# Reti di Telecomunicazione

## **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<sub>min</sub> to f<sub>max</sub>)



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)**



 $B = total available bandwidth (f_{max} - f_{min})$   $b_s = signal bandwidth$  $b_g = guard band$ 

# **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<sub>b</sub>=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)**

- The choice of the *slot duration* is very important (this is a parameter chosen when the slotted system is designed):
  - *n<sub>i</sub>* 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:  $T_a = n_i/c$ c (bit/s)

<u>Remark</u>: each source/sender produces bits exactly with rate cThe  $n_i$  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

C (bit/s)

### **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

super-frame



- 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 <u>codeword</u> C<sub>i</sub> 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

$$C_{0} = \{1,1,1,1\}$$

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

$$C_{2} = \{1,1,-1,-1,-1\}$$

$$C_{3} = \{1,-1,-1,1\}$$

$$C_{3} = \{1,-1,-1,1\}$$

$$C_{1}$$

$$C_{2}$$

$$C_{2}$$

$$C_{3}$$

### **CDM (Code Division Multiplexing)**



# **CDMA: spreading and despreading**

The code "expands" the radio bandwidth of the signal



# **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)

**De-spreading** 



nВ

B

#### **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**



#### **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
- **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)





*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  $2\tau = 2 \ge 35 / 3 \ge 10^8 = 233 \ \mu s$
- which is equivalent to 68,25 bits at carrier rate of 270.8 kbit/s

# Efficiency

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

- It depends on the ratio  $T_g/T_i$
- The efficiency decreases:
  - When distances from the BS increase (*T<sub>g</sub>* 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

# **Multiple Access in Mobile Radio Networks**



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

- **downlink:** 
  - <u>Multiplexing</u> of flows towards mobile users

- uplink:
  - <u>multiple access</u> of mobile stations

# **Radio Access**



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

- **First generation systems:** 
  - TACS (Europe) AMPS (US)
  - FDM/FDMA (downlink/ uplink)
    - Third generation:
       UMTS
       CDM/CDMA
    - Fourth generation:
       LTE (Long Term Evolution)

# **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 + ...)Improves data rate in networks based on UMTS

#### **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<sub>min</sub>



# **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





- 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, ...



- If we know/if we set the SIR<sub>min</sub> 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:

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



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

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

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



- 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<sub>min</sub> we can compute R<sub>min</sub>
- Then, if  $\mathbf{R}_{\min}$  is known, we can obtain K since we can observe that:  $K = \frac{R^2}{3}$

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

and therefore:

### Exercise

Let us dimension a cluster for a cellular system that tolerates SIR<sub>min</sub> = 18 dB, considering the case where the path-loss exponent η is equal to 3.9

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

- 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**



#### **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:

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

# **Assignment constraints**

- Once the cluster size is selected, the assignment of *channels* to *cells* is usually subject to <u>additional constraints</u>
- 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



## **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

$$G \cdot P \to G_{dB} + P_{dB}$$
$$P / A \to P_{dB} - A_{dB}$$

#### **Summary**

#### Notable values

 $2 \rightarrow 3dB$   $3 \rightarrow 4.77dB$   $4 = 2 \cdot 2 \rightarrow 3 + 3 = dB$   $5 \rightarrow 7dB$  $6 \rightarrow 7.77dB$ 

 $8 \rightarrow 9dB$   $9 \rightarrow 9.54dB$   $10 \rightarrow 10dB$   $100 \rightarrow 20dB$  $1000 \rightarrow 30dB$