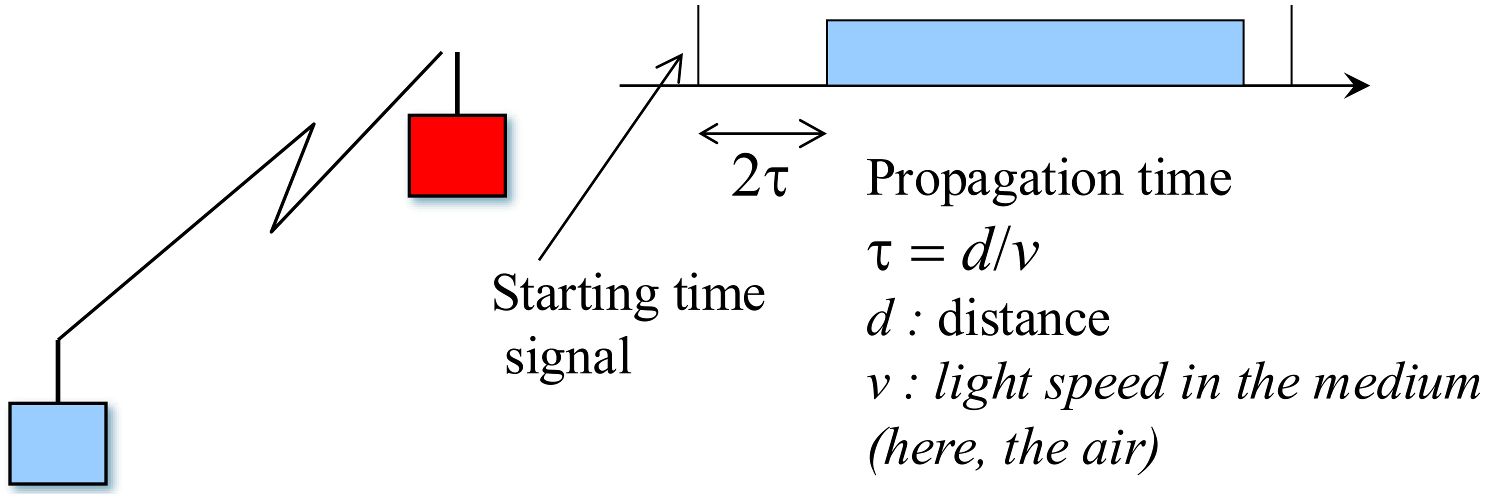
Wired-Wireless networks: Main differences

- Radio channel
  - Variable channel characteristics
  - Advanced modulation and coding schemes



Centralized broadcast channel

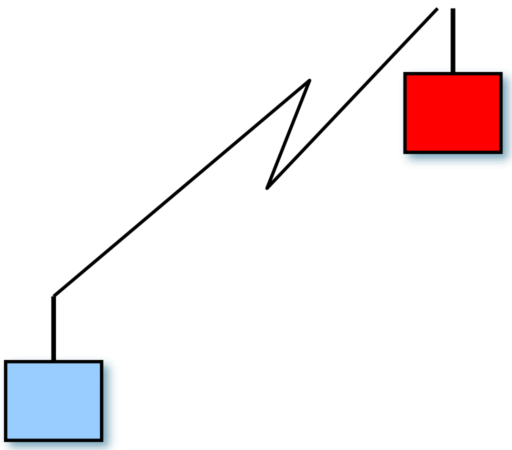
- The Base Station is vital to enforce synchronization among mobile terminals
- Its transmissions are used to synchronize all transmissions (e.g., sending a signal to say when the frame starts)

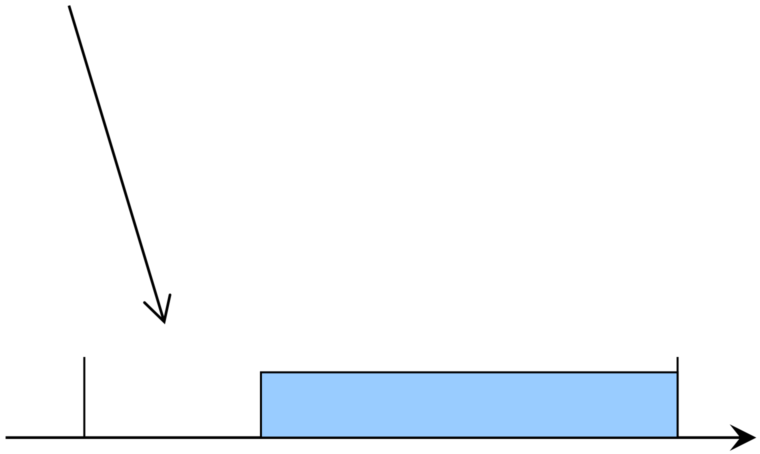


Centralized broadcast channel

- **Guard time:**

$$T_g = \max_i(2\tau_i)$$

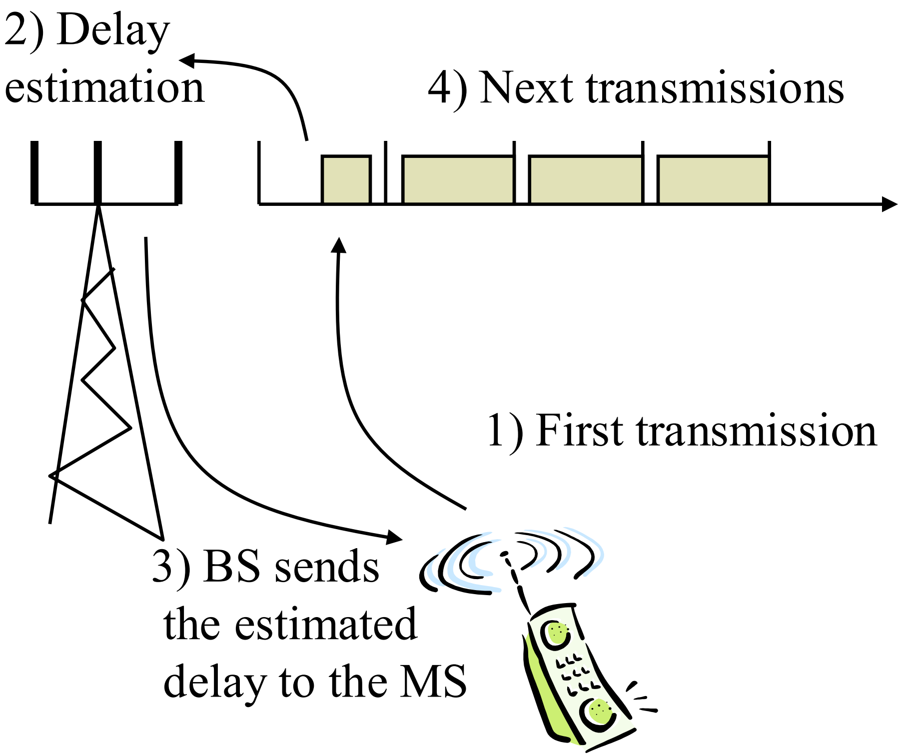




Obviously: the guard time is dominated by the ***farthest*** *node from the BS*

Centralized broadcast channel

- Timing Advance:
  - If each node knows the propagation delay towards the BS, it can anticipate its transmission!
  - Propagation delay τ must be estimated (it can be time-varying)
  - Estimation error is still possible: time guards are reduced, but they are not null!
  - Technique used in GSM



Timing Advance in GSM

- **GSM is designed for cells with a radius of up to Rmax=37.8 km**
- **The guard time should then be $2\tau = 2 \times 35 / 3 \times 10^8 =$ 233 µs**
- **which is equivalent to 68,25 bits at carrier rate of 270.8 kbit/s**

Efficiency

$$\eta = \frac{T_i}{T_i + T_g} = \frac{1}{1 + \frac{T_g}{T_i}} = \frac{1}{1 + T_g \frac{C}{n_i}}$$

- **It depends on the ratio T_g/T_i**
- **The efficiency decreases:**
  - **When distances from the BS increase (T_g increases)**
  - **When the channel speed C increases**
  - **When the slot duration decreases**

CDMA
Code Division Multiple Access

- In CDMA it is impossible to have perfect synchronization among different nodes' transmissions

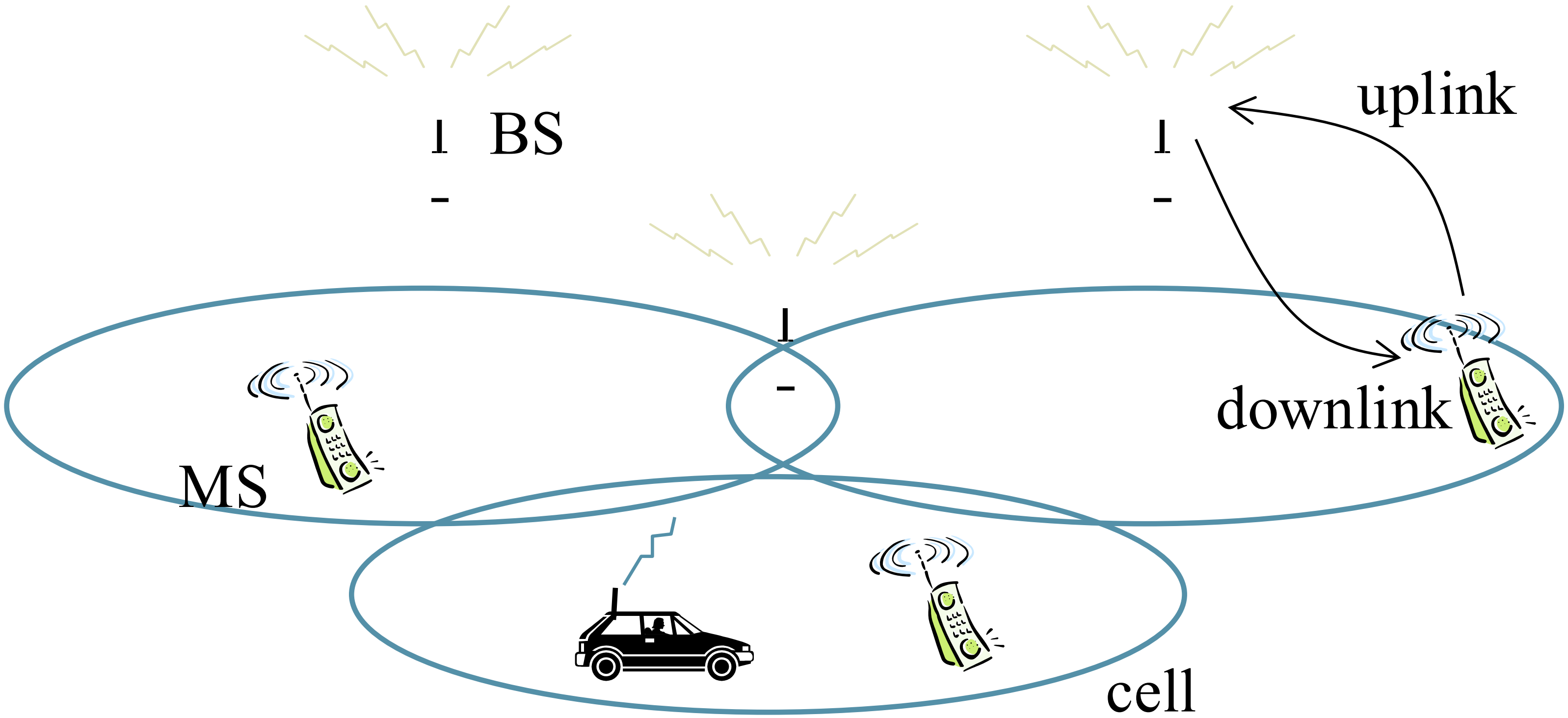
$$\int_0^T C_1(t) \cdot C_2(t) \neq 0$$

- Hence code orthogonality is *lost*
- We use codes with very low correlation for every possible time shift Δ among themselves

$$\int_0^T C_1(t) \cdot C_2(t+\Delta)$$

- Used in 3rd generation systems (UMTS)

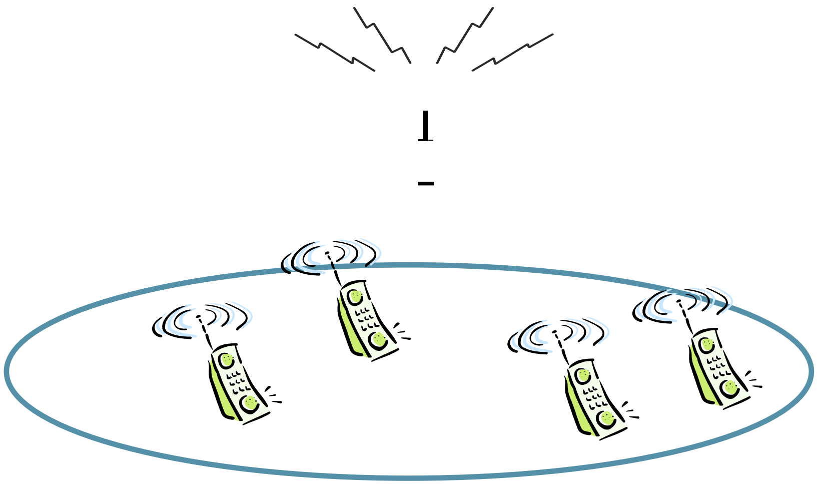
Cellular (Mobile) Systems



MS = Mobile Station
BS = Base Station

Uplink = from the MS to the BS
Downlink = from the BS to the MS

Multiple Access in Mobile Radio Networks

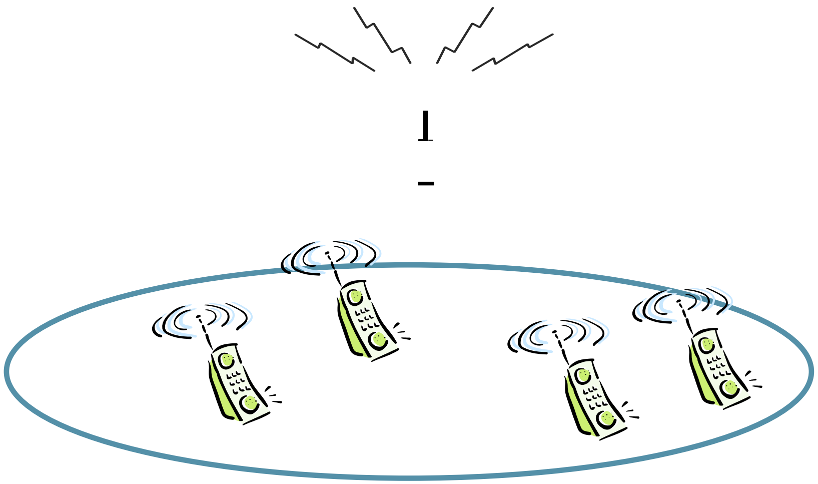


- Radio resource sharing among different communication flows among base stations and user terminals

- downlink:
  - Multiplexing of flows towards mobile users

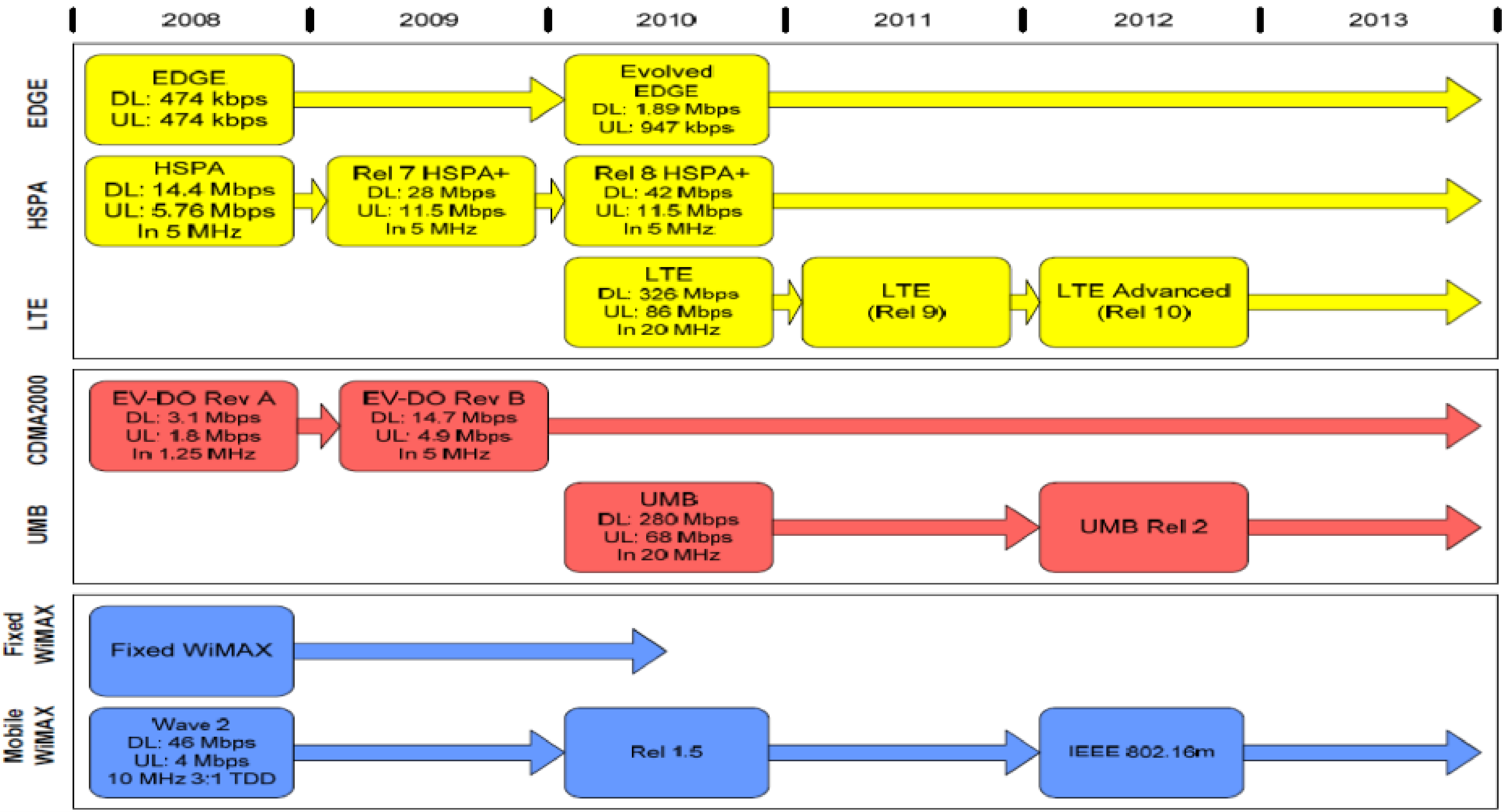
- uplink:
  - multiple access of mobile stations

Radio Access



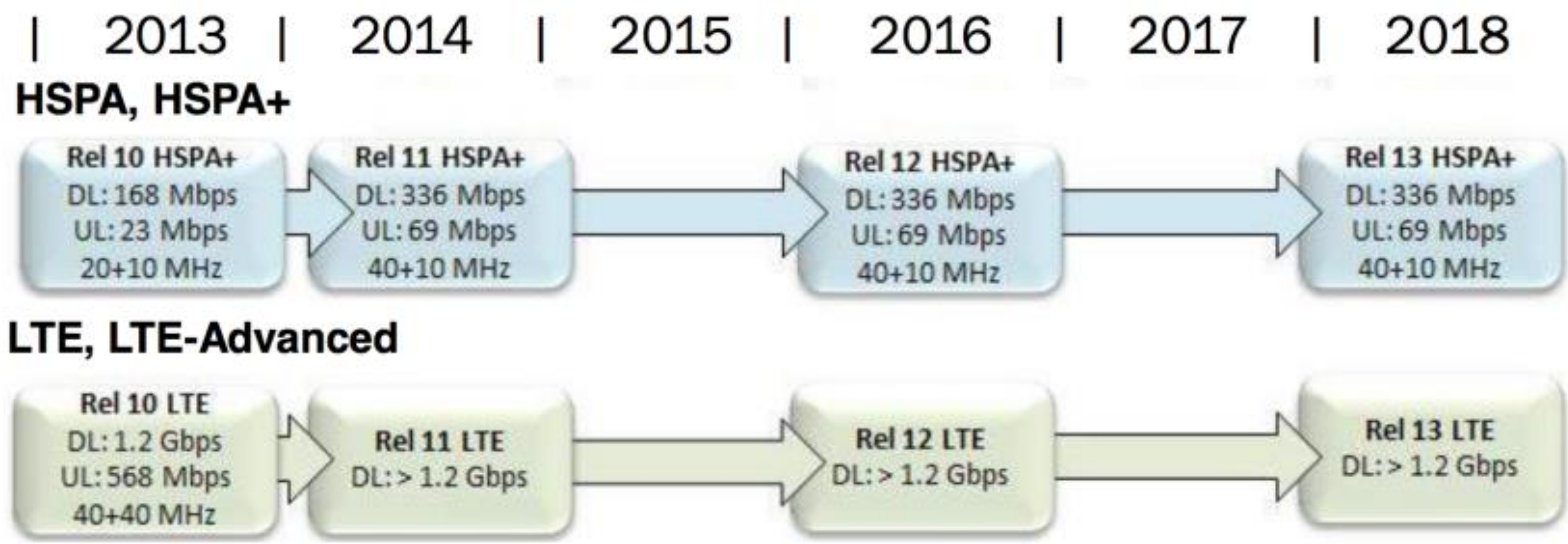
- First generation systems:
  - TACS (Europe) AMPS (US)
  - FDM/FDMA (downlink/uplink)
- Second generation:
  GSM (Europe and then worlwide)
  D-AMPS (US)
  - multi-carrier TDM/TDMA
- Third generation:
  UMTS
  CDM/CDMA
- Fourth generation:
  LTE (Long Term Evolution), OFDM/OFDMA

Evolution CDMA/OFDMA/TDMA



Notes: Throughput rates are peak theoretical network rates. Radio channel bandwidths indicated.
Dates refer to expected initial commercial network deployment except 2008 which shows available technologies that year.
No operator commitments for UMB.

Evolution CDMA/OFDMA/TDMA



HSPA= High Speed Packet Access (aka 3.5G, 3G+ …)
Imrpoves data rate in networks based on UMTS

Evolution After 2018: 5G NR → 5G-Advanced

2019	2020	2022	2024	2025+
Rel-15 *5G Phase 1* NR (NSA/SA) First commercial wave	**Rel-16** *5G Phase 2* URLLC, industrial V2X, positioning	**Rel-17** Expansion RedCap (e.g., IoT) NTN (satellite)	**Rel-18** "5G-Advanced" RAN evolution AI/efficiency push	**Rel-19** 5G-Advanced (cont.) More XR/AI Bridge toward 6G

V2X= Vehicle-to-Everything.

RedCap = Reduced Capacity

NTN= Non Terrestrial Networks

XR = Extended Reality

Many early networks used **NSA** mode, meaning **Non-Standalone**: the 5G radio was added on top of an existing LTE core network. Then **SA**, **Standalone**, comes when 5G runs with a **5G Core** without needing LTE as the anchor.

After 2018, LTE continues in parallel, but the main evolution path becomes 5G New Radio (NR, Rel-15 → Rel-19). Rel-18+ is commonly referred to as **5G-Advanced.**

After 2018: What Changes in Multiple Access & Multiplexing

1) The basic idea stays the same

Users are multiplexed on a time–frequency grid via scheduling --> The base station assigns small chunks of time and frequency—called **resource blocks**—to different users.
5G New Radio (NR) is still OFDM/OFDMA-based at its core (like LTE).

2) 5G becomes much more flexible

Multiple *numerologies* (different subcarrier spacings and slot durations) adapt to bands and latency needs.
More dynamic TDD (In **TDD**, **uplink (UL)** and **downlink (DL)** use the **same frequency band**, but they take turns **in time**), mini-slots, and tighter latency tools for specific services.

3) The <u>spatial</u> dimension becomes central

Massive MIMO + beamforming enable spatial multiplexing: multiple users/streams in the same time–frequency resources.
Capacity gains come increasingly from spatial processing (not only more bandwidth).

Toward 6G: IMT-2030 and Beyond

5G-Advanced as a bridge (Rel-18/Rel-19)

Continues improving spectrum efficiency, energy efficiency, and mobility.
Adds stronger AI/ML-based optimization and new features (XR, positioning, sensing).

International Mobile Telecommunications (IMT-2030) vision (often called "6G")

ITU's IMT-2030 framework defines goals for the next generation toward the 2030 time frame.
Focus: extreme performance, sustainability, and tighter integration of communication + sensing + computing.

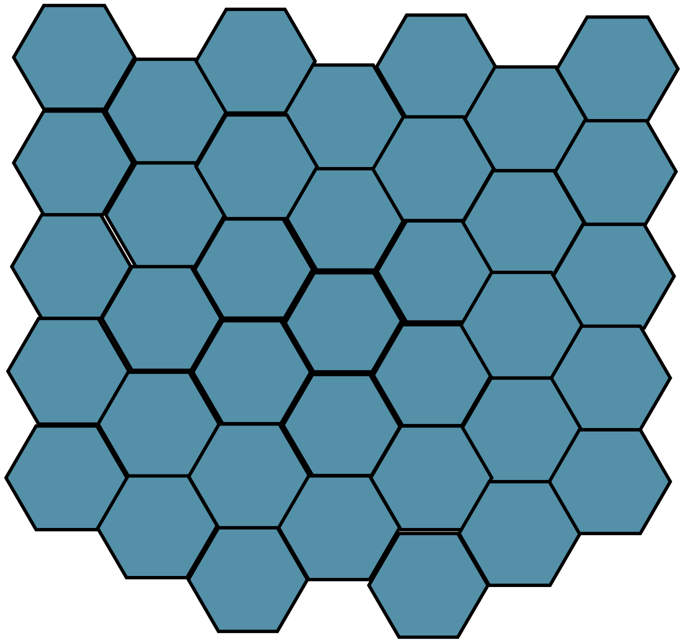
Key takeaway: after 2018 the waveform family remains OFDMA-based, but flexibility (numerology), spatial multiplexing, and system intelligence increase dramatically.

Frequency reuse

- Available frequencies are <u>not</u> sufficient for all users
- Solution: we reuse the same frequency in different cells (*spatial reuse*)
- Spatial reuse causes *co-channel interference*
- Spatial reuse is made possible if cells are sufficiently far apart so that interference can be small/tolerable (in order to guarantee a good quality of the transmitted signal)

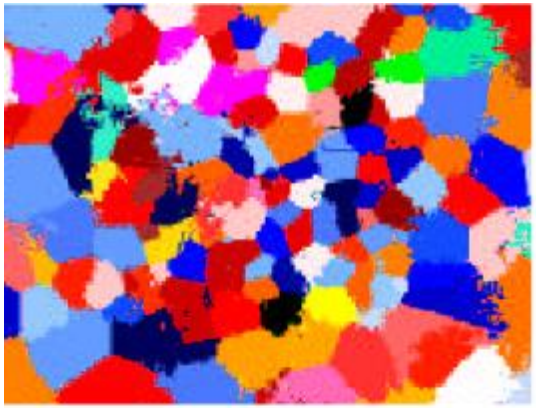
Spatial reuse

- The *interference* is therefore a fundamental, intrinsic feature of cellular systems
- Usually we assume that system quality is good when the ratio between the signal power and the interference power, named *SIR* (Signal-to-Interference Ratio) is higher than a predefined threshold, SIR_{min}



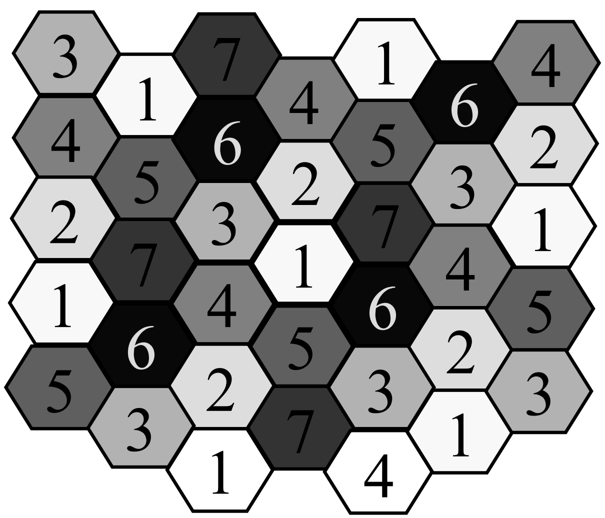
Cell shape

- Traditionally, for describing in a simplified way the structure of cellular systems, the shape of cells is depicted as hexagonal
- Obviously, due to base station positions and non uniform propagation of signals due to obstacles, the real shape of cells is usually much different
- The use of the regular hexagonal shape is however a good approach to make a rough dimensioning of the system and for us to understand the basic principles of reuse

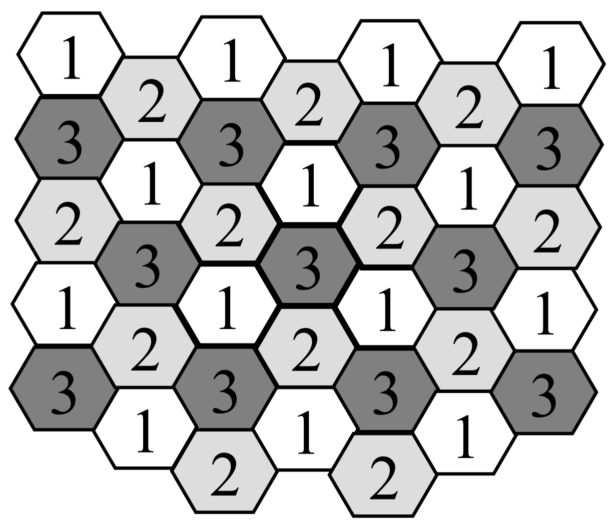


Cluster dimensioning

- All available frequencies are divided into K groups
- We assign a group to each cell in order to maximize the distance between 2 cells that use the same group of frequencies
- Frequency reuse efficiency = 1/K
- Possible K values: K=1,3,4,7,9,12,13, …



K = 7



K = 3

Cluster dimensioning

- If we know/if we set the SIR_{min} value tolerated by the system, then we can estimate the maximal efficiency of the system, i.e., the minimum K value that can be used
- Received power:

$$P_r = P_t \cdot G \cdot d^{-\eta}$$

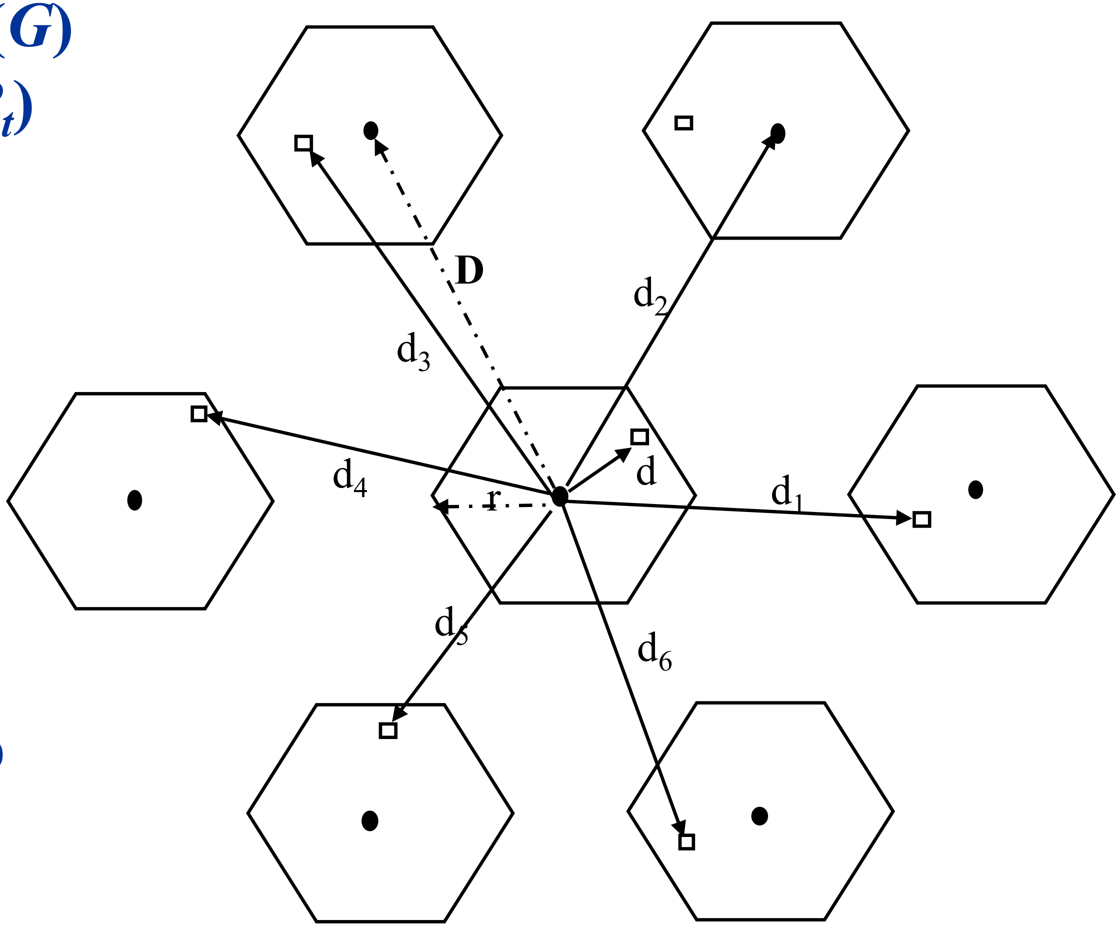
Cluster dimensioning

- **Hip.: same antennas (*G*) and same tx power (P_t)**

$$SIR = \frac{P_t \cdot G \cdot d^{-\eta}}{\sum_{i=1}^{6} P_t \cdot G \cdot d_i^{-\eta}} = \frac{d^{-\eta}}{\sum_{i=1}^{6} d_i^{-\eta}}$$

- **Worst case: $d = r$**
- **Approximation: $d_i = D$**

$$SIR \cong \frac{r^{-\eta}}{6D^{-\eta}} = \frac{1}{6}\left(\frac{1}{R}\right)^{-\eta}$$



Cluster dimensioning

- **The SIR depends exclusively on the reuse ratio *R=D/r* (and on *η*) *but not* on the absolute transmission power or on the cell dimension**
- **If we fix SIR_{min} we can compute R_{min}**
- **Then, if R_{min} is known, we can obtain K since we can observe that:**

$$K = \frac{R^2}{3}$$

- **and therefore:**

$$K_{\min} = \frac{(6\,SIR)^{2/\eta}}{3}$$

Exercise

- **Let us dimension a cluster for a cellular system that tolerates SIR_{min} = 18 dB, considering the case where the path-loss exponent η is equal to 3.9**

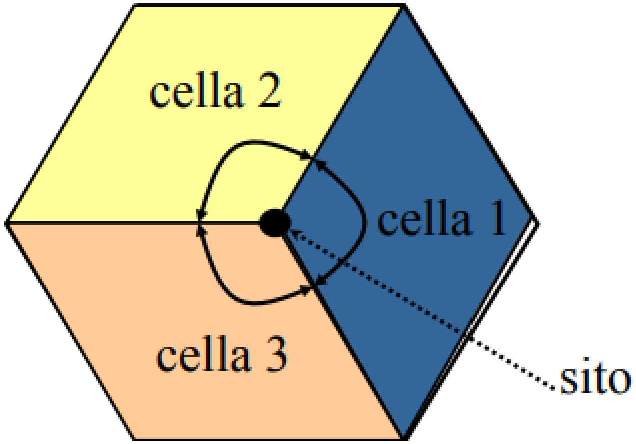
$$K_{\min} = \frac{(6\,SIR)^{2/\eta}}{3} = \frac{(6 \cdot 63.1)^{2/3.9}}{3} = 6.99$$

Cluster dimensioning

- Some key comments:
  - In the model we made several simplifying assumptions
    - Distances
    - Only first ring of interferers
    - No thermal noise
    - Propagation with only path loss
  - The objective of the dimensioning is to guarantee a good SIR to all users and for this reason we have to consider the most critical cases
  - For including fast fading and shadowing we can consider a margin on SIRmin (similarly to what we did for the cell dimensioning)

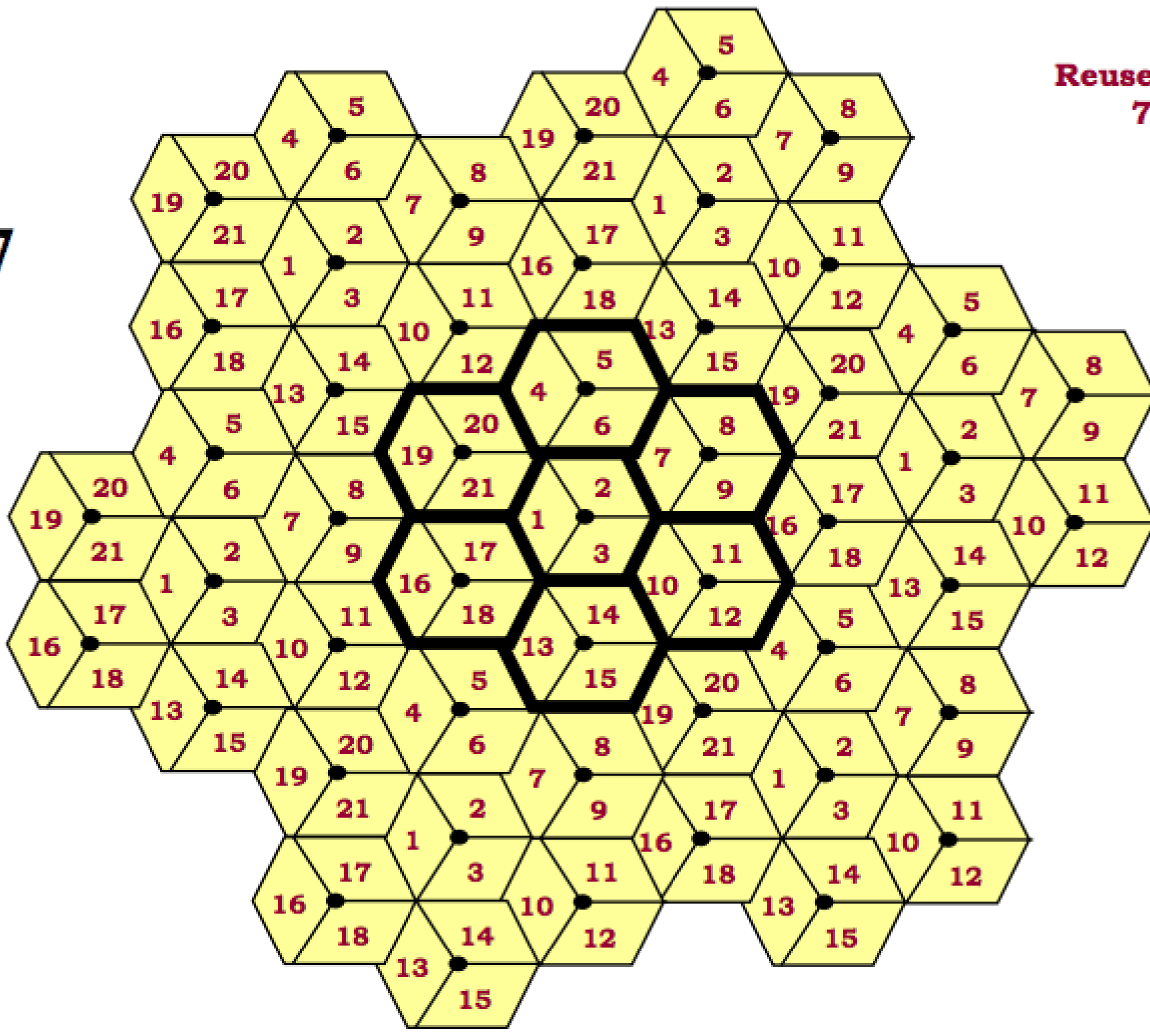
Sectorial antennas

- The use of directive antennas allows to modify the cellular layout and reduce interference received
- In cellular systems the use of directive antennas with a 120° angle of the main lobe is quite common



Reuse with Sectors

K=7



Reuse Pattern
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Reuse with Sectors

- For the SIR we can use the same formula:

$$SIR \cong \frac{r^{-\eta}}{6D^{-\eta}} = \frac{1}{6}\left(\frac{1}{R}\right)^{-\eta}$$

- With a small modification

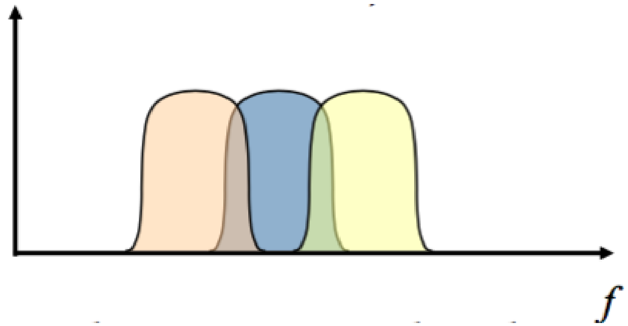
$$SIR \cong \frac{r^{-\eta}}{MD^{-\eta}} = \frac{1}{M}\left(\frac{1}{R}\right)^{-\eta}$$

- Where M is the number of interferers (first ring) visible form a single sector (M=6/#sectors)
- And therefore:

$$K_{min} = \frac{(M \cdot SIR)^{2/\eta}}{3}$$

Assignment constraints

- Once the cluster size is selected, the assignment of *channels* to *cells* is usually subject to additional constraints
- Adjacent frequencies have often slightly overlapped spectrum and therefore can generate mutual interference (adjacent channel interference)



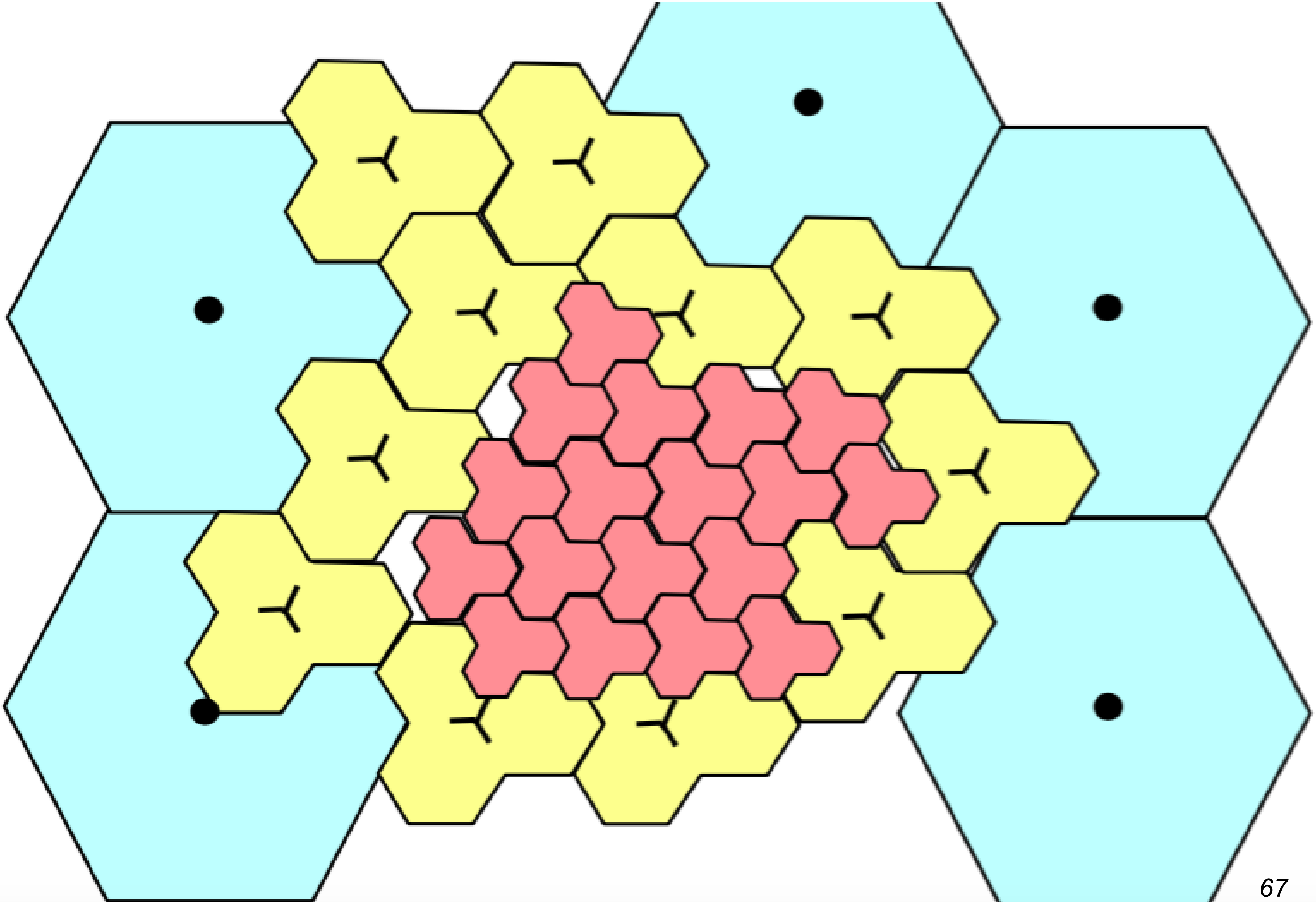
- The problem can be more complex due to sectors that usually have secondary lobes in the antenna diagram that generate interference in the neighboring cells
- As a results it is not usually possible to assign adjacent frequencies to cells of the same site

Cellular layouts

- Important observation:
- The simplified formula for cluster dimensioning does not depend on the cell radius but only on the distance ratios

- Varying the cell radius we can vary the number of channels available per unit area
- This gives us the freedom to plan the cellular layout (cell sizes) based on the traffic density estimated in different areas

Cellular layouts



Summary

- dB
  - Logarithmic scale
  - If we use absolute powers

$$P_{dB} = 10\log_{10} P$$

$$P = 10^{P_{dB}/10}$$

Summary

- The *product* in linear scale corresponds to a *sum* using dB
- The *ratio* corresponds to a *difference* in dB

$$G \cdot P \rightarrow G_{dB} + P_{dB}$$

$$P / A \rightarrow P_{dB} - A_{dB}$$

Summary

- **Notable values**

$$2 \rightarrow 3dB$$

$$3 \rightarrow 4.77dB$$

$$4 = 2 \cdot 2 \rightarrow 3 + 3 = dB$$

$$5 \rightarrow 7dB$$

$$6 \rightarrow 7.77dB$$

$$8 \rightarrow 9dB$$

$$9 \rightarrow 9.54dB$$

$$10 \rightarrow 10dB$$

$$100 \rightarrow 20dB$$

$$1000 \rightarrow 30dB$$