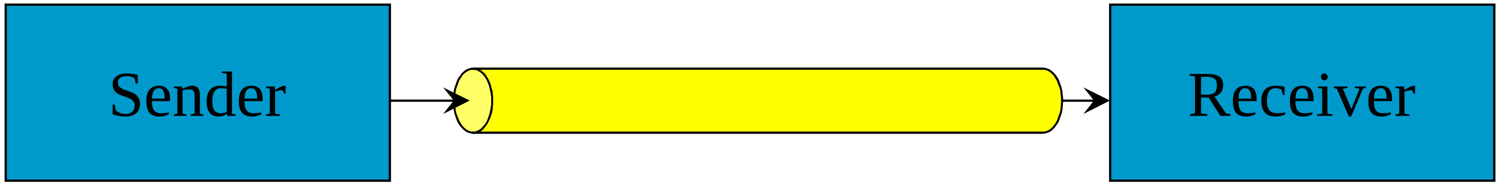
POLYTECH
PARIS-SUD

Réseaux

Channels and Multiplexing

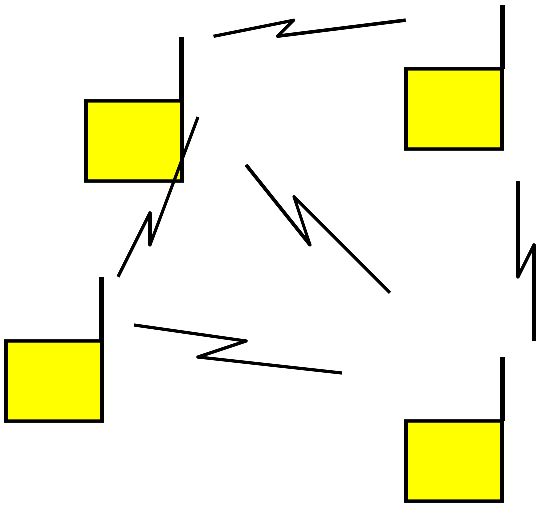
Point-to-point Channels

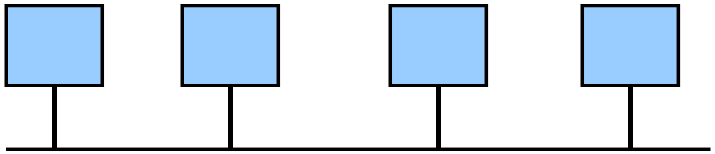
- **They are permanent connections between a sender and a receiver**
- **The receiver can be designed and optimized based on the (only) signal it must receive**
- **Data transmission can be *continuous* or divided into *frames* (this raises synchronization problems)**



Broadcast Channels

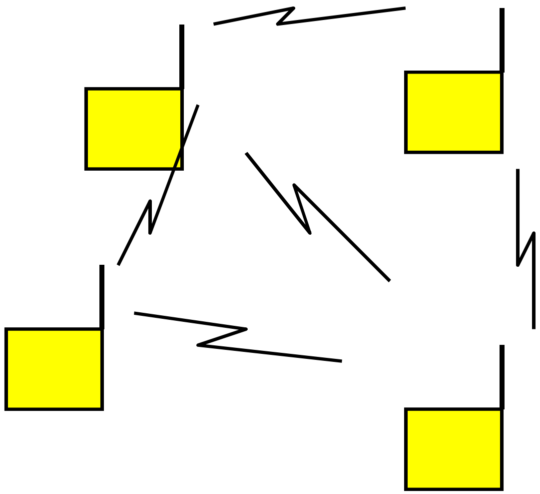
- Many stations/nodes can access a broadcast channel in parallel. The channel is «shared» among all stations
- The transmissions of a station reaches all other stations

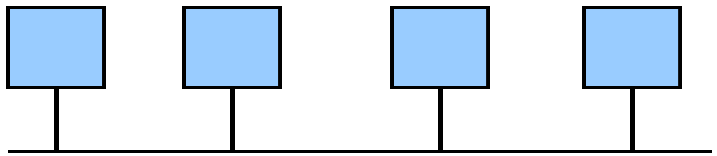




Broadcast Channels

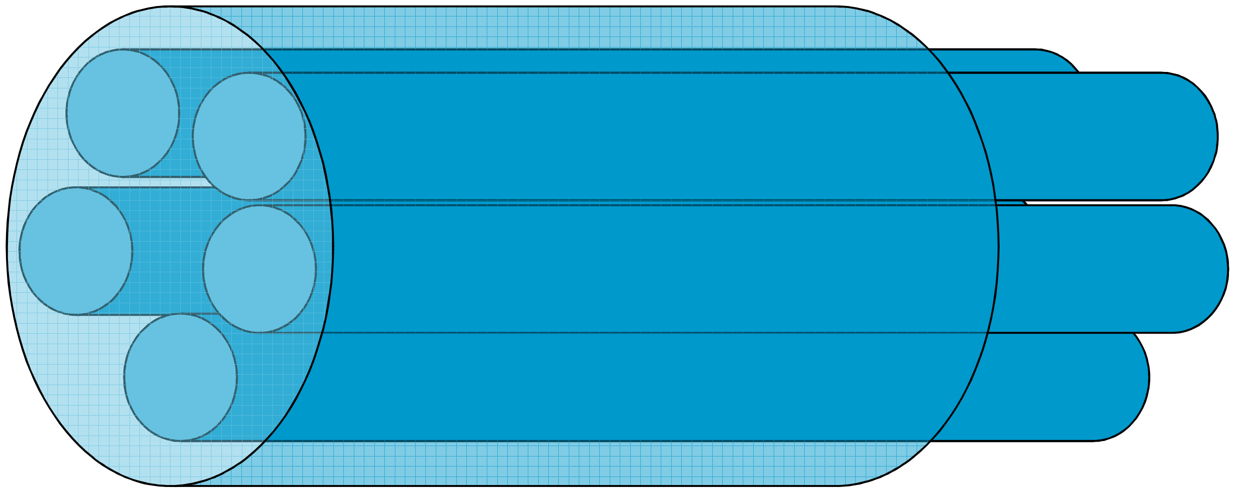
- The receiver can receive several transmissions which differ in their *power level* and *synchronization*, and it must be able to adapt itself to such differences, and single out the right transmission
- Transmissions usually start with a *preamble* (*synchronization character*) to achieve synchronization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





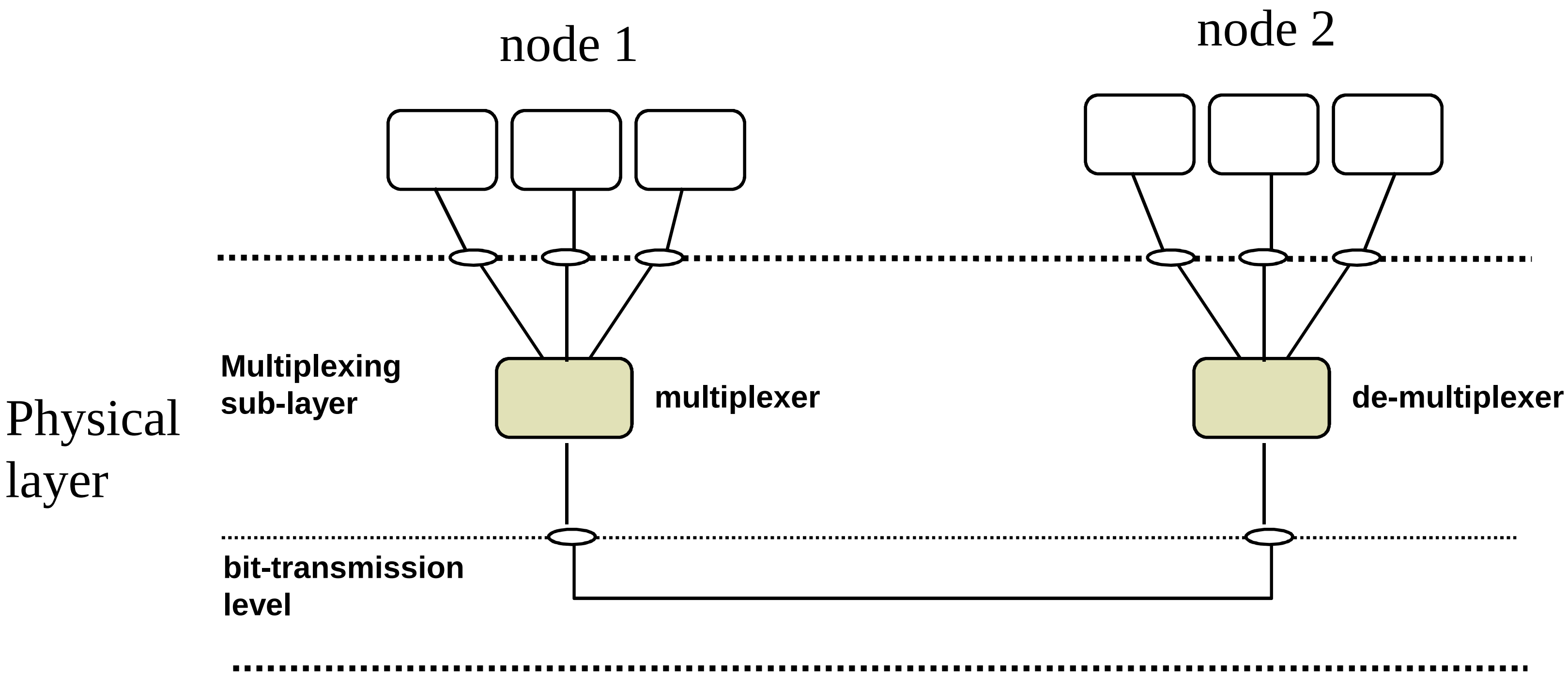
Multiplexing

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



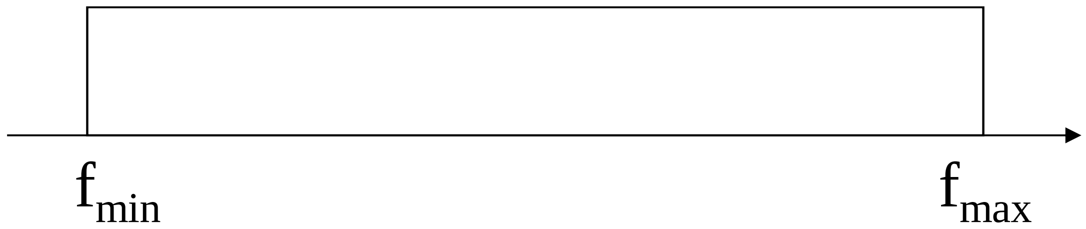
Physical Multiplexing

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

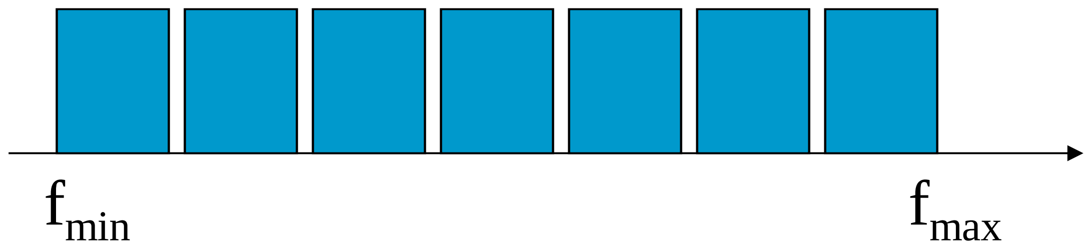


FDM (Frequency Division Multiplexing)

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

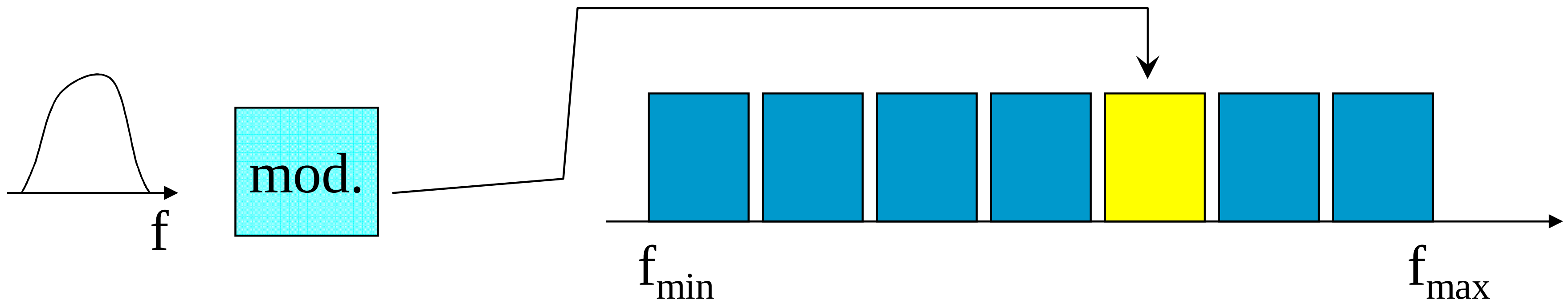


- **Such bandwidth can be divided into sub-channels, and we can associate a communications to each sub-channel**

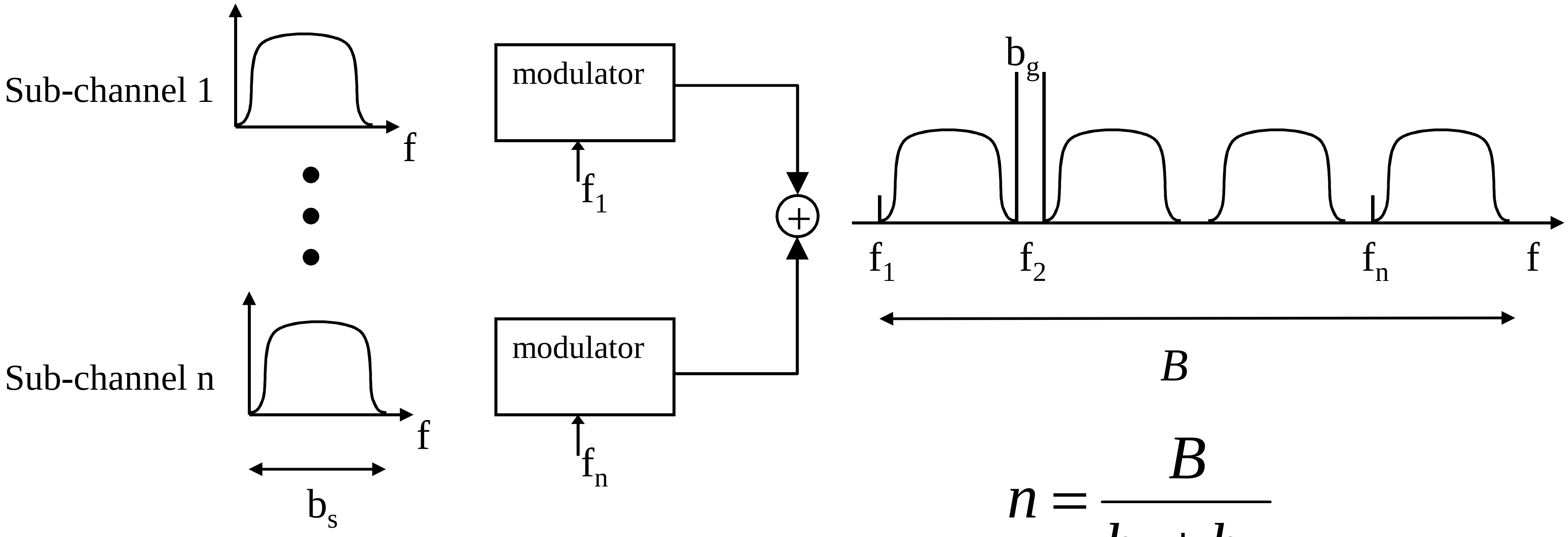


FDM (Frequency Division Multiplexing)

- 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)



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

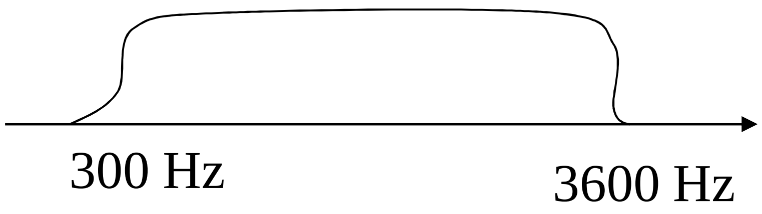
$B = total\ available\ bandwidth\ (f_{max} - f_{min})$

$b_s = signal\ bandwidth$

$b_g = guard\ band$

FDM - Telephony

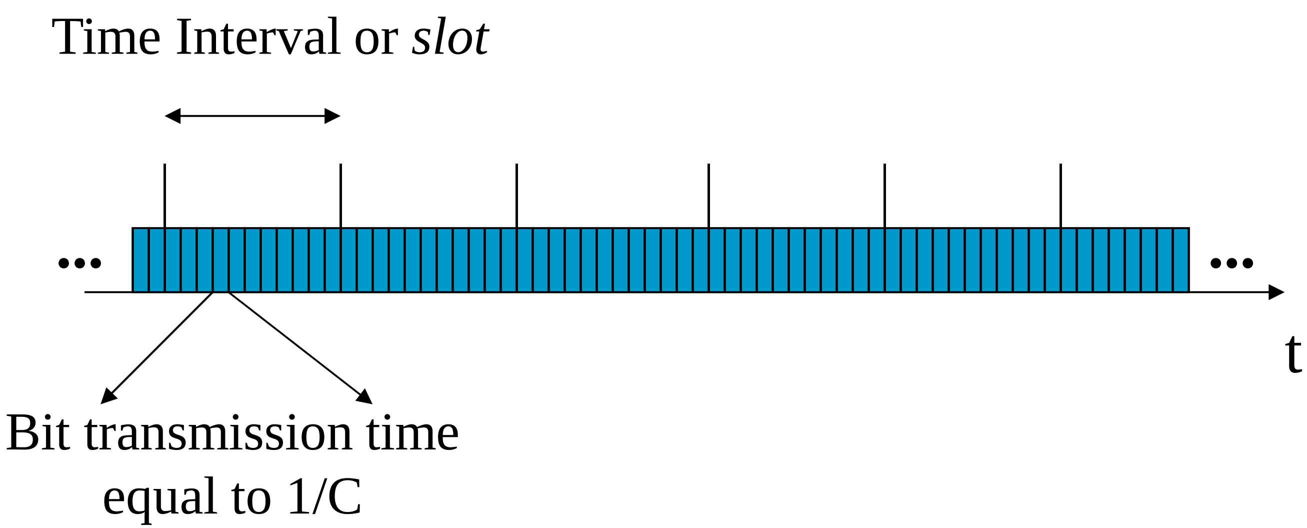
- **In the past, FDM was used as a multiplexing technique to transmit voice calls between phone centrals**
- **Voice call bandwidth: approximately 4 kHz**



- **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)**

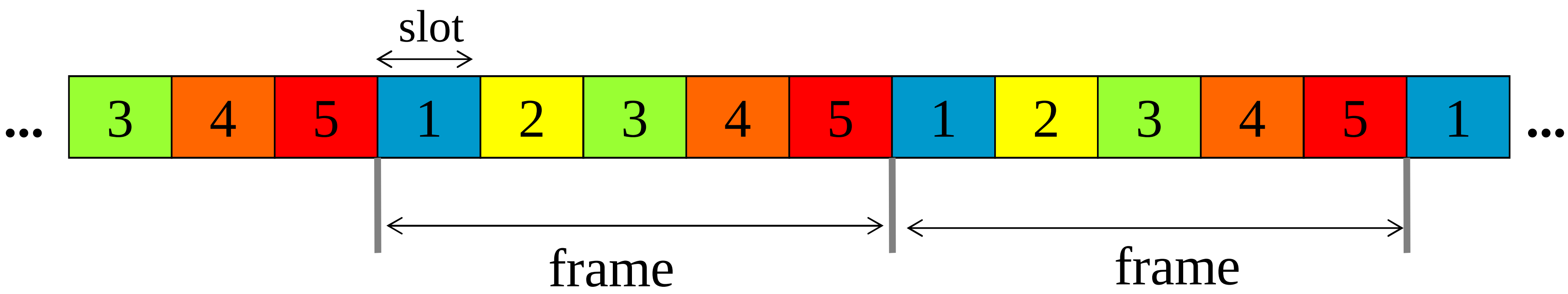
TDM (Time Division Multiplexing)

- **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 $t_b=1/C$**

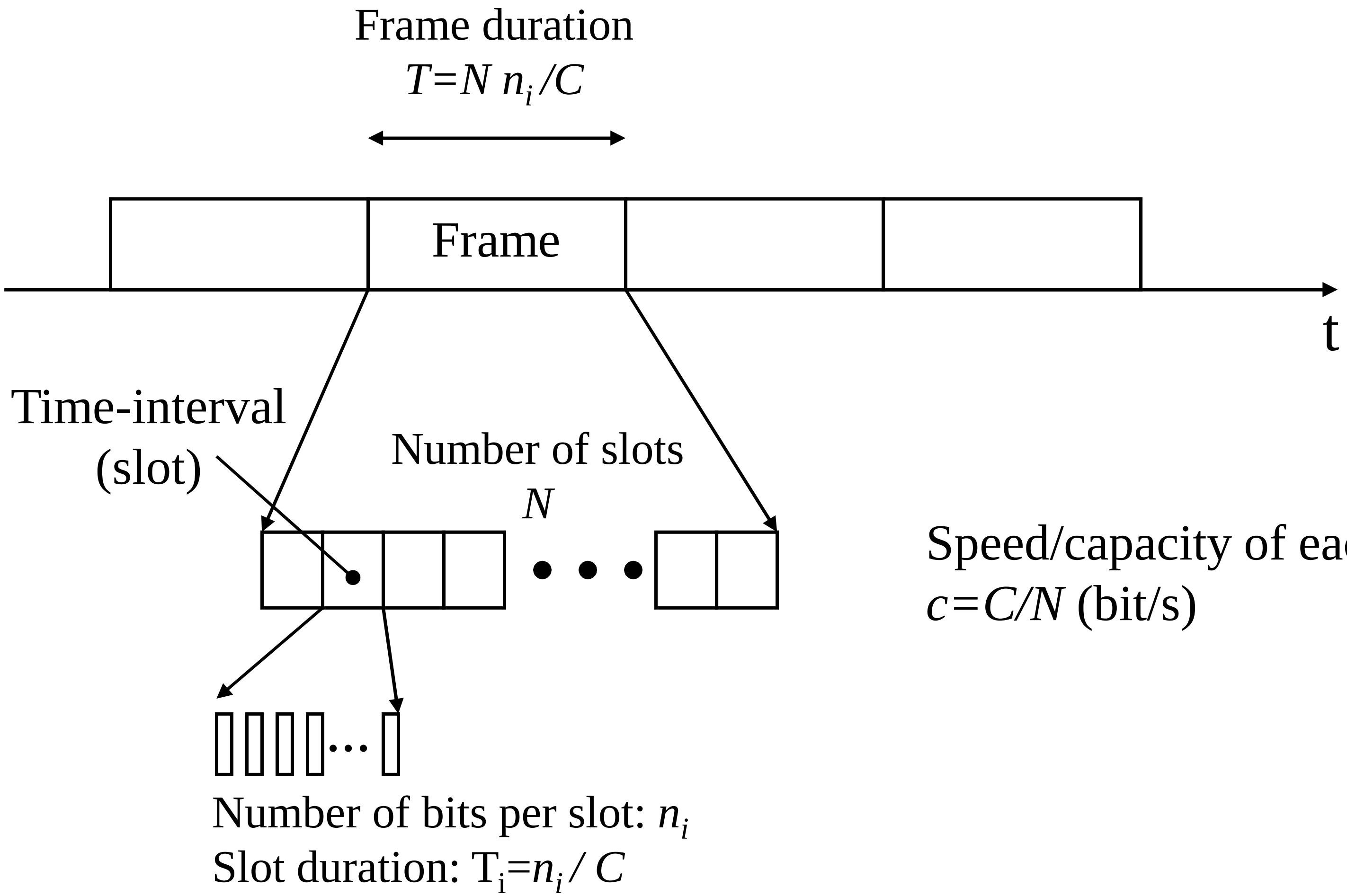


TDM (Time Division Multiplexing)

- **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**



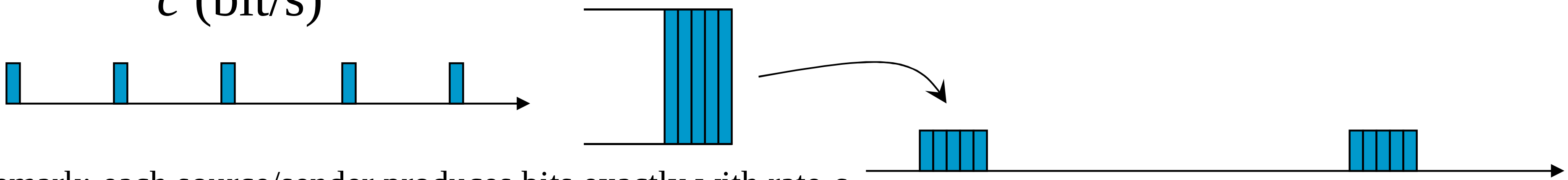
TDM (Time Division Multiplexing)



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* <u>does not</u> depend on T_i but <u>only</u> on *N* ($c = C/N$)**
- **Time to collect n_i *bits*: $T_a = n_i / c$**



<u>Remark</u>: 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 <u>begins</u>.
Clearly, the source needs n_i / c seconds to produce and accumulate the n_i bits

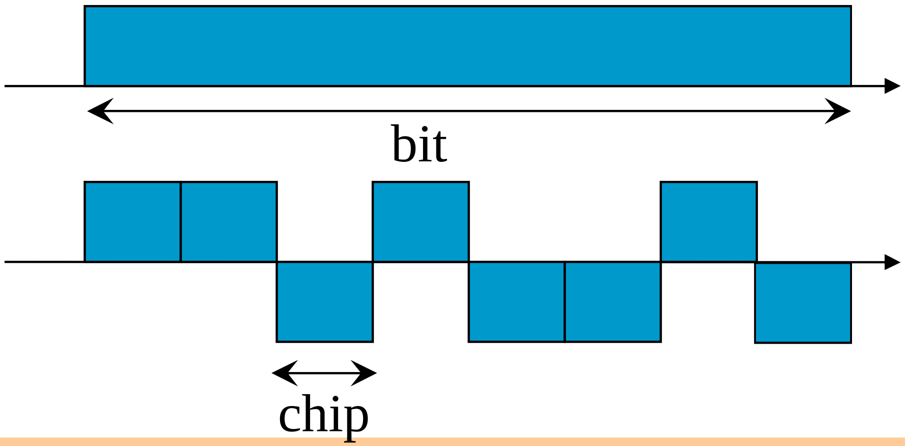
Exercise

- **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)

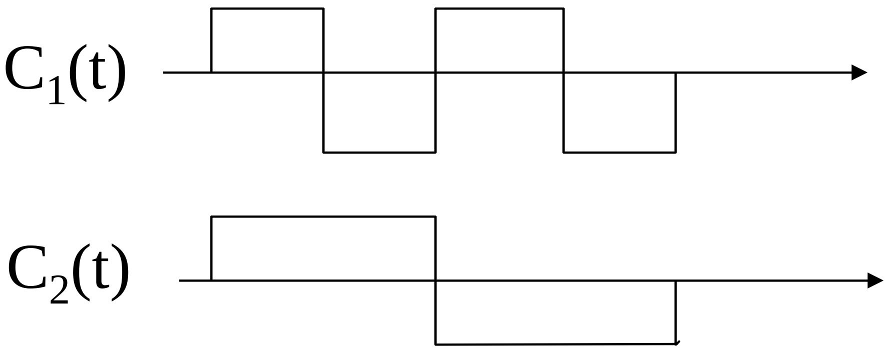
- The CDM technique consists in mixing (i.e., adding) *N* bit flows (N transmissions), just after having multiplied each one of them with a <u>codeword</u> C_i chosen among the *N* codewords of an orthogonal code
- Codewords are constituted by *N* binary symbols, called *chips* in order to distinguish 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:

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

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

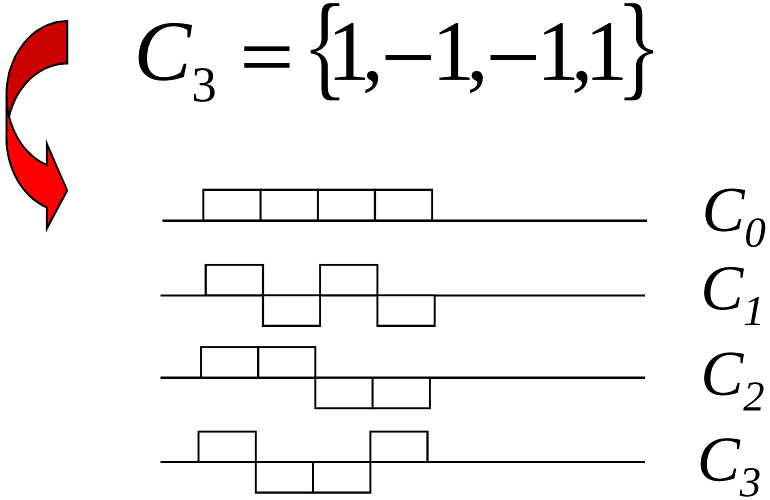
Example for N=4

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

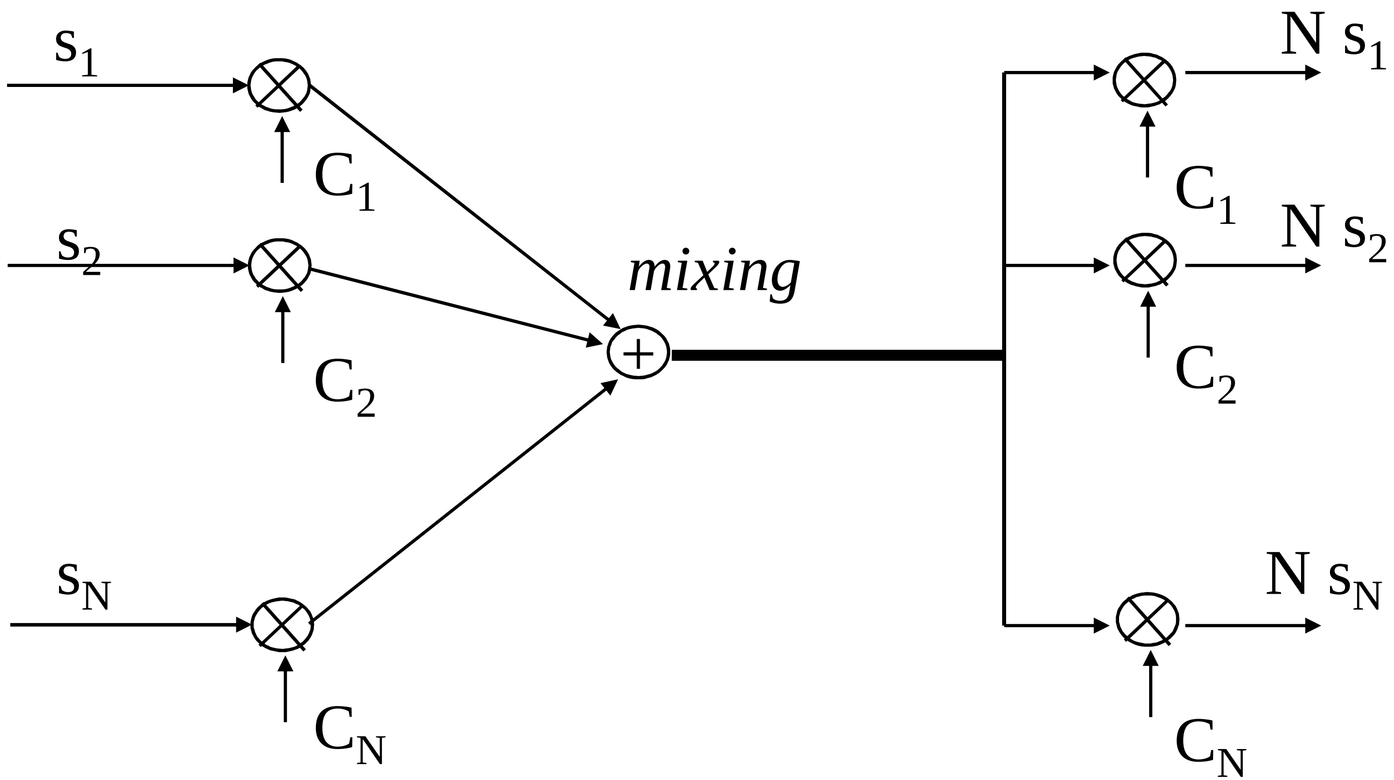
$$C_1 = \{1,-1,1,-1\}$$

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

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



CDM (Code Division Multiplexing)



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

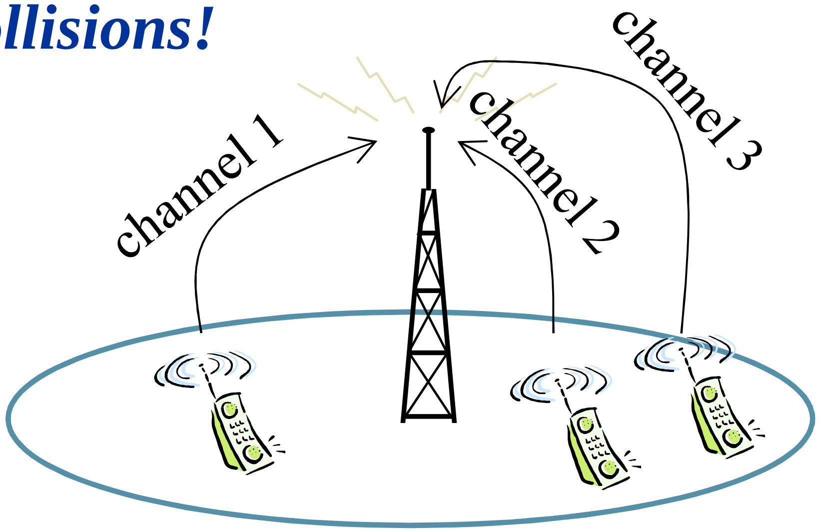
$$\left(\sum_{i=1}^{N} s_i C_i \right) \cdot C_k = N \cdot s_k$$

WDM (Wavelength Division Multiplexing)

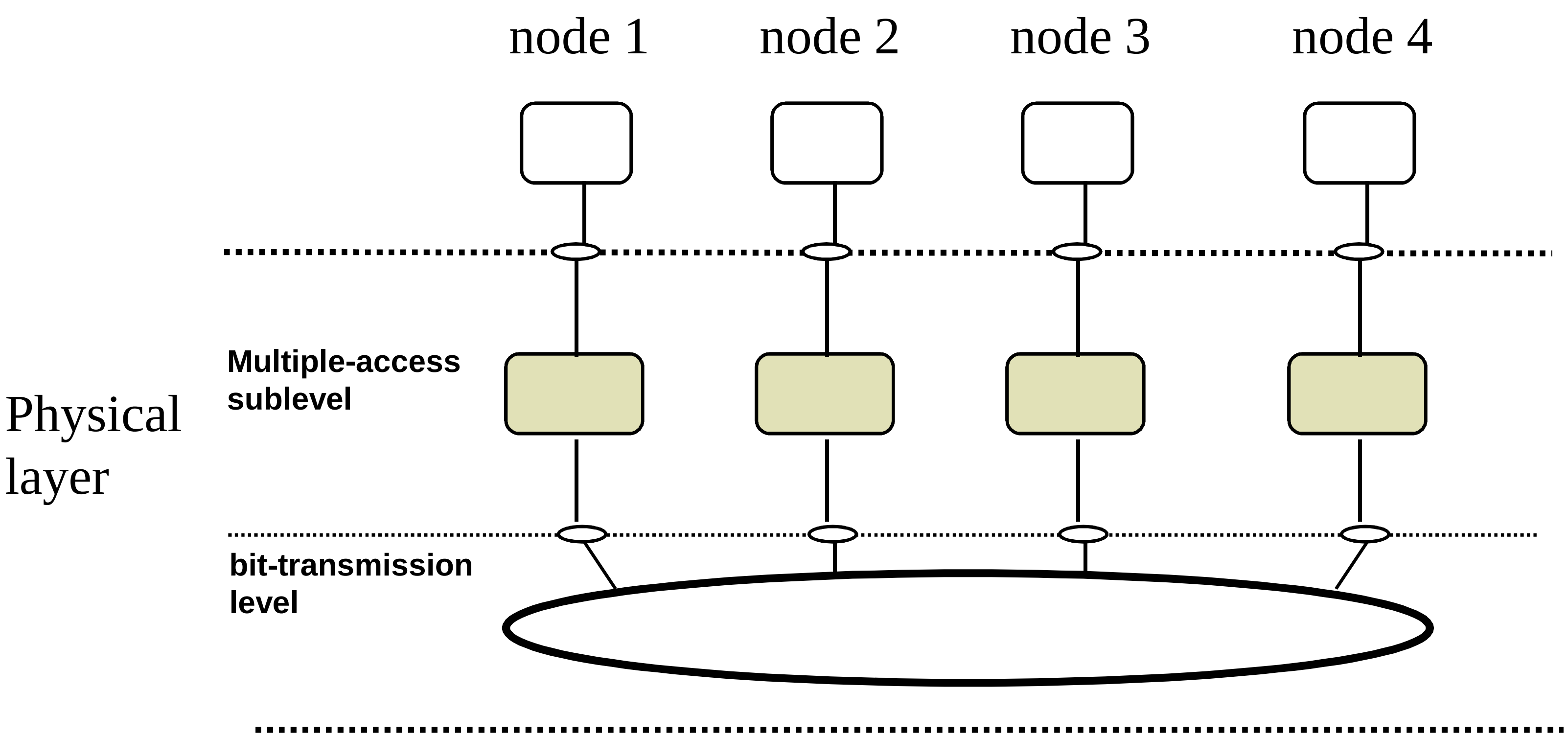
- **It's the same as FDM; it is called WDM for historical reasons, related to the development of optical fibers**
- **Different signals are modulated using different wavelengths on optical fibers**
- **Each wavelength can carry huge amount of information (5-10 Gbit/s)**
- **Technological limit: related 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

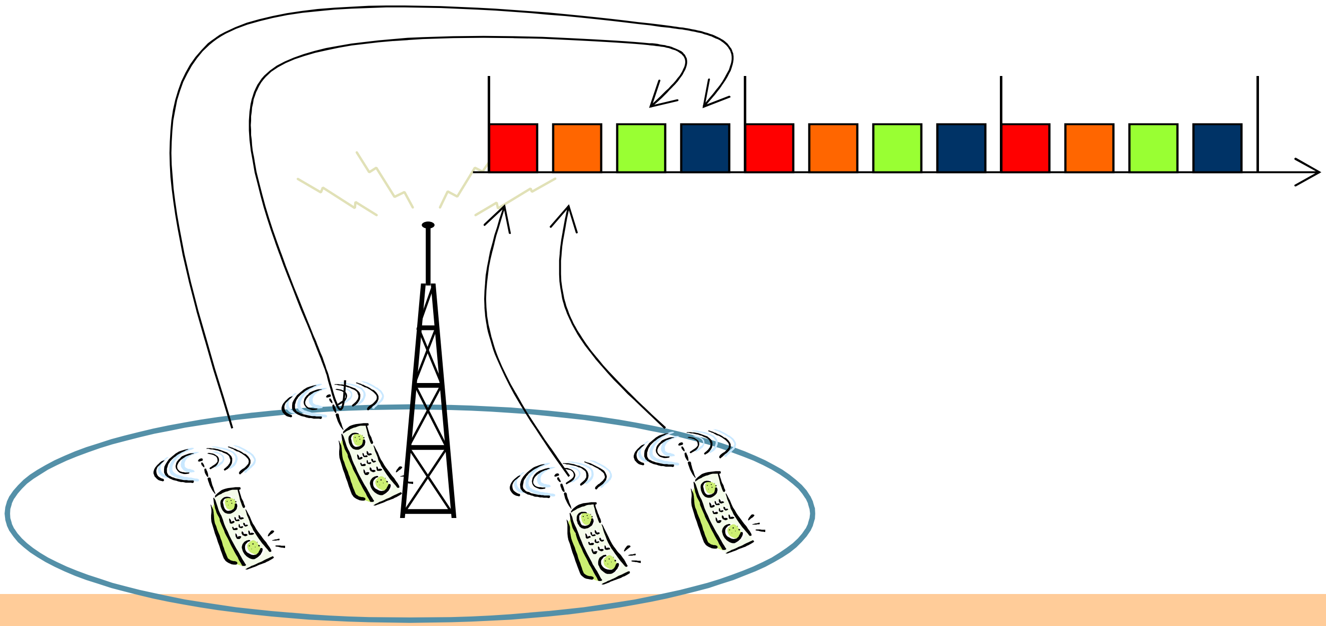


FDMA
Frequency Division Multiple Access

- **It’s analogous to FDM**
- **Different nodes/stations need to coordinate to access the channel, but this is not a problem with FDMA**
- **Examples:**
  - **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

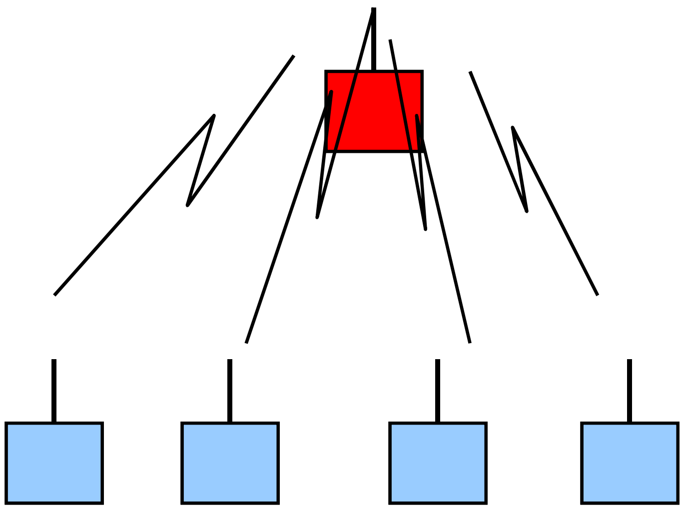
- It’s similar to TDM …
- … but here it is necessary for stations to coordinate among themselves to find a common timing reference (necessary to know when slots/frames start and end)
- Synchronization cannot be perfect: *guard times* are necessary to avoid overlapping

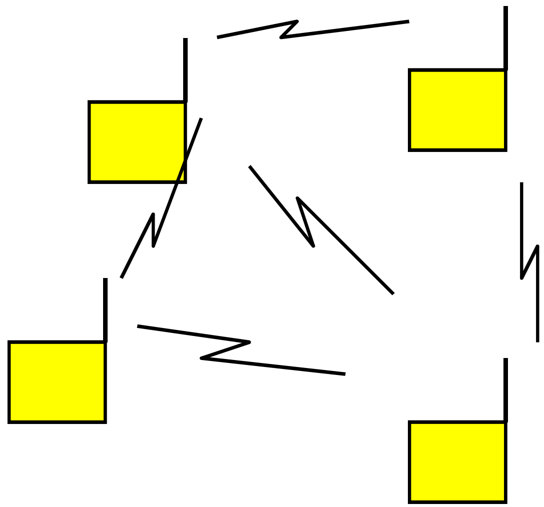


Broadcast channel

Centralized broadcast channel

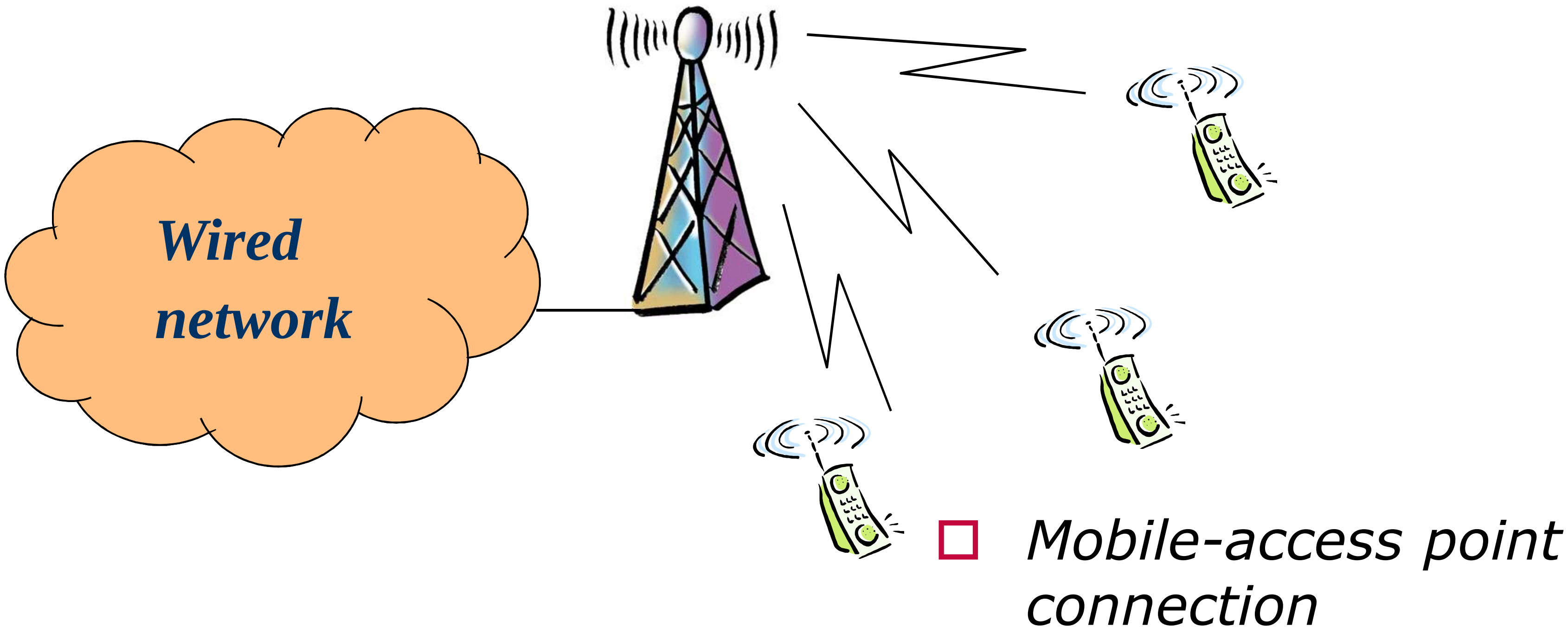
Distributed broadcast channel





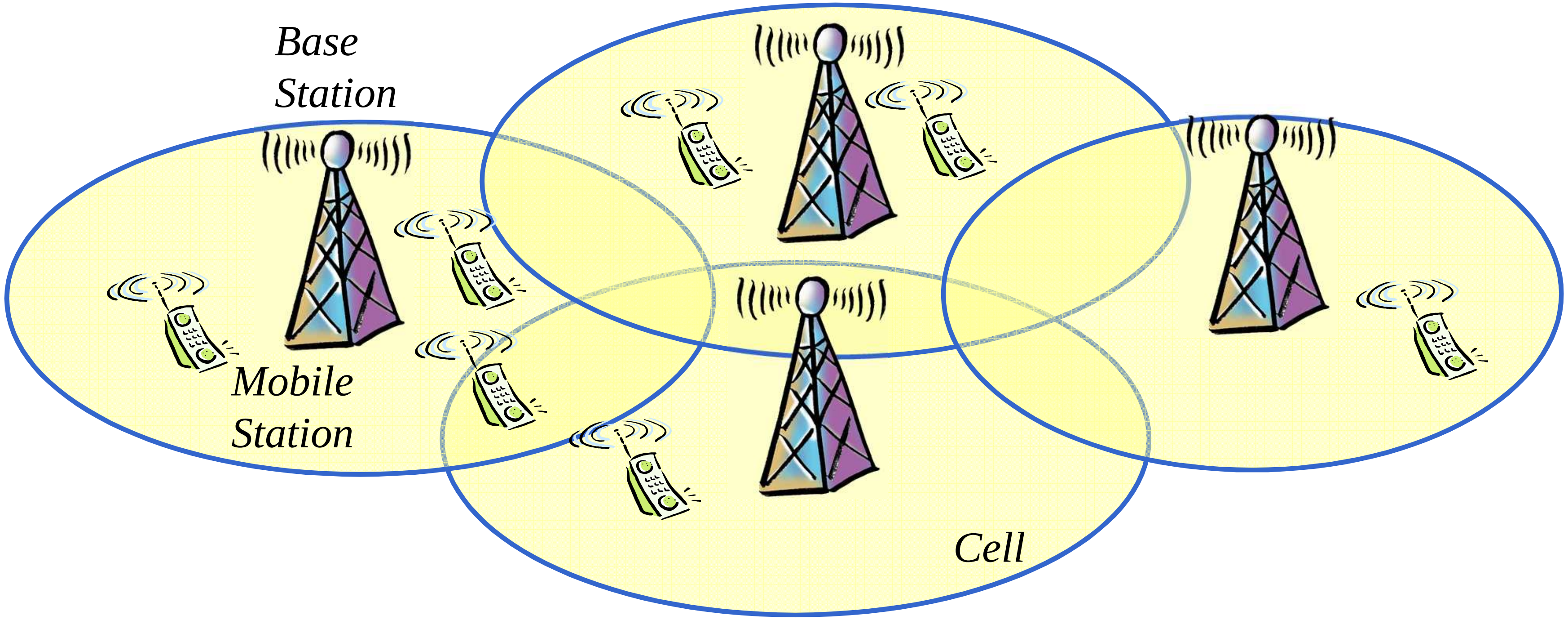
Centralized broadcast channel

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



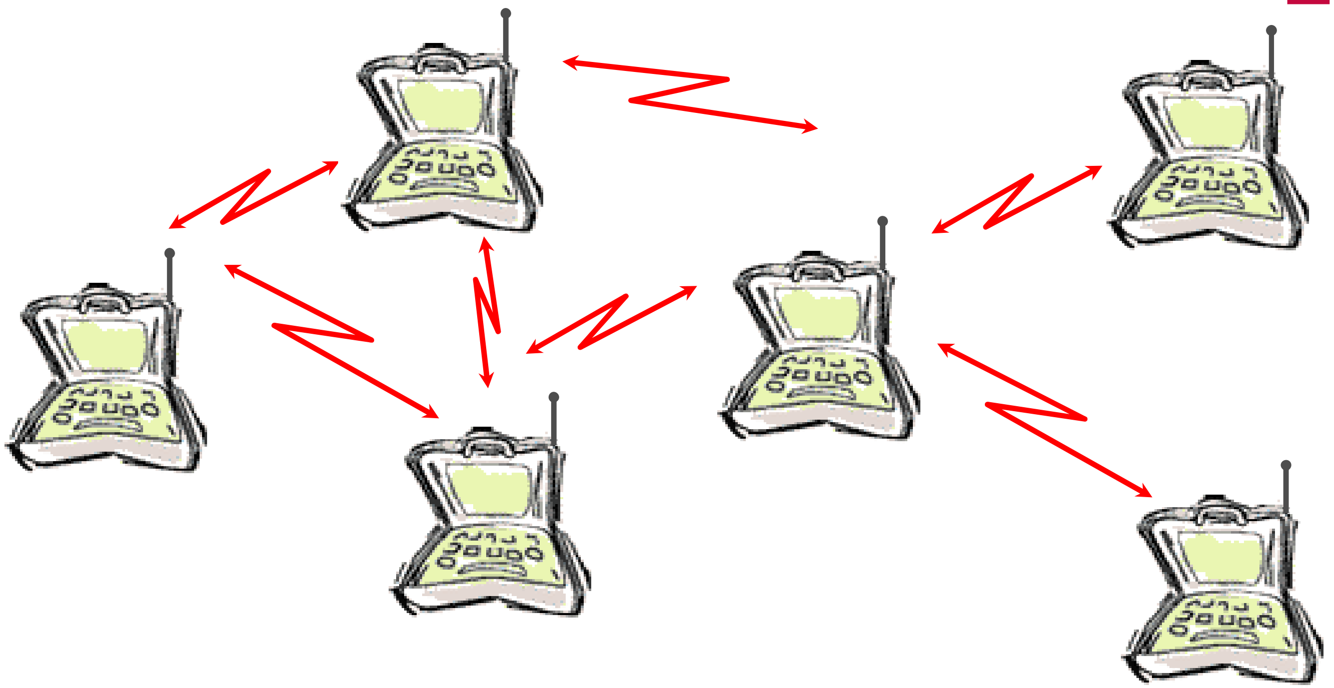
Centralized broadcast channel

- **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

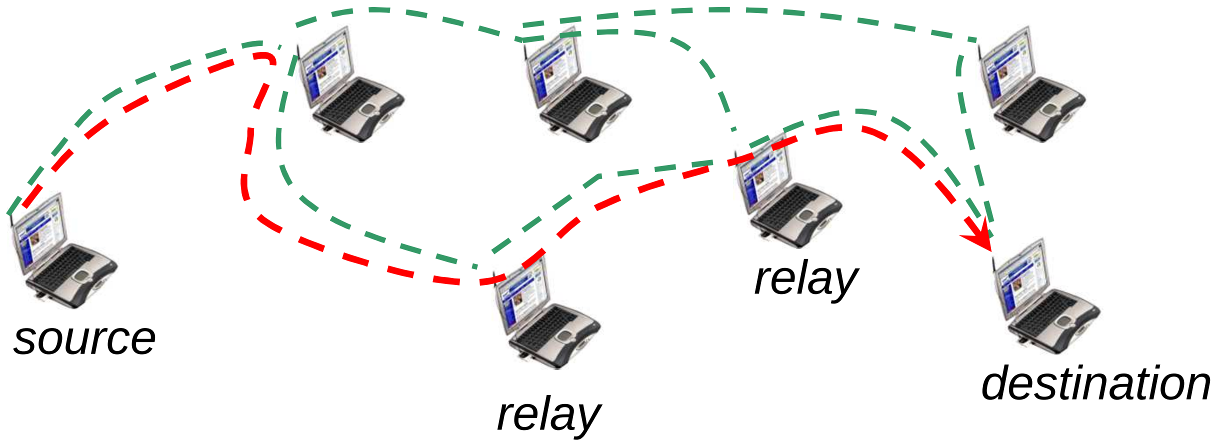
- **Ad-hoc wireless networks (mesh networks, sensor networks)**



- *mobile - mobile connections*

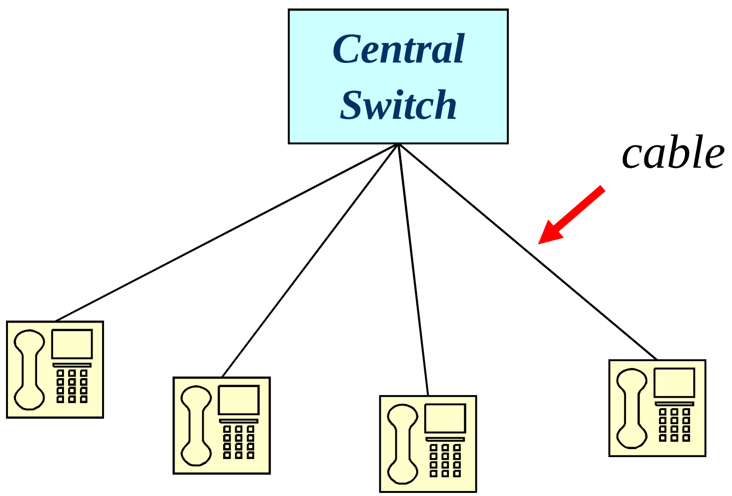
Distributed broadcast channel

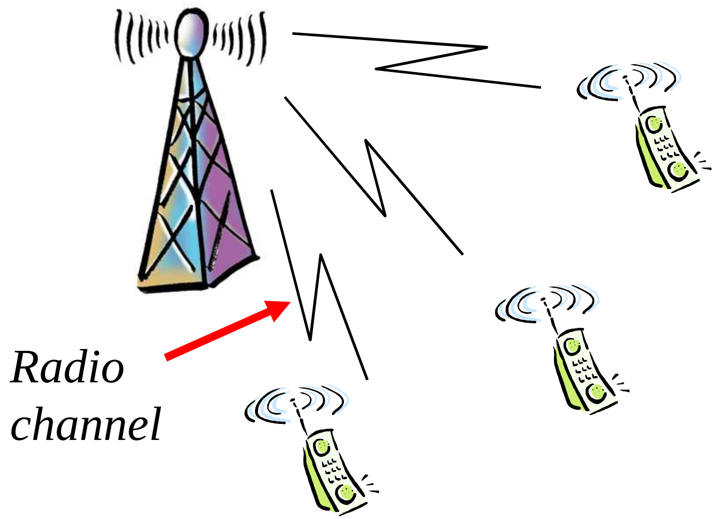
- **In multi-hop operation mobile stations can forward information**



Wired-Wireless networks: Main differences

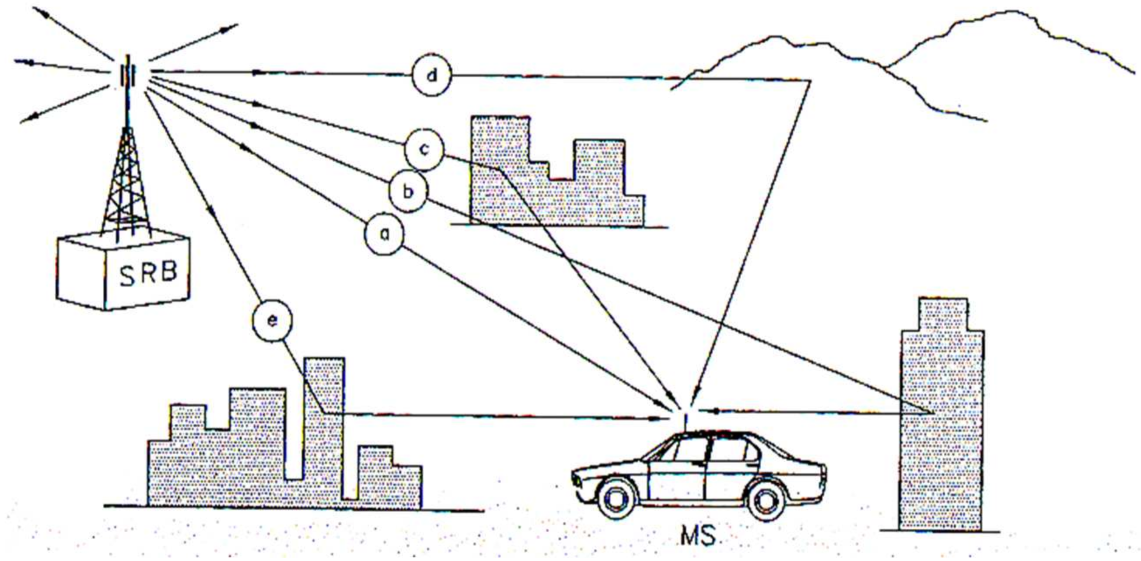
- **Shared transmission medium**
  - ➔ **Multiple access mechanisms**
  - ➔ **Radio resource reuse**





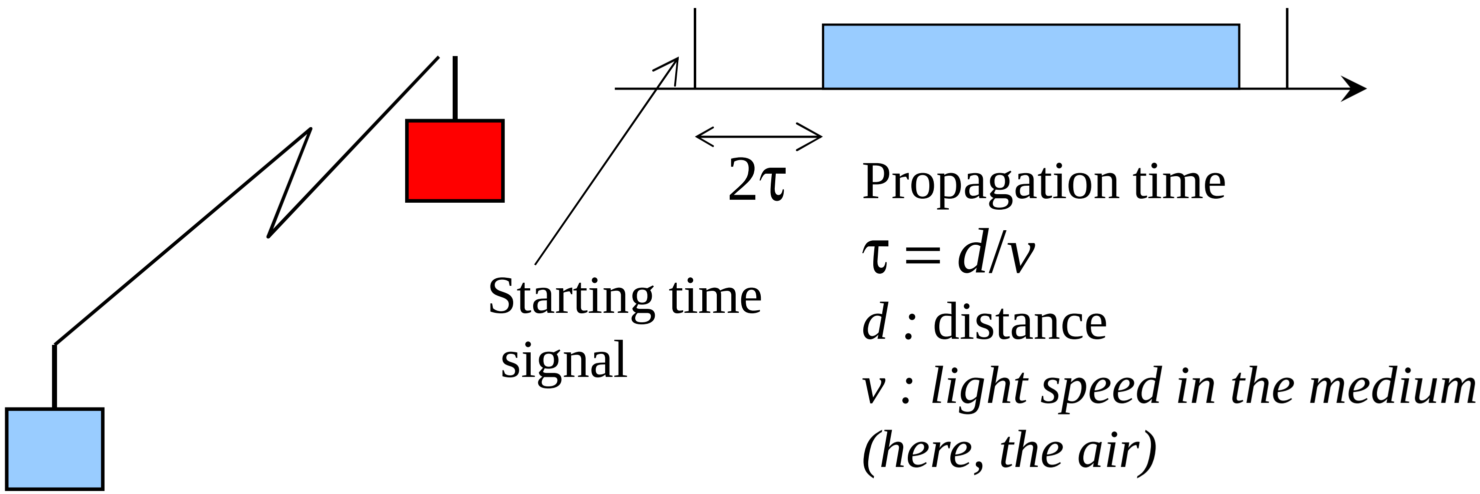
Wired-Wireless networks: Main differences

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



Centralized broadcast channel

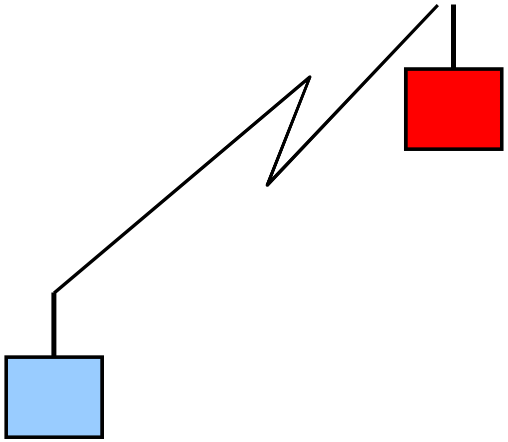
- **The Base Station is vital to enforce synchronization among mobile terminals**
- **Its transmissions are used to synchronize all transmissions (e.g., sending a signal to say when the frame starts)**

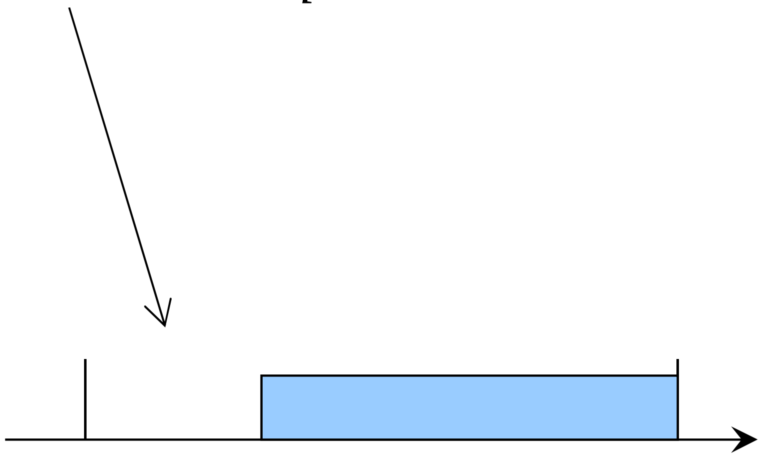


Centralized broadcast channel

- **Guard time:**

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

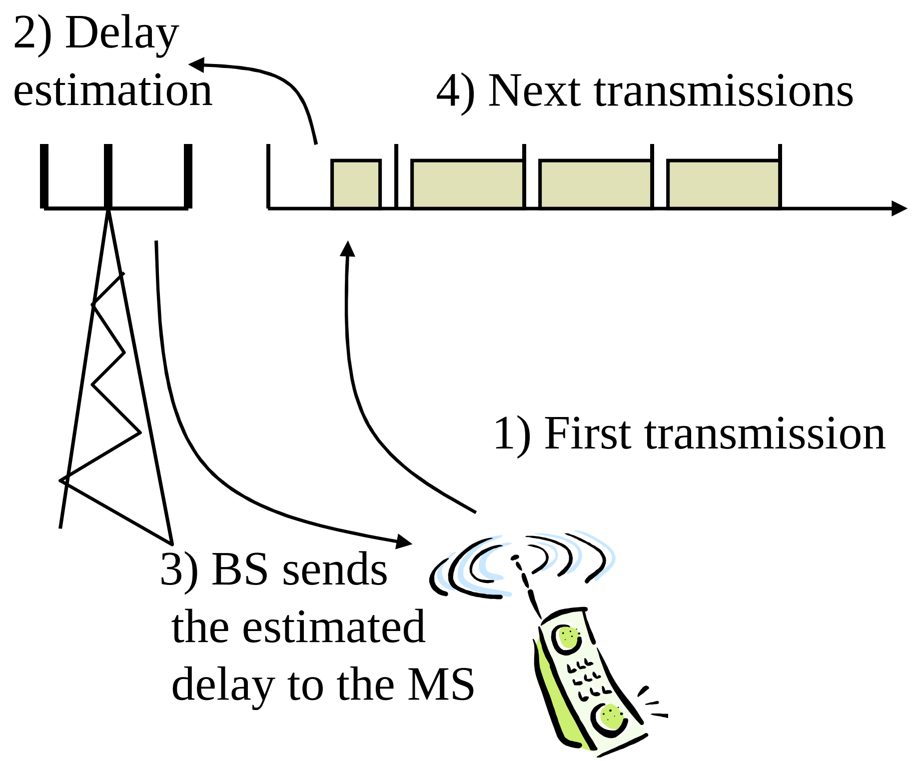




Obviously: the guard time is dominated by the ***<u>farthest</u>*** *node from the BS*

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**



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**

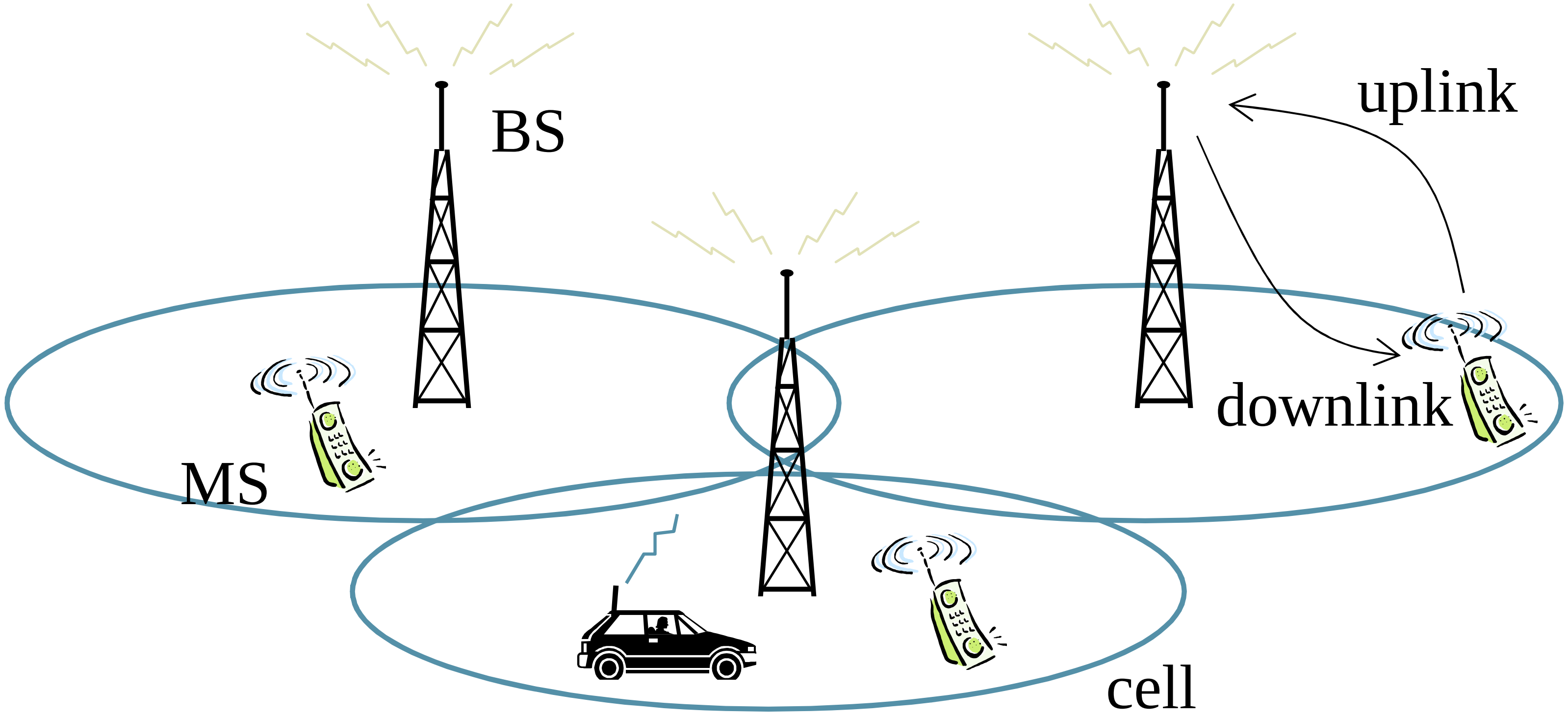
CDMA
Code Division Multiple Access

- **In CDMA it is impossible to have perfect synchronization among different nodes' transmissions**
- **Hence code orthogonality is *lost***
- **We use codes with very low correlation for every possible time shift Δ among themselves**
- **Used in 3rd generation systems (UMTS)**

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

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

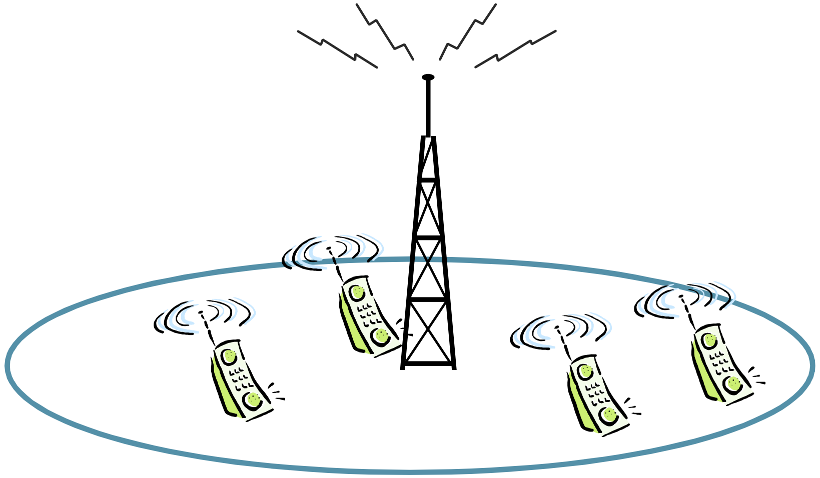
Cellular (Mobile) Systems



MS = Mobile Station
BS = Base Station

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

Radio Access

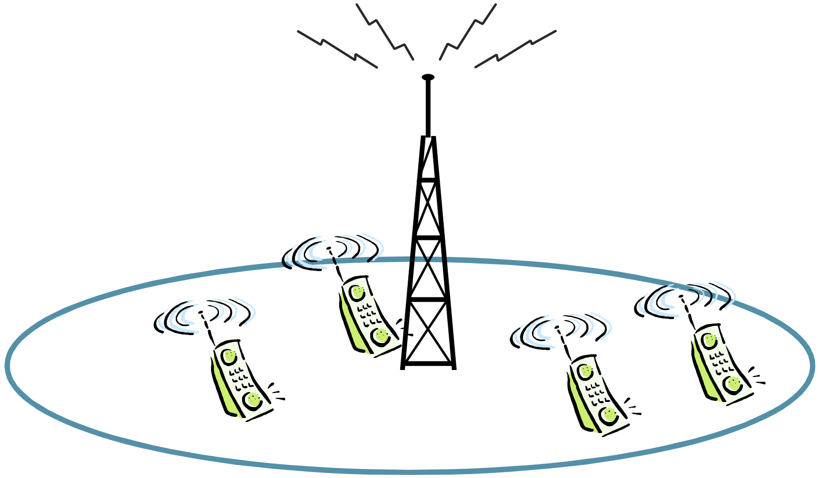


- The radio access problem is related to the way in which the users in the cell share radio resources

- downlink:
  - <u>multiplexing</u> is used

- uplink:
  - <u>multiple access</u> is used

Radio Access



- **First generation systems:**
  - **TACS (Europe)**
    AMPS (US)
  - **FDM/FDMA (downlink/uplink)**

- **Second generation:**
  GSM (Europe)
  D-AMPS (US)
  - **multi-carrier TDM/TDMA**

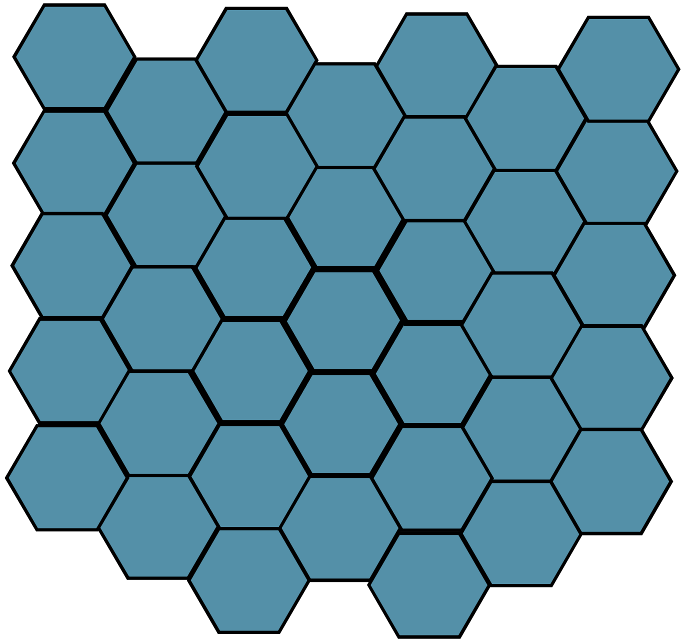
- **Third generation:**
  UMTS
  CDM/CDMA

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)**

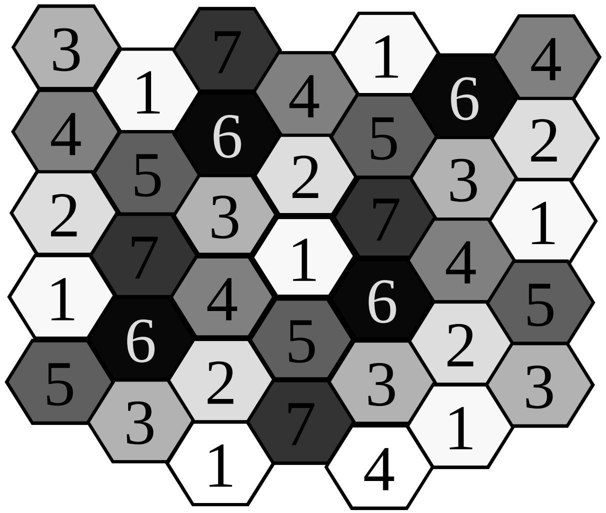
Spatial reuse

- 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}

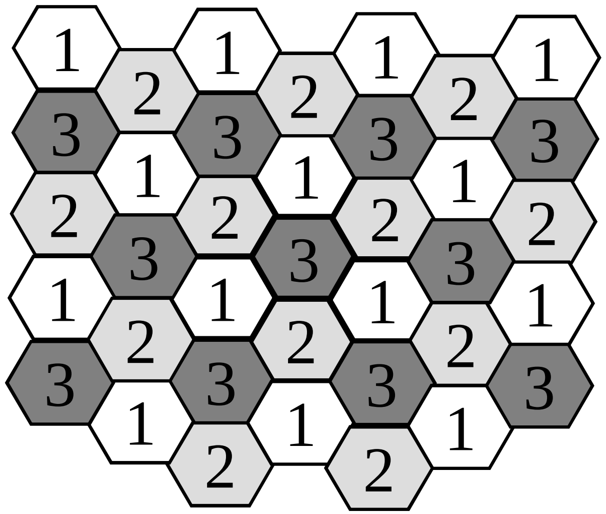


Cluster dimensioning

- **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

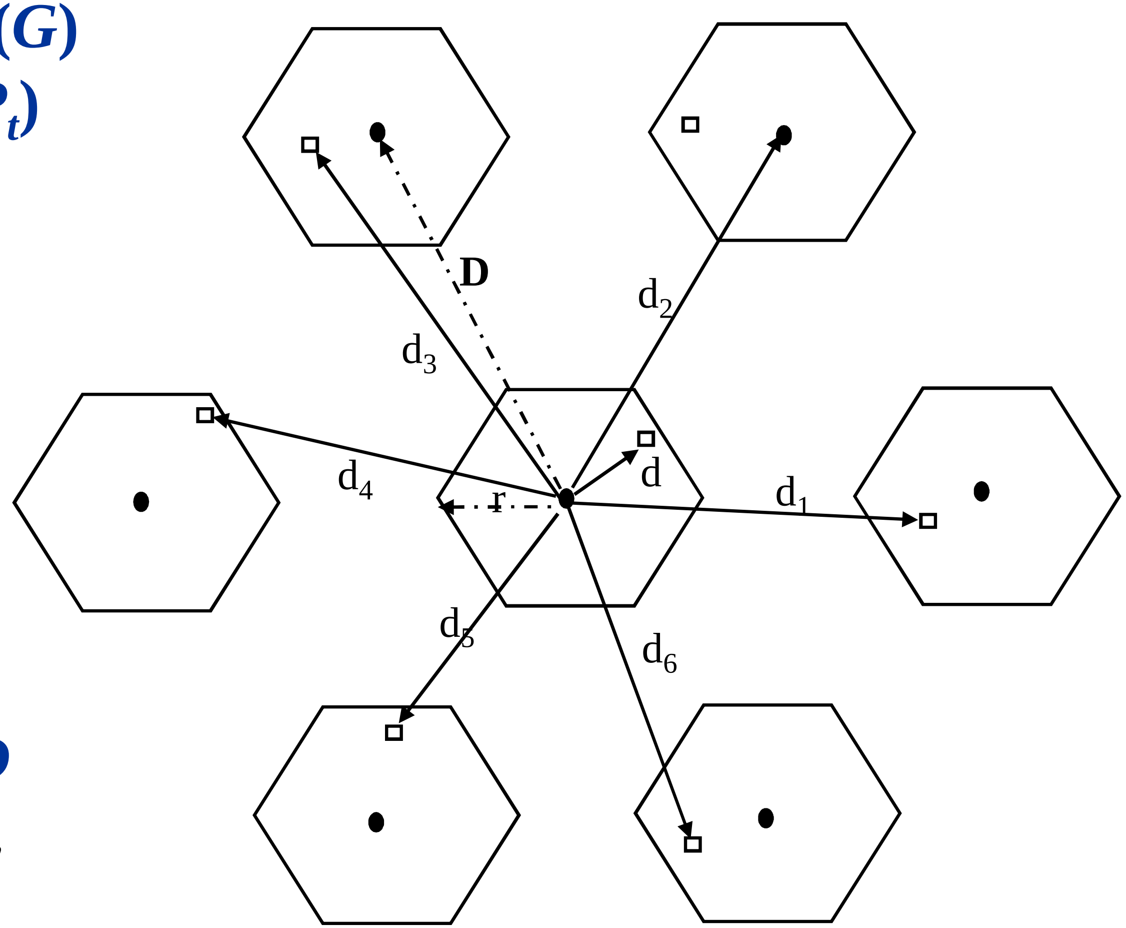
- **Hip.: same antennas (*G*) and same tx power (*P*)**

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

$$= \frac{d^{-\eta}}{\sum_{i=1}^{6} d_i^{-\eta}}$$

- **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:**

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

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**

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

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**

$$2 \rightarrow 3dB$$

$$3 \rightarrow 4.77dB$$

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

$$5 \rightarrow 7dB$$

$$6 \rightarrow 7.77dB$$

$$8 \rightarrow 9dB$$

$$9 \rightarrow 9.54dB$$

$$10 \rightarrow 10dB$$

$$100 \rightarrow 20dB$$

$$1000 \rightarrow 30dB$$