Facoltà di Scienze Matematiche, Fisiche e Naturali

Dipartimento di Scienze dell’Informazione

Corso di Laurea Specialistica in Scienze di Internet (SdI) e Informatica (Inf)

Sistemi e Reti Wireless

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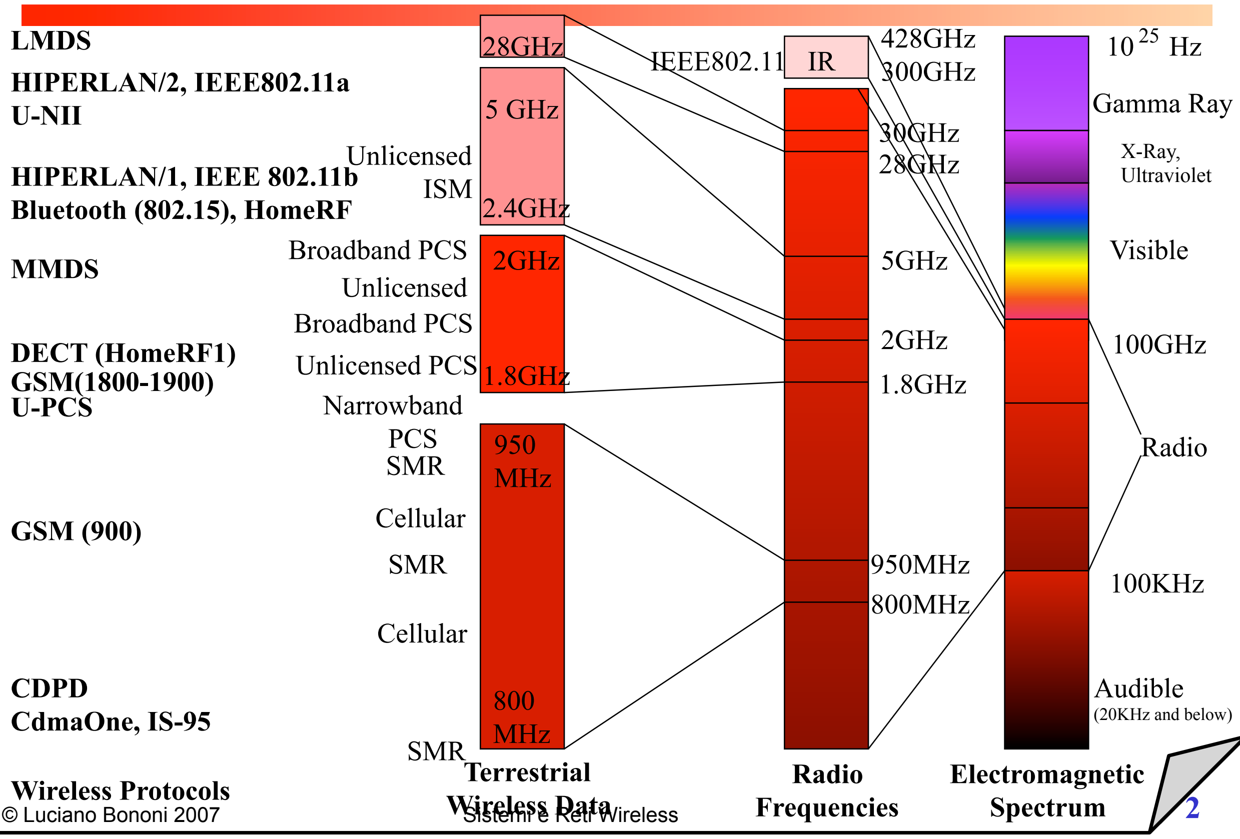
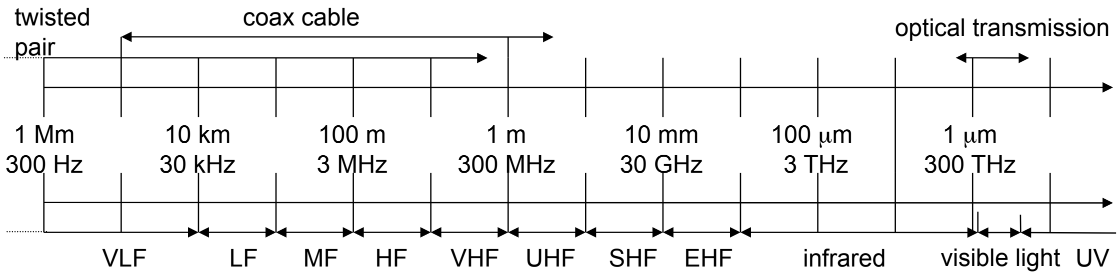
Ricevimento: sempre aperto .
Si consiglia di concordare via e-mail almeno un giorno prima
(informazioni in tempo reale sulla home page personale)

Figure-credits: some figures have been taken from slides published on the Web, by the following authors (in alfabethical order):
J.J. Garcia Luna Aceves (ucsc), James F. Kurose & Keith W. Ross, Jochen Schiller (fub), Nitin Vaidya (uiuc)

Wireless networks’ spectrum



Frequencies for (wired and wireless) communicat.



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency
- Frequency and wave length:
- $\lambda = c/f$
- wave length λ, speed of light $c \cong 3x10^8$m/s, frequency f

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequencies for mobile communication

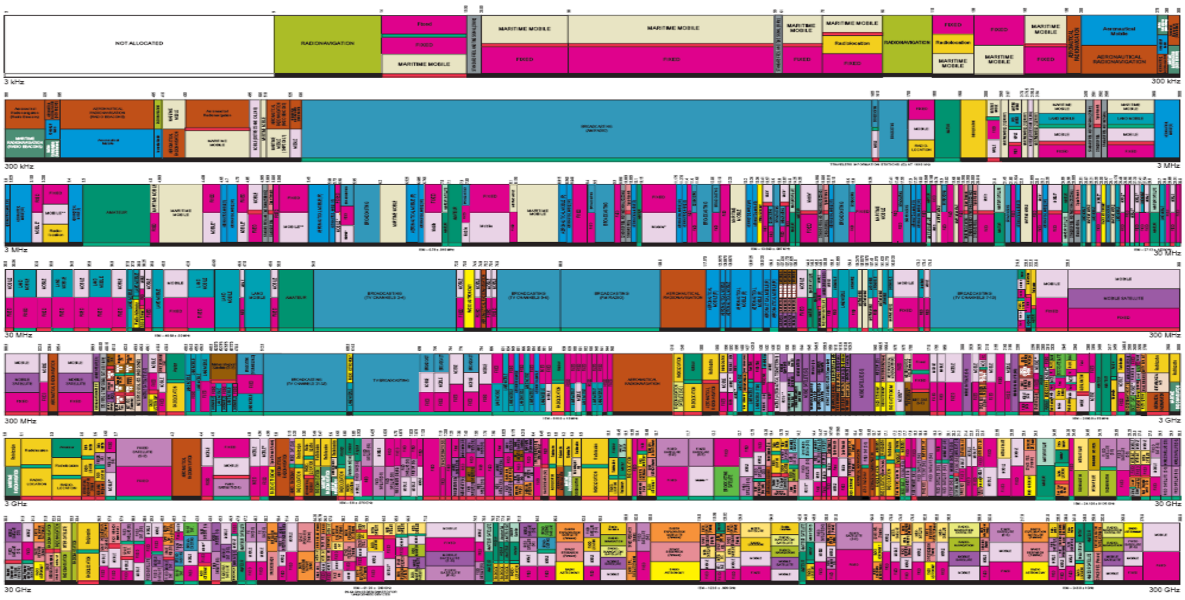
- VHF/UHF ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, large bandwidth available
- Wireless LANs use frequencies in UHF to SHF spectrum
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - weather dependent fading,
      signal loss caused by heavy rainfall...

Frequencies and regulations

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

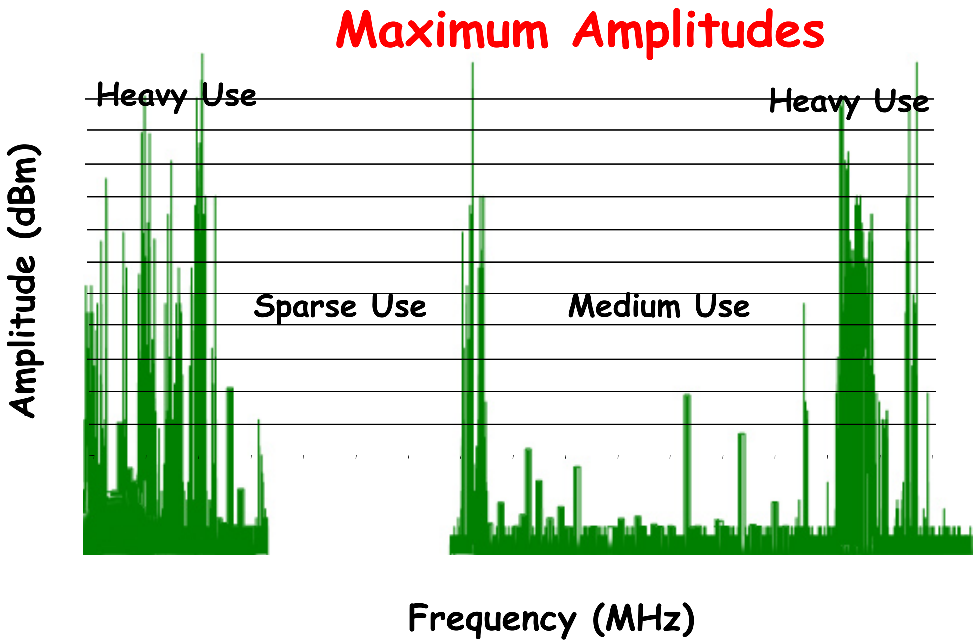
	Europe	USA	Japan
Cellular Phones	**GSM** 450-457, 479-486/460-467,489-496, 890-915/935-960, 1710-1785/1805-1880 **UMTS** (FDD) 1920-1980, 2110-2190 **UMTS** (TDD) 1900-1920, 2020-2025	**AMPS**, **TDMA**, **CDMA** 824-849, 869-894 **TDMA**, **CDMA**, **GSM** 1850-1910, 1930-1990	**PDC** 810-826, 940-956, 1429-1465, 1477-1513
Cordless Phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 254-380
Wireless LANs	**IEEE 802.11** 2400-2483 **HIPERLAN 2** 5150-5350, 5470-5725	902-928 **IEEE 802.11** 2400-2483 5150-5350, 5725-5825	**IEEE 802.11** 2471-2497 5150-5250
Others	**RF-Control** 27, 128, 418, 433, 868	**RF-Control** 315, 915	**RF-Control** 426, 868

Fixed spectrum assignment



Slide credits: IFA'2007, prof. Ian Akyildiz @ Gtech

Fixed spectrum utilization



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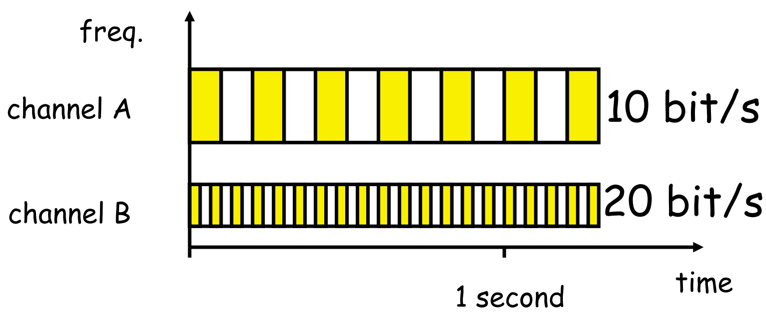
Wireless networks Bandwidth and Spectrum

- **how can wireless channels have different bandwidth?**
  - bits run less or more faster? (NO)
    - Light speed: ˜ <300.000 Km/s for every bit
  - the channel pipe (spectrum) is bigger (YES/NO)
  - the channel requires less time to accomodate (i.e. to code) one bit on the channel (YES)

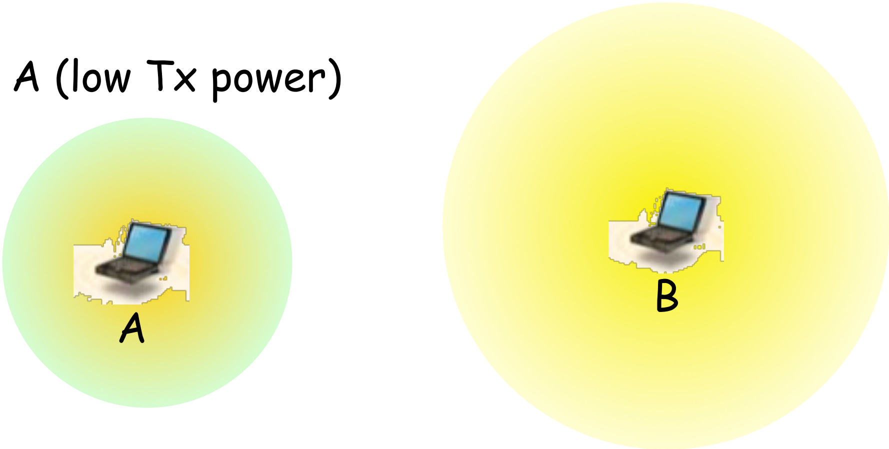


Wireless networks' technology

- **Radio transmission coverage**

host B (high Tx power)

host A (low Tx power)

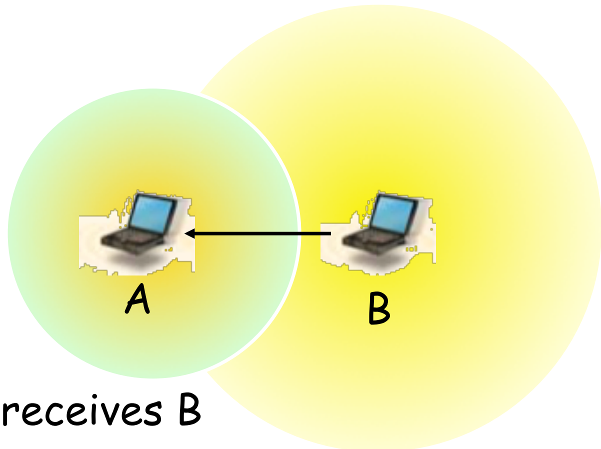


"...is there anybody outhere?"

both isolated

Wireless networks' technology

- **Radio transmission coverage**



A receives B

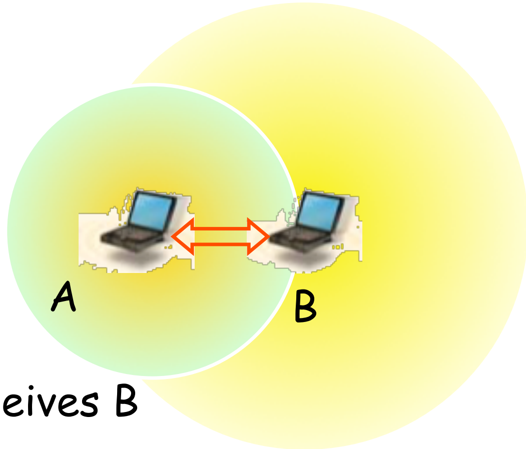
B cannot receive A

unidirectional(*) link

(*) sometimes improperly referred to as "asymmetric link"

Wireless networks' technology

- **Radio transmission coverage**



A receives B

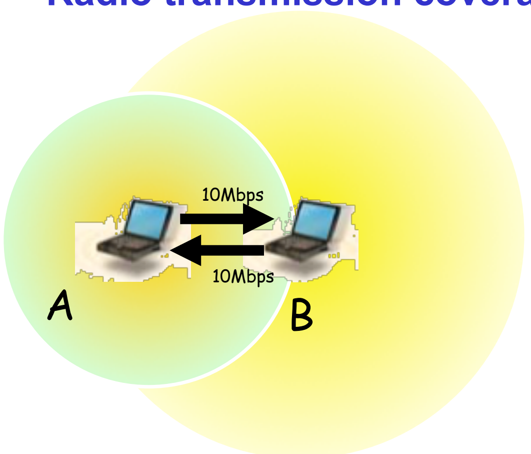
B receives A

bidirectional(*) link

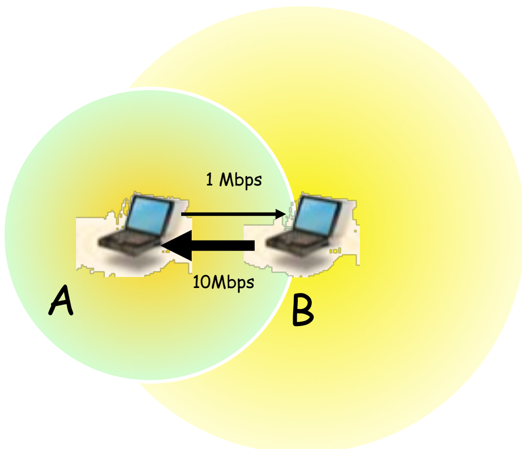
(*) sometimes improperly referred to as "symmetric link"

Wireless networks' technology

- **Radio transmission coverage**



bidirectional symmetric link



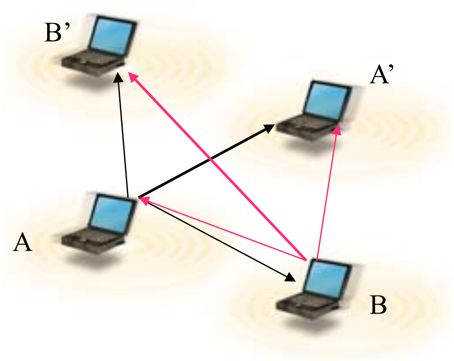
bidirectional asymmetric link

Wireless networks' technology

- **Narrowband radio system**
  - transmit/receive using a single radio frequency
- **Spread Spectrum technology**
  - bandwidth efficiency vs. reliability and security
  - Frequency Hopping Spread Spectrum
    - narrowband carrier hopping in a pattern sequence
  - Direct Sequence Spread Spectrum
    - bit coding and transmission spreading over the spectrum
- **Infrared technology**
  - line of sight or diffused, short range (in room)

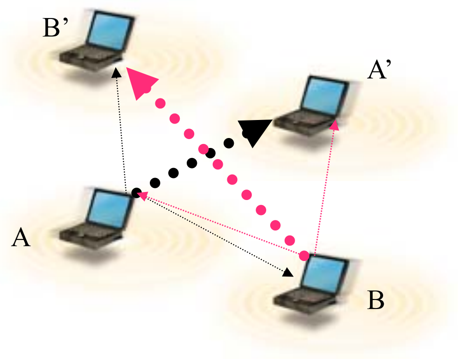
Wireless networks' technology

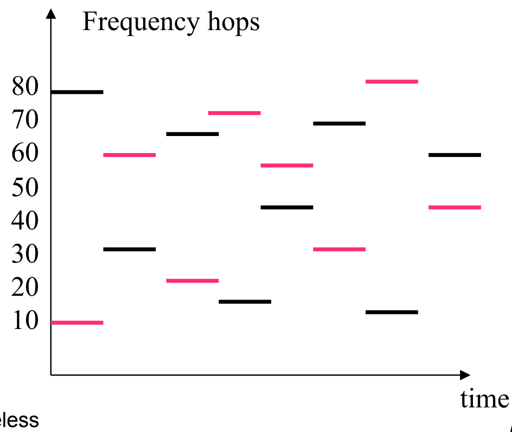
- **Narrowband radio system**
  - transmit/receive using a single, licensed, as narrow as possible radio frequency
  - undesired cross-talk between channels requires coordination and license for each site
  - low data-rates
  - e.g. → frequency X
  - e.g. → frequency Y



Wireless networks’ technology

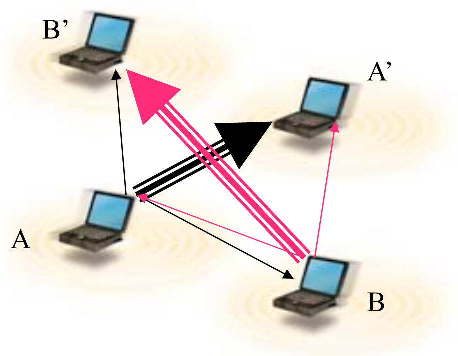
- **Frequency Hopping Spread Spectrum**
  - narrow band carrier changes frequency in a pattern known by both transmitter and receiver (single logical channel)
  - to unintended receiver FHSS appears as impulse noise

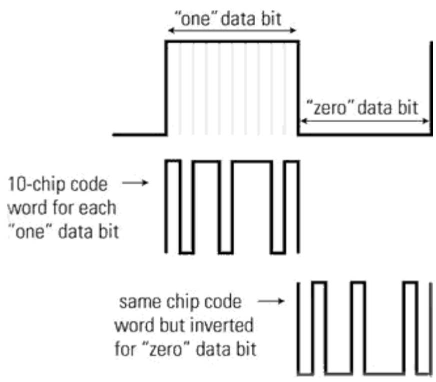




Wireless networks’ technology

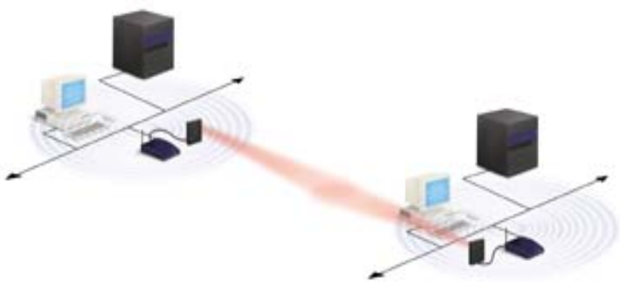
- **Direct Sequence Spread Spectrum**
  - redundant bit pattern (chipping code) spreaded over a large spectrum. Long chips increase probability of recovering the original bit (with no retransmission)
  - to unintended receiver DSSS appears as low power wideband noise





Wireless networks' technology

- **Infrared Technology (IR)**
  - frequencies just below the visible light
  - cannot penetrate opaque objects, and low diffusion
  - line-of-sight limitates mobility
  - short range technology (indoor, PAN, LAN nets)
  - High data-rate potential



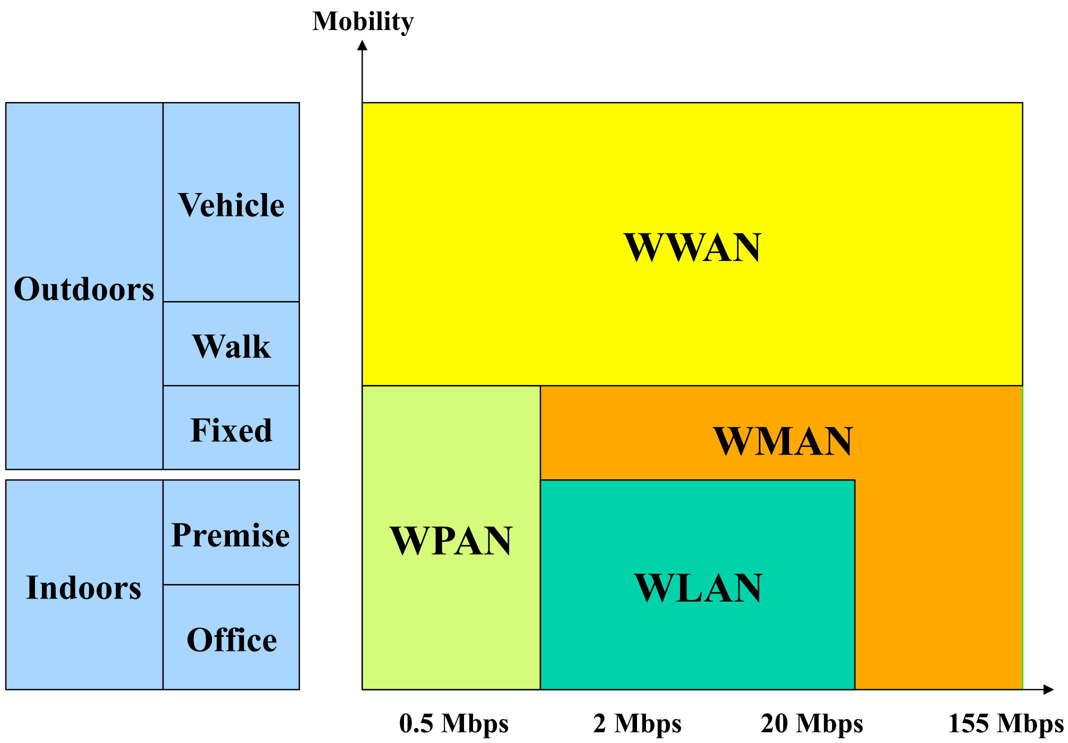
Transmission Technique Comparison

	PROS	CONS
Frequency Hopping Spread Spectrum (FHSS)	· Use less power than DSSS · Lower cost · Increased security due to frequency switching	· Lower throughput than DSSS
Direct Sequence Spread Spectrum (DSSS)	· High performance · Low interference · Increased security due to chip coding	· Expensive
Narrowband Microwave	· Long distance	· Line-of-sight with satellite dish · Requires FCC license · Not designed for WLAN use
Infrared	· High bandwidth	· Easily obstructed · Inexpensive

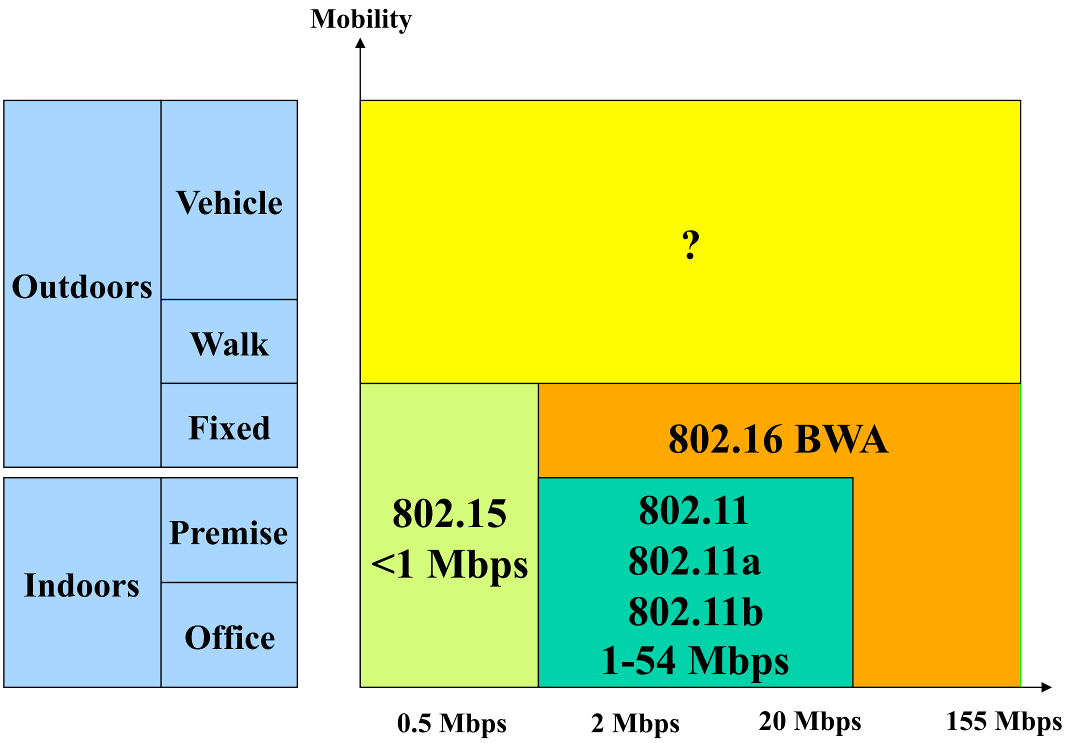
Wireless networks' coverage classification

- **Wireless Wide Area Network (WWAN)**
  - geographic coverage (e.g. satellite, cellular)
- **Wireless Metropolitan Area Net. (WMAN)**
  - Metropolitan coverage (e.g. town, large campus)
- **Wireless Local Area Network (WLAN)**
  - local area coverage (e.g. campus, building, home)
- **Wireless Personal Area Network (WPAN)**
  - reduced local area coverage (e.g. house, office)
- **Wireless Indoor Area Network (indoor)**
  - short range coverage (e.g. room, office)

Wireless network positioning

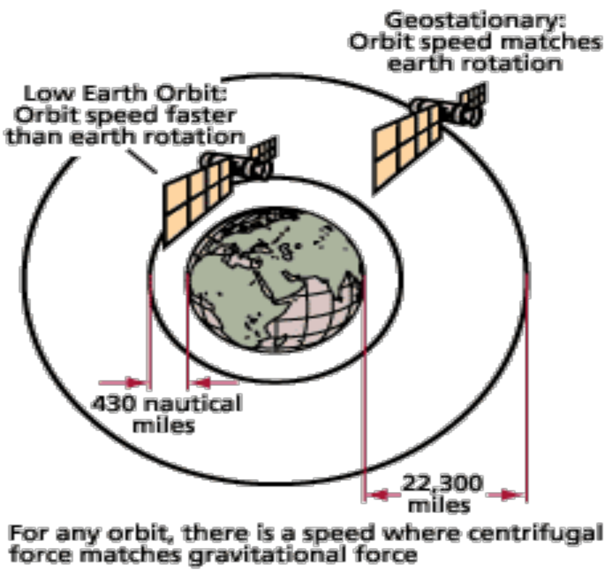


IEEE 802 Wireless standards



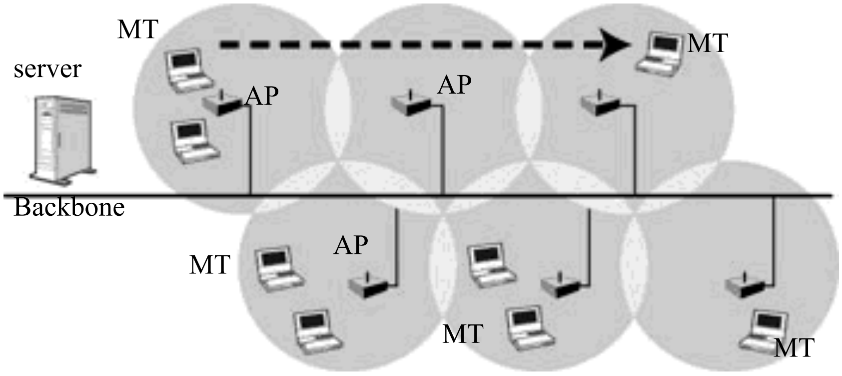
Wireless network structures

- **WWAN and WMAN**
  - Satellite (low orbit, geo-stationary)



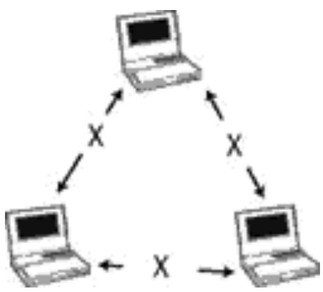
Wireless network structures

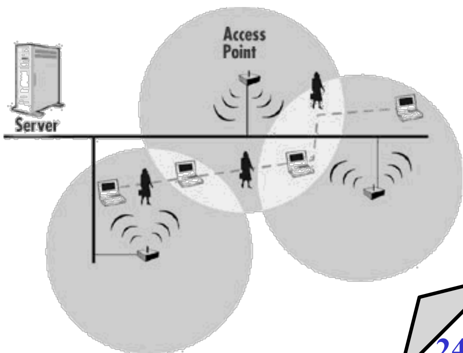
- **WWAN and WMAN**
  - Cellular or multi-Infrastructure WLAN
    - grid of Access Points (AP), managing local Mobiles terminals (MT), and connected to Backbones



Wireless network structures

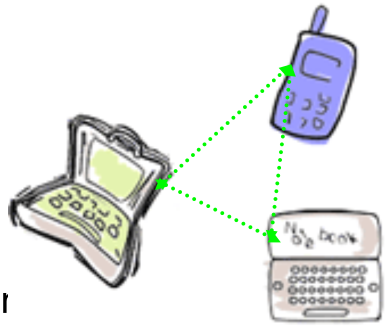
- **WLAN:**
  - Ad Hoc:
    - peer-to-peer (P2P) "on the fly" communication
    - the network "is" the set of computers
    - no administration, no setup, no cost?
  - Infrastructure:
    - Centralized control unit (Access Point, local server)
    - Roaming between cells
    - resource sharing and backbone connection





Wireless network structures

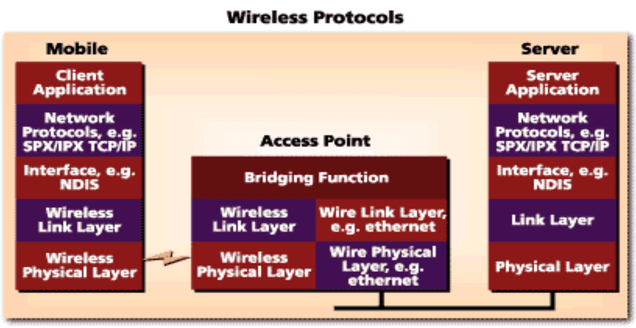
- **WPAN:**
  - cable connection alternative for in-home/office/workspace device connection
  - common technology and protocols required (e.g. HomeRF, Bluetooth)



- **Indoor:**
  - in room/workspace device conn

Wireless/Wired extension

- **Wireless protocols' design, integration, optimization**
  - layering, bridging functions
  - mobile IP
  - support and management for QoS
- **support for Wired-like applications**
  - Internet connectivity, DB access, e-mail
  - value added services



Wireless vs. Wired

Attribute	Wireless PAN/LAN	Wired LAN/PAN
Throughput	1-10 Mbps	10-100 Mbps
Integrity & Reliability	Subject to interference	Highly reliable
Simplicity/ Ease of Use	• No need to pull cable • Set up time is significantly lower • Moves, additions & changes much simpler	• Cable required • Set up time is significantly higher
Security	• Susceptible to interception • encryption	• Not as susceptible to interception

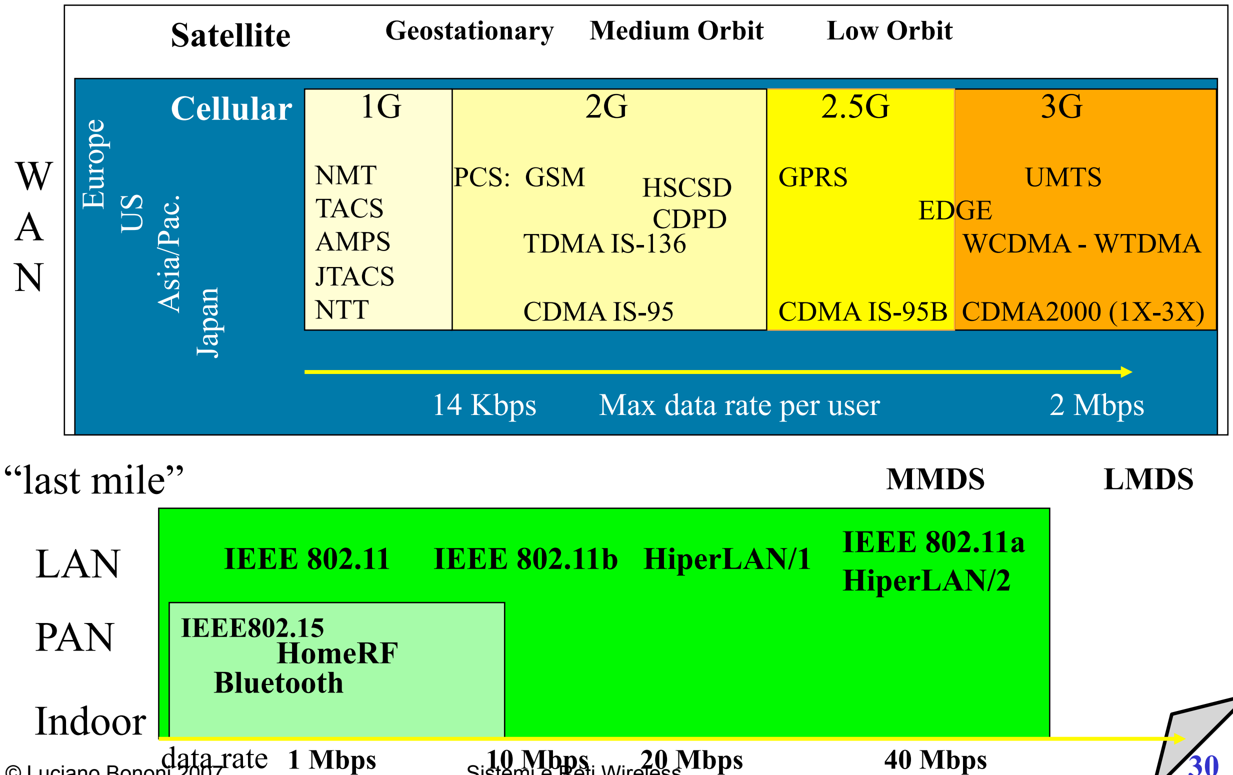
Wireless vs. Wired

Attribute	Wireless LAN/PAN	Wired LAN/PAN
Cost	• Initial investment in hardware costs more • Installation expenses and maintenance costs can be significantly lower	• Investment cost in hardware lower • Installation and maintenance costs can be significantly higher
Scalability	simple to complex networks	simple to complex networks
Safety	Very little exposure to radio frequency energy	No exposure to radio frequency energy
Mobility	Provides access to real-time information anywhere	Does not support mobility

Wireless networks' interoperability

- **...with the Wired Infrastructure:**
  - most WLANs support industry-standard like Ethernet (802.3) and Token-Ring (802.5)
  - newer solutions support ATM, FireWire, PPP...
- **…with other Wireless infrastructures:**
  - several types of interoperability are possible
  - the role of Standard definitions is to allow compliant products to interoperate
  - interference is possible in co-located solutions
  - security achieved through encryption

Wireless networks' taxonomy



Wireless World means...

- **New assumptions for the physical system...**
- **...willing to maintain needs for services and applications**
  - e.g. audio/video applications, interactive services
- **... dealing with limited resources (e.g. bandwidth, energy)**
- **... dealing with device limits (I/O, user interfaces)**
  - limited display, no keyboard, no mouse
- **... mobility of users and devices**
  - variable number of users in the system
- **... QoS problems, reliability, negotiation**

Wireless World integration

- **One possible solution for Integraton with wired world:**
  - to uncouple wired and wireless networks
  - protocol integration, maintaining services and protocols view from both sides
  - protocols and SW structures to adapt the contents transferred to etherogeneous devices
  - adaptive behavior of network protocols (from the wireless side)
    - the wired host does not know if the other host is wireless and dialogue with it in the standard wireless way (protocol transparency)
    - the wireless host know it is wireless and implements adaptive behavior

Wireless drawbacks

- **reduced Channel Capacity (1 or 2 order of magnitude)**
  - e.g. 54 Mbps vs. Gigabit Ethernet
- **Limited spectrum (etherogeneous frequency windows) available**
  - need for international frequency-allocation plans
  - need for frequency reuse
- **Limited energy (batteries): +20% every 5 years**
  - Moore law: SoC transistors double every year
- **Noise and Interference have great impact on performances and system design**
  - need for high power, bit error correction
- **Security: sensible information travels "on the air"**
  - need for protection based on cyphering, authentication, etc.

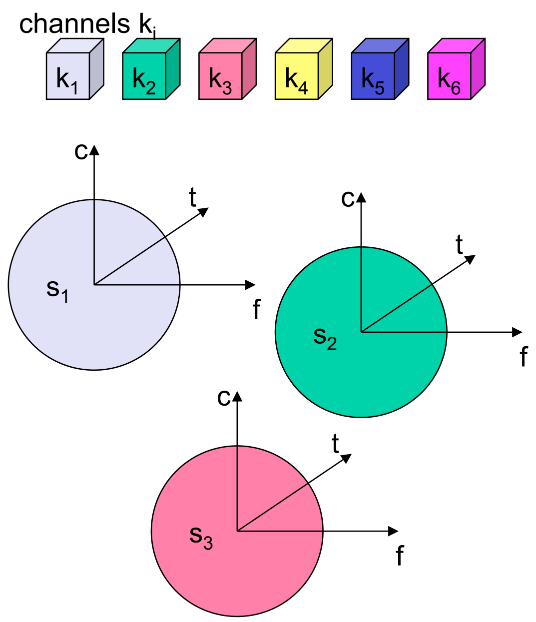
Wireless drawbacks

- **Mobility management**
  - **addressing and routing (eg. Mobile IP)**
- **Location Tracking**
  - **Broadcasting (paging) to find users/hosts**
  - **support for Location Based Services**
- **QoS Management**
  - **not a single layer management (application, transport, network, MAC)**
  - **depends on the system/user/application scenario**
  - **managed for the wireless cell only (no multi-hop)**
  - **advance reservation, admission control policies (centralized, distributed)**
  - **scheduling (centralized, distributed) for resources' allocation**
- **Best effort services**

Logical wireless channel

Multiplexing: multiple use of shared medium

- **Multiplexing in 4 dimensions**
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

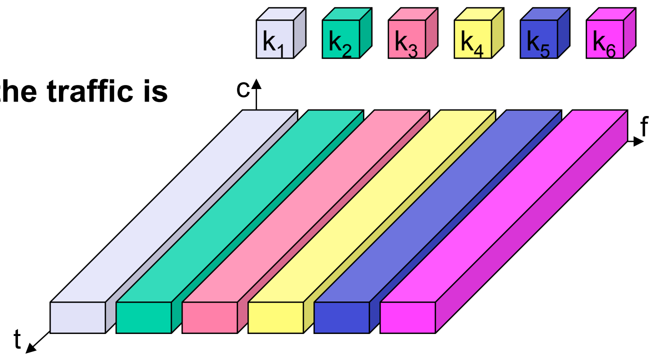


- **Goal: multiple use of a shared medium**

- **Important: guard spaces needed!**

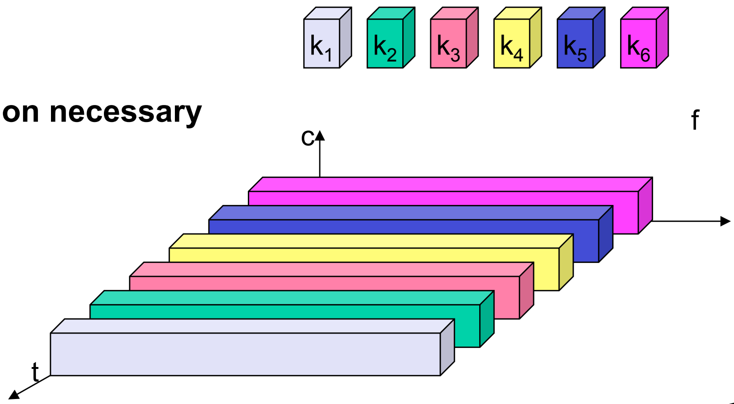
Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages:
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces



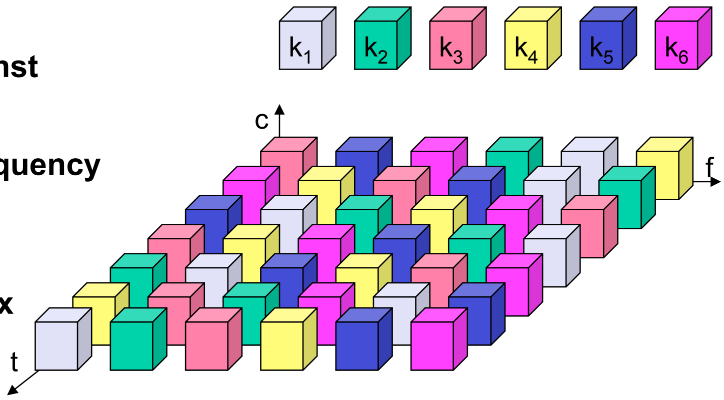
Time multiplex

- A channel gets the whole spectrum for a certain amount of time
- Advantages:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages:
  - precise synchronization necessary



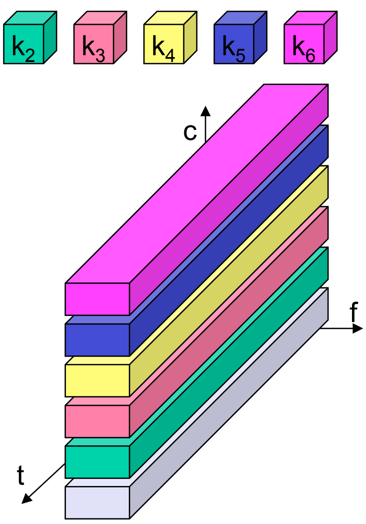
Time and frequency multiplex

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
  - Example: GSM
- Advantages:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code mux
- but:
  - precise coordination required



Code multiplex

- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages:
  - lower user data rates
  - more complex signal regeneration (€)
- Implemented using spread spectrum technology

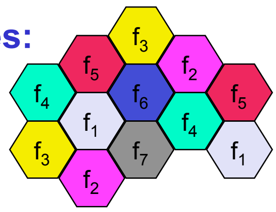


Space division mux: cell structure

- space division multiplex:
  - base station covers a certain transmission area (cell)
- Mobile stations communicate only via the base station
- Advantages of cell structures:
  - higher capacity, higher number of users
  - less transmission power needed
  - more robust, decentralized
  - base station deals with interference, transmission area etc. locally
- Problems:
  - fixed network needed for the base stations (infrastructure)
  - handover (changing from one cell to another) necessary
  - interference with other cells
- Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies

Frequency planning I

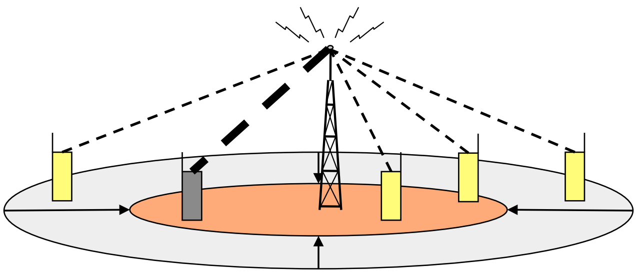
- Frequency reuse only with a certain distance between the base stations
- Standard model using 7 frequencies:



- Fixed frequency assignment:
  - certain frequencies are assigned to a certain cell
  - problem: different traffic load in different cells
- Dynamic frequency assignment:
  - base station chooses frequencies depending on the frequencies already used in neighbor cells
  - more capacity in cells with more traffic
  - assignment can also be based on interference measurements

Cell breathing

- CDM systems: cell size depends on current load
- Additional traffic appears as noise to other users
- If the noise level is too high users drop out of cells

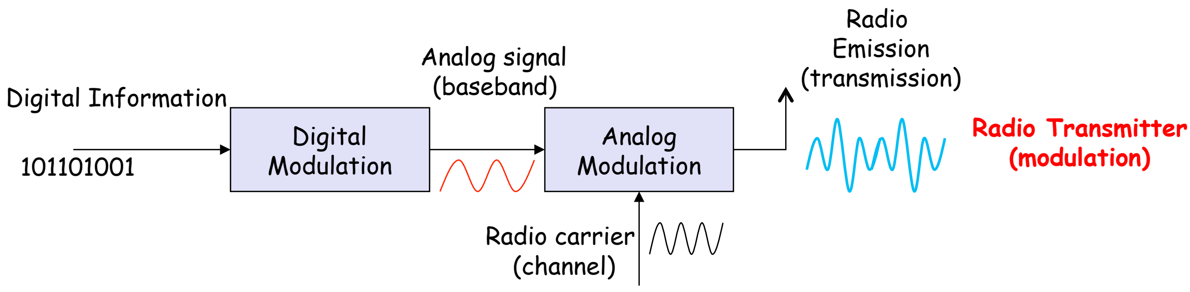


Modulation

- Digital modulation
  - digital data is translated into an analog signal (baseband)
  - ASK, FSK, PSK differences in spectral efficiency, power efficiency, robustness
- Analog modulation
  - shifts center frequency of baseband signal up to the radio carrier (i.e. FM)
- Motivation
  - smaller antennas (e.g., $\lambda/4$)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

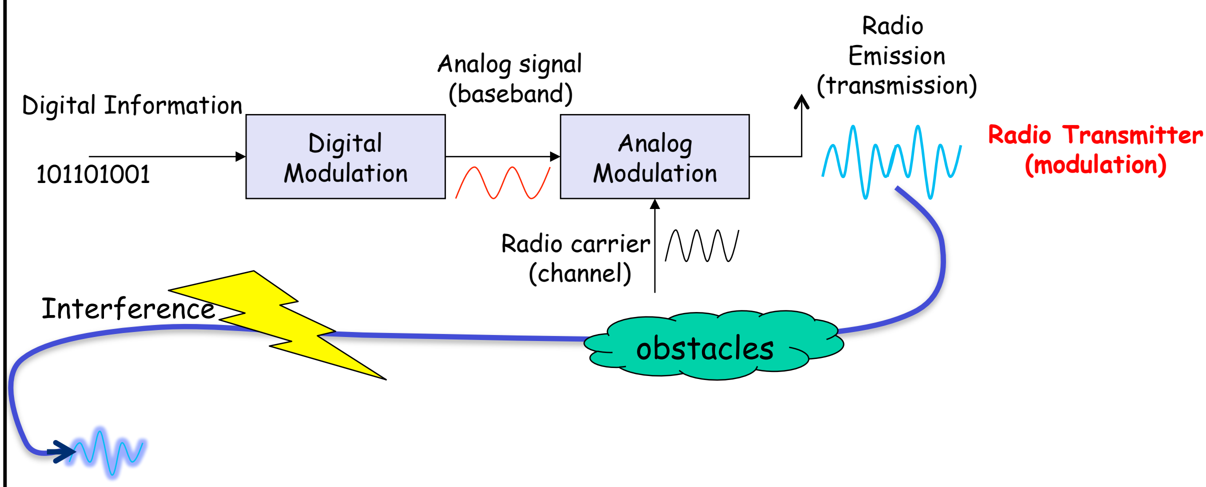
How to transmit bits with radio waves?

Digital Modulation and Demodulation



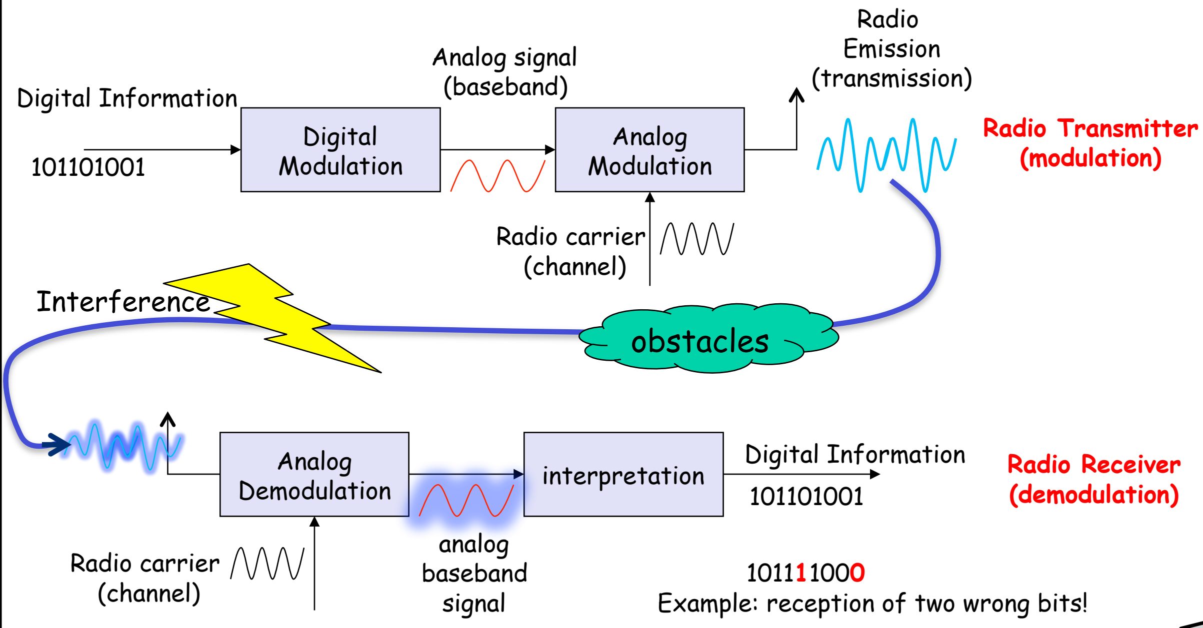
How to transmit bits with radio waves?

Digital Modulation and Demodulation



How to transmit bits with radio waves?

Digital Modulation and Demodulation



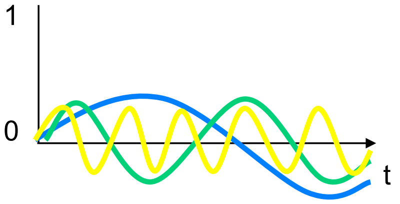
Signals I

- **physical representation of data**
  - function of time and location
- **signal parameters: parameters representing the value of data**
- **classification**
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
- **signal parameters of periodic signals: period T, frequency f=1/T, amplitude A, phase shift φ**
  - sine wave as special periodic signal for a carrier:

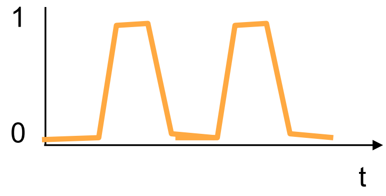
$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

Fourier representation of periodic signals

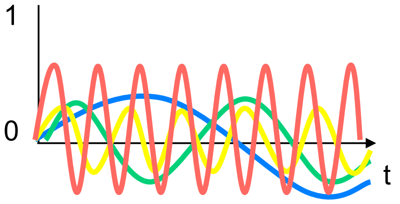
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$



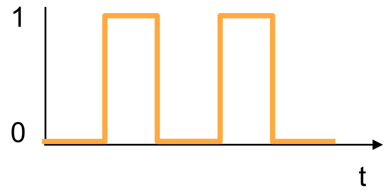
few harmonics composition



periodic signal



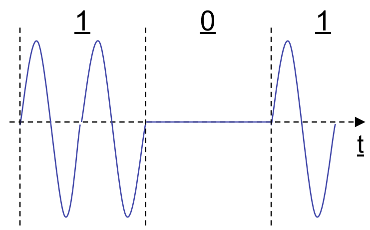
many (infinite) harmonics



ideal periodic signal

Digital Modulation Techniques

- Signal Modulation (Shift Keying)
- Amplitude Shift Keying (ASK):
  - Simple (on/off)
  - Uses few spectrum resources
  - But subject to high interference



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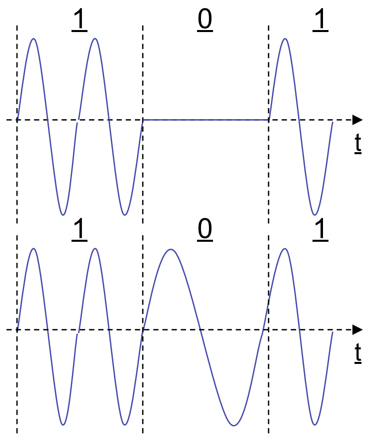

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- Frequency Shift Keying (FSK):
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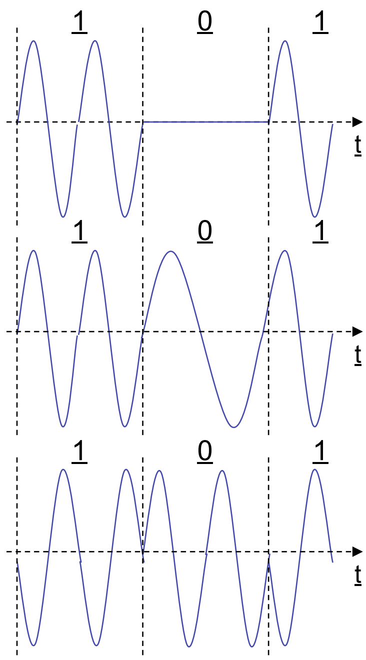
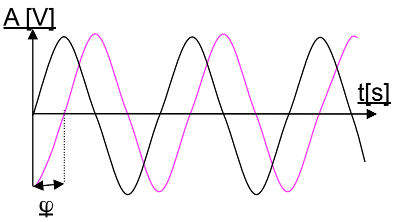
- Phase Shift Keying (PSK):
  - More complex to implement
  - More robust against interference
  - Many phase levels of signal possible



Signal Representation

- There are different ways to graphically represent the characteristics of a radio signal:
  - (a) Amplitude Domain



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- There are different ways to graphically represent the characteristics of a radio signal:
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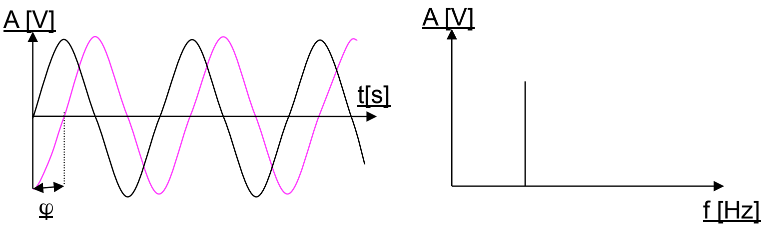
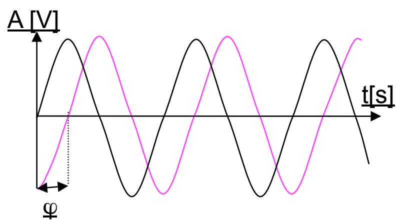
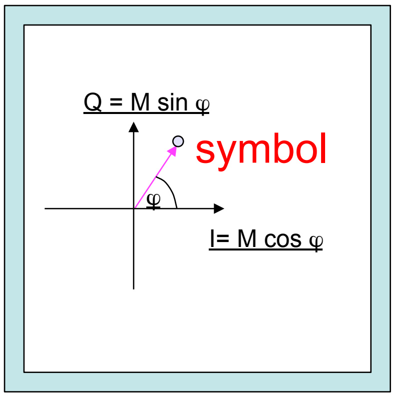


Signal Representation

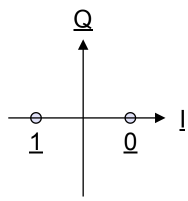
- There are different ways to graphically represent the characteristics of a radio signal:
  - (a) Amplitude Domain
  - (b) Frequency Domain
  - (c) Stat diagram of phase and amplitude (amplitude M and phase φ in polar coordinates)
    - Every SYMBOL represents a possible state (phase and amplitude) of the transmitted (and received) radio frequency.





One example?

- **BPSK (Binary Phase Shift Keying):**
  - **Every symbol represents a bit value:**
    - **Bit 0: transmitted signal sin(t) (in phase 0)**
    - **Bit 1: transmitted signal sin(t) in phase 180°**
  - **Simple and robust example of PSK**
  - **Es. Used in satellite communications**
  - **But has low spectral efficiency (few bits per spectrum unit)**



Can we do better?

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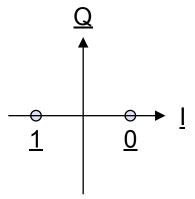
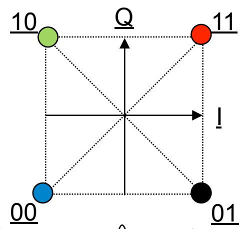
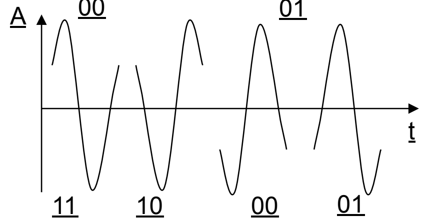


Can we do better?

- **QPSK (Quadrature Phase Shift Keying):**
  - **Every symbol represents a value on two bits:**
    - **Bit 11: transmitted signal sin(t) in phase +45°**
    - **Bit 10: transmitted signal sin(t) in phase +135°**
    - **Bit 11: transmitted signal sin(t) in phase +225°**
    - **Bit 10: transmitted signal sin(t) in phase +315°**
  - **More complex and vulnerable**
    - **How much interference is needed to realize a wrong interpretation of a symbol on the receiver?**





Imagine a target shooting…

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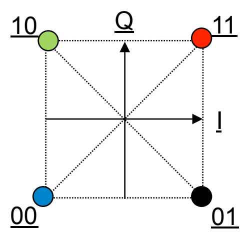
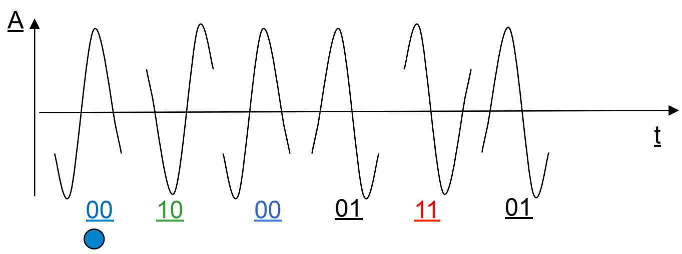
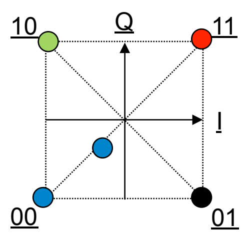
- **001000011101… = 00 10 00 01 11 01….**
- **Emitting a wave assuming in sequence the characteristics of the symbols associated to pairs in the bit sequence:**





- **…the receiver tries to understand the symbols**
- **Despite the symbols falls out of the target it would be possible to interpret them as the "nearest" target**



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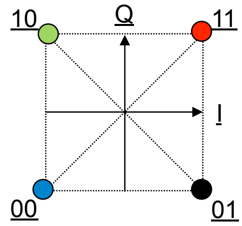

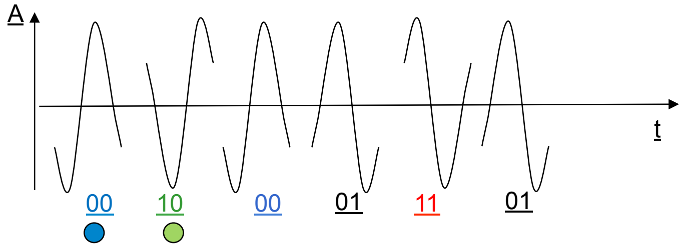

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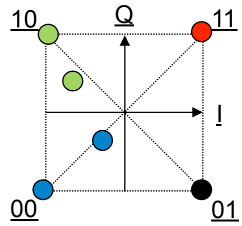

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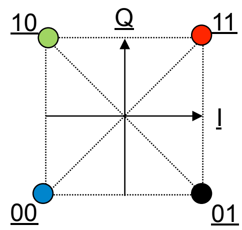

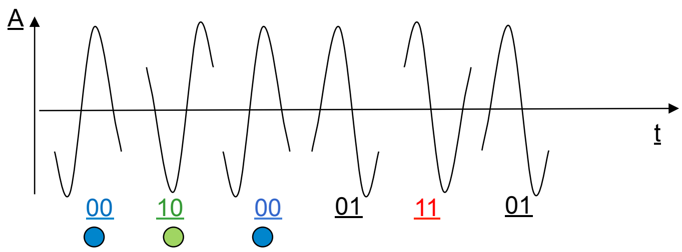

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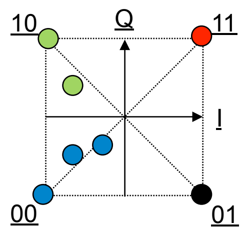

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http://corsi.unibo.it/informatica
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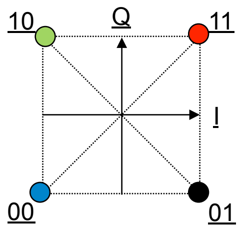

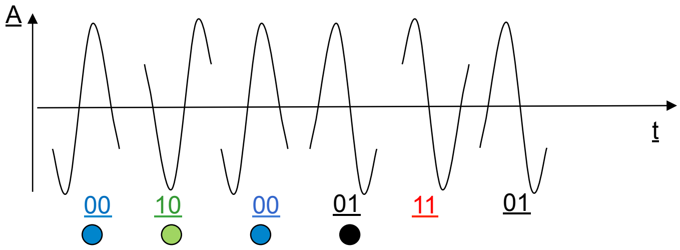

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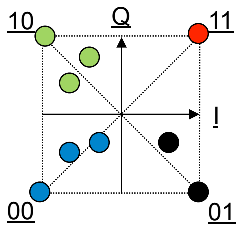

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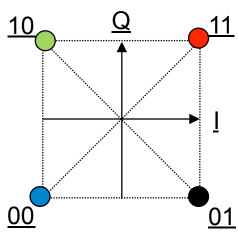

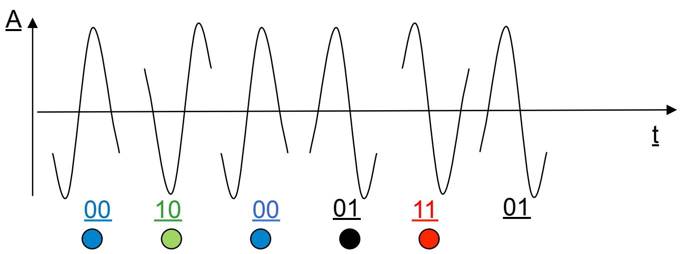

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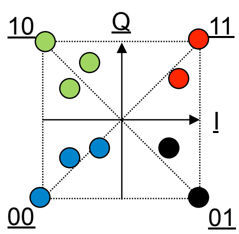

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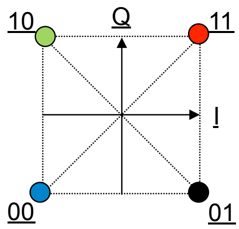

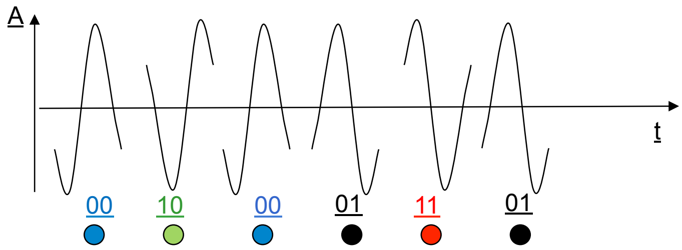

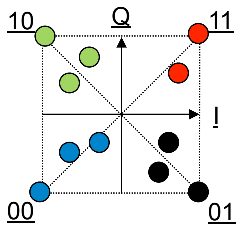

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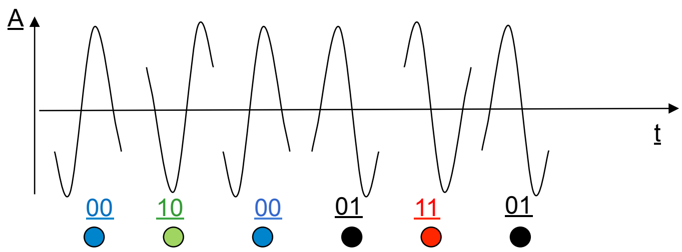
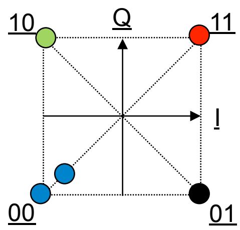
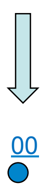
- Let’s see one example step by step







Ok the first symbol: bits received 00

Imagine a target shooting…

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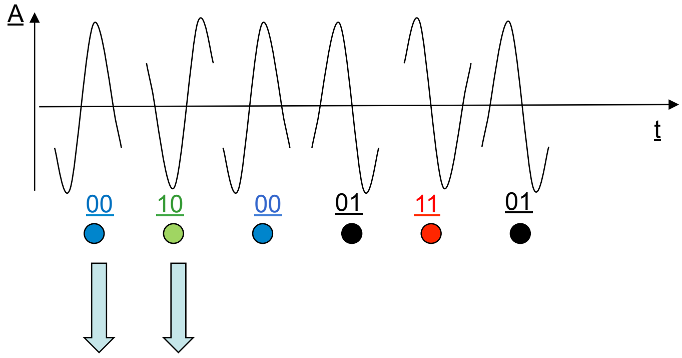
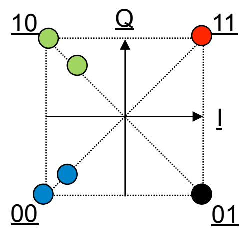
- **Let's see one example step by step**





00 10

All is fine with 2nd symbol! Received bits 00 10

Imagine a target shooting…

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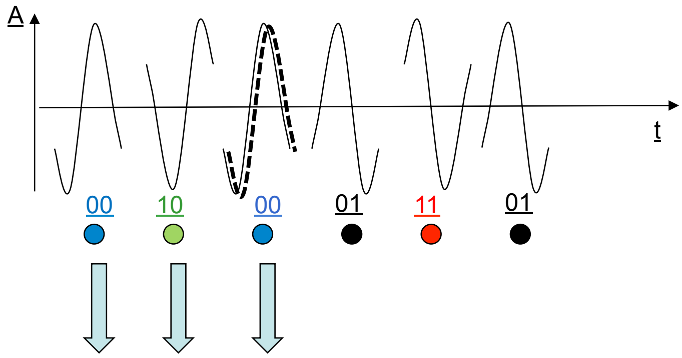
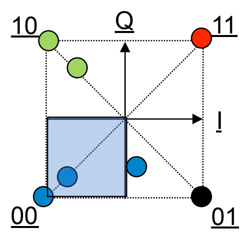
- **A: when the changes of phase and amplitude are so high that the limits of the target are exceeded, that is, the area of the target is not hit.**





00 10 01

3rd symbol has arrived…
It resembles ● ! So the received bits are 00 10 01: **Error!**

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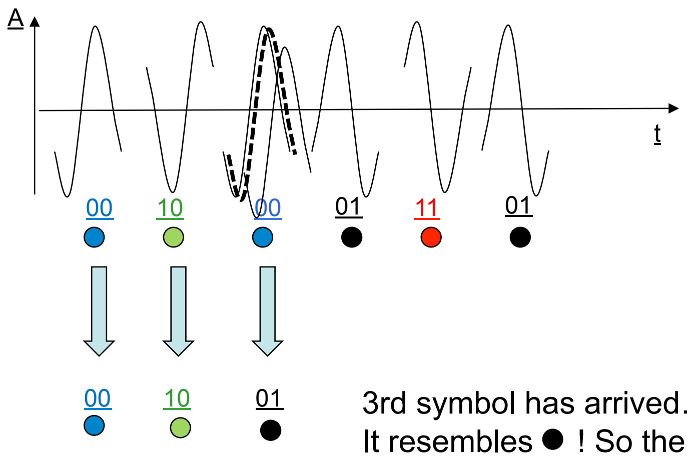

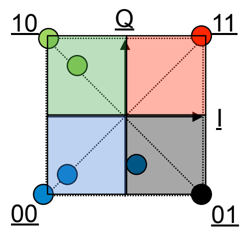

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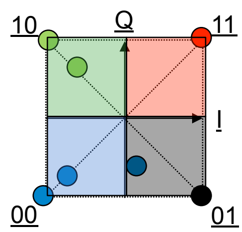
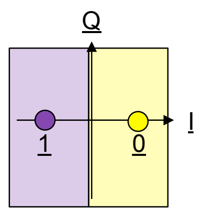
The area of the target…

- **Useful observation:** when the area of the target is small, a small error is sufficient to cause some wrong bits!
- **How could we change this fact in positive?**
- **1) when the channel is noisy, we can use a BPSK with just 2 symbols (distance 180°) , i.e. we increase the target area!**
  - **advantage: all the bits sent are correct despite the noise**
  - **disadvantage: we get half of the nominal bitate (1 bit per symbol)**
  - **00 10 00 01 11 01… = 0 0 1 0 0 0 0 1 1 1 0 1**
- **2) when the channel is good (low noise, a majority of bits received correctly) we can "push on the encoding accelerator" by increasing the nominal bitrate of the channel.**



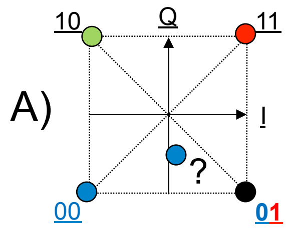


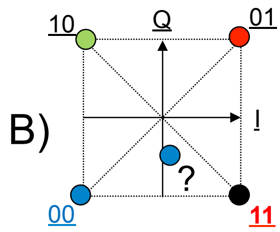
Bits and symbols associations

- **Second observation:** it is highly probable that a noisy channel would cause a symbol to be wrong **but misplaced with the adjacent ones (near to the border).**
- **How to exploit this assumption?**
- **1) we can decide to use a more "intelligent" labelling of the symbols.**
- **Example: what happens if the same symbol is wrong in case A and B?**
- **Case A: sent 00 → received 01: 1 bit error!**
- **Case B: sent 00 → received 11: 2 bit errors!**

N.B. given the same channel noise errors are doubled!!!

- **So, not all the same labelling associations of bits with symbols are equivalent…**





- **The best labelling are those where the number of different bits between adjacent symbols is minimum. So we must find those labelling and use them!**

Detecting wrong bits

- **Third useful observation:** why it is important that max 1 bit is wrong?
- Because we invented a nice algorithm to reveal the wrong bits: **Parity bits.**
- *"given a sequence of bits to transmit, we add a final bit which will make even the number of 1s"*
- **Example. 10010101 0 (4 bits have value one, and 4 is already even)**

Sender
10010101 0 → Receiver
10010101 0

Note: whatever different bit would make the number of ones odd:
This allows to detect the existence of a wrong bit!

Q: what if 2 bits are wrong?

Detect and correct wrong bits

- **Third useful observation:** why it is important that max 1 bit is wrong?
- Because we invented a nice algorithm to reveal the wrong bits, and in case the wrong bit is just one, also to correct it! : **Parity bits matrix.**
- *“Given a sequence of bits to be transmitted we organize the bits in a matrix structure MxN and we put a parity bit after each row (M bits) and column (N bits).”*

Sender

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

Receiver

1 0 0 1 0
0 0 1 0 0 !
0 0 0 1 1
1 1 0 1 1
0 0 1 1
!

Like in a battleship game, if we detect a row and a column with errors we identify the wrong bit!
Then we can also correct it!

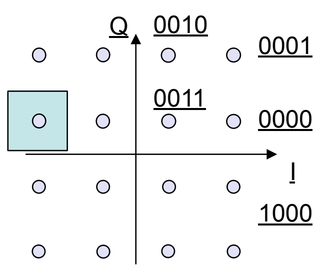
Q: what if the wrong bits are 2?

Quadrature Amplitude Modulation

- **Fourth observation:** what if the channel is even better quality?
- **We can push the encoding even more!**
- **Quadrature Amplitude Modulation (QAM):** it combines modulation of both amplitude and phase of the signal for each transmitted symbol.
- 2^n defined symbols: every symbol identifies by itself a combinatin of n bits!
- …however, be careful, since the area of the target always reduces when n grows!

Area of the target (see figure)

Example in figure: **16-QAM (16 symbols, 1 symbol = 4 bit)**



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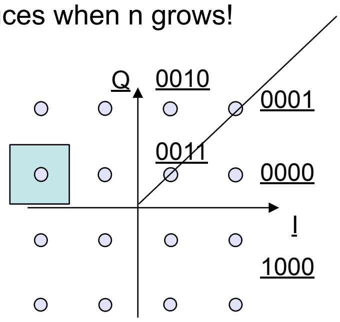

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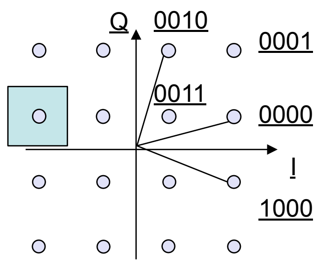


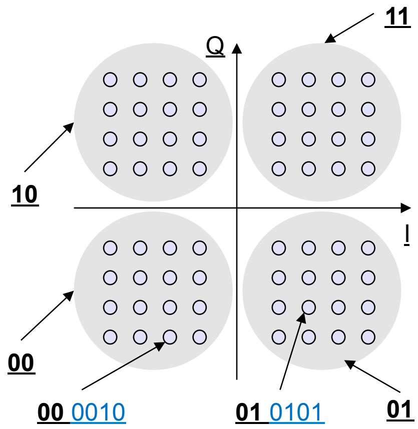
- Note. the symbols 0011 and 0001 have same phase but different amplitude

- This enconding was used in the early 9600 bit/s modems, and also in Digital TV, in Wi-max (multicarrier OFDM)…etc.

- Let's have a look at a simulation of the modulation (with variable channel errors): file:///Users/Luciano/Desktop/Didattica/Mambo_20140315/QAM16_demo/QAM16.html

Hierarchical Modulation

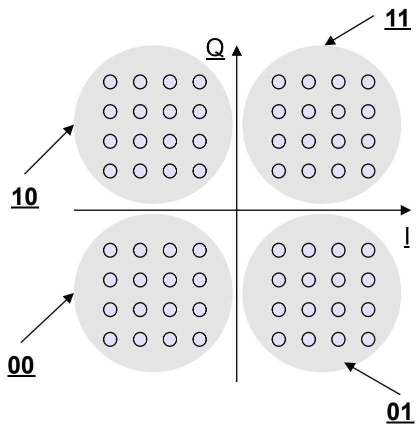
- **Fifth observation:** let's introduce a new magic thing!
- Q1: with the QAM encoding could I modulate two different sequences of bits?
- Q2: and could I give them different priority in transmission (protection from errors)?
- Example: **64-QAM with Hierarchical Modulation**
- **Each symbol oncodes 6 bits!**
  - Each "gray cloud" contains 16 symbols
    - Used to encode the bit sequence with LOW priority
    - …as an example: the video info of a video-call
  - Each "gray cloud" is labelled with the value of a combination of 2 bits
    - Used to encode the bit sequence with HIGH priority
    - …as an example: the voice info of a video-call



  - Q: what happens when channel has low noise?
  - Q: what happens when channel starts having high noise?

The mobile Video-call

- Ex. Let's assume a video-call generates these sequences of bits to transmit:
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…



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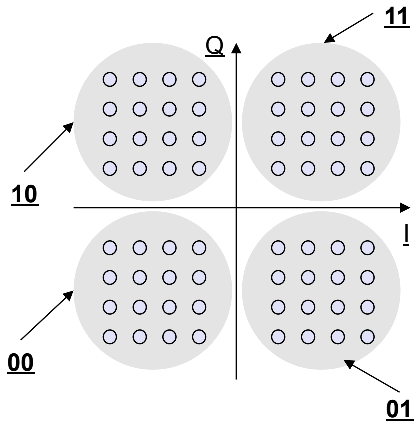
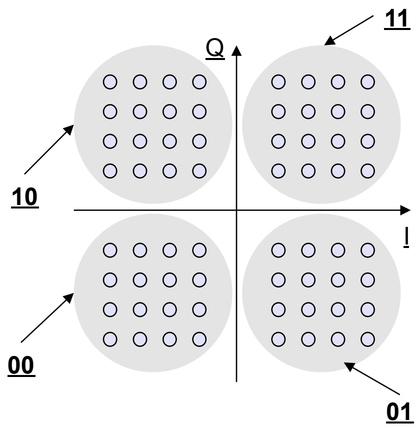
The mobile Video-call

- Ex. Let's assume a video-call generates these sequences of bits to transmit (which will be merged into a unique sequence as follows)
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…
- 100010



The mobile Video-call

- Ex. Let's assume a video-call generates these sequences of bits to transmit (which will be merged into a unique sequence as follows)
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…
- 100010 011001



The mobile Video-call

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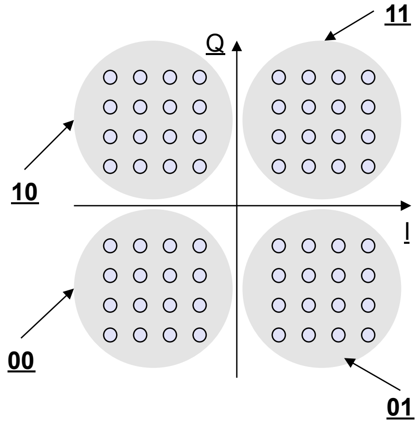
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…
- 100010 011001 111100



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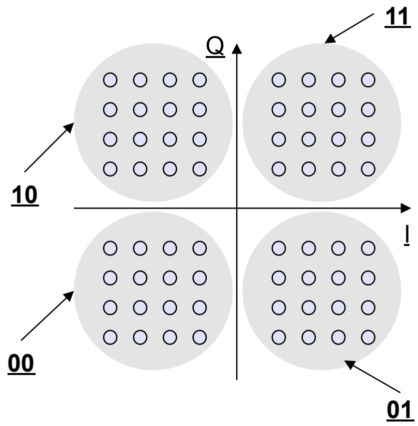
- 100010 011001 111100 000101



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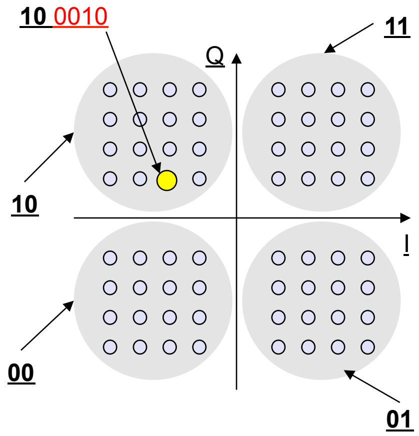
- 100010 011001 111100 000101



Q: what happens if the channel has low noise?

- All the symbols are hit correctly with high probability!

The mobile Video-call

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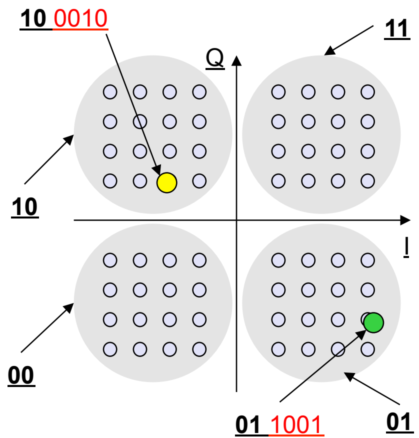

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The mobile Video-call

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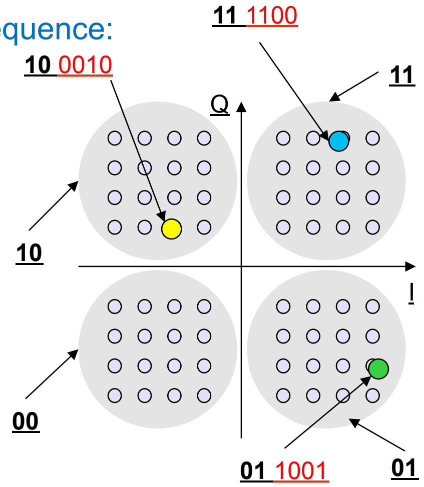

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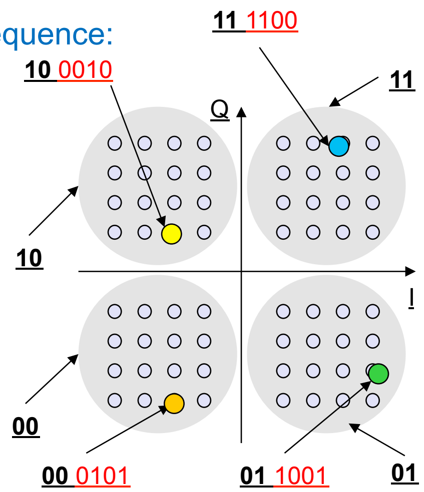

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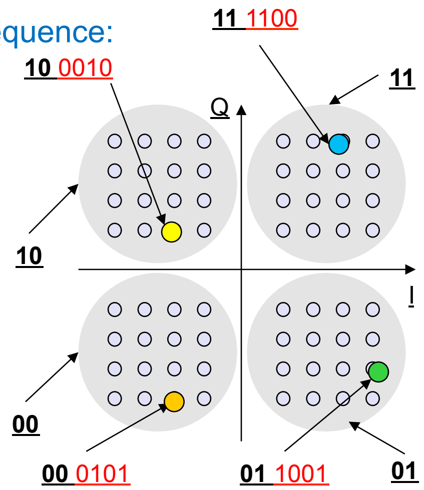


Q: what happens if the channel has low noise?

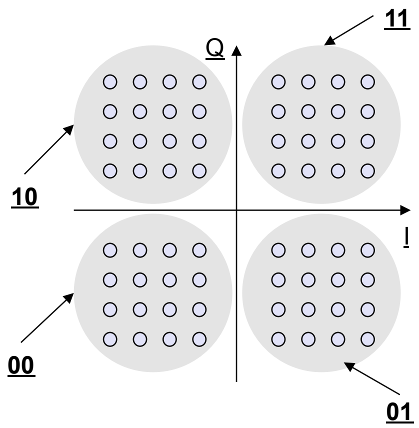
- All the symbols are hit correctly with high probability!
- ...so the receiver can correctly interprete both voice and video

Supercalifragilisti cexpialidocious!!!!

The mobile Video-call

- Ex. Let's assume the call generates the following bit sequence to transmit:
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…
- Which will be merged as the following sequence:
- 100010 011001 111100 000101

Q: what if the channel has a high noise?



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- Voice: 10 01 11 00…
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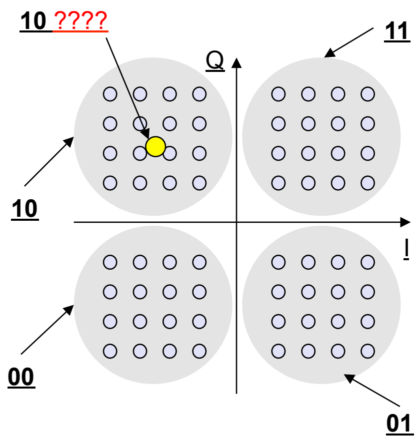
Q: what if the channel has a high noise?

- Many symbols are NOT hit correctly with high probability! ?



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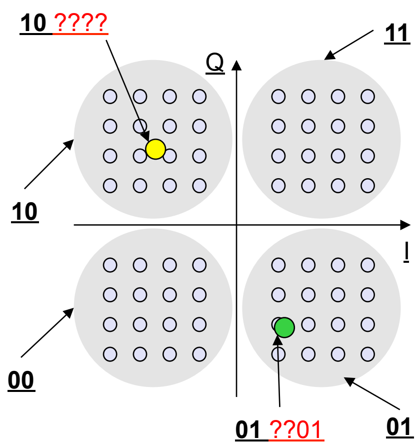

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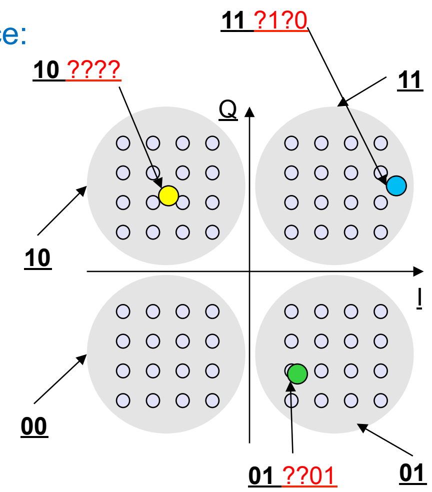

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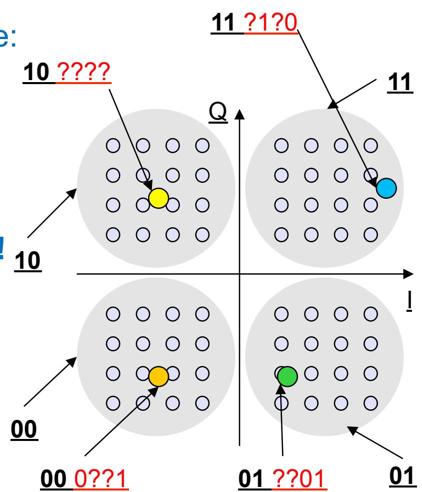
Q: what if the channel has a high noise?

- Many symbols are NOT hit correctly with high probability! ? ? ? ?
  BUT the right CLOUD is always hit correctly!



The mobile Video-call

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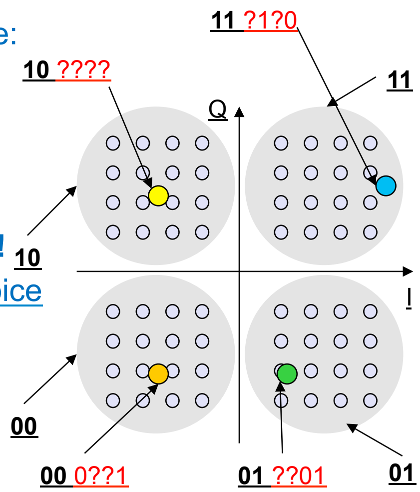
- Voice: 10 01 11 00…
- Video: 0010 1001 1100 0101…
- Which will be merged as the following sequence:
- 100010 011001 111100 000101

Q: what if the channel has a high noise?

- Many symbols are NOT hit correctly with high probability! ? ? ? ?
  BUT the right CLOUD is always hit correctly!
- So the receiver is able to correctly detect the voice by sacrificing the video quality!



Conclusion

Where is the difference between the Good and the Bad in the wireless transmissions, given the same physical conditions?

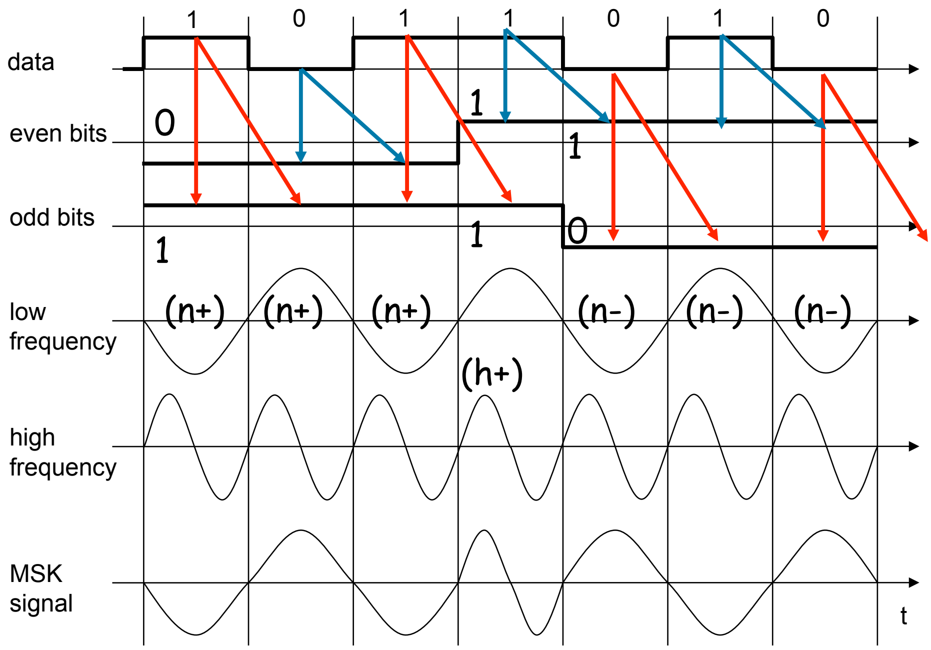
"It is mostly in the the choices about efficient and effective protocol components, data structures and algorithms and HW advances, used in a way based on correct assumptions and by exploiting in the most practical and "intelligent" way the opportunities to turn a drawback or limits into a practical advantage or synergy".

Previous examples clarify the active and relevant role of protocols to achieve a transmission potential in a harsh world.

Advanced Frequency Shift Keying

- bandwidth needed for FSK depends on the distance between the carrier frequencies (range of frequency variation).
- special pre-computation avoids sudden phase shifts
  ➔ MSK (Minimum Shift Keying)
- bit separated into even and odd bits, the duration of each bit is doubled
- depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- the frequency of one carrier is twice the frequency of the other
- Equivalent to offset QPSK (relative to last two phase changes)
  - (US) IS 136, PACS, (Jap) PHS
- even higher bandwidth efficiency using a Gaussian low-pass filter
  ➔ GMSK (Gaussian MSK), used in GSM

Example of MSK



bit	
even	0 1 0 1
odd	0 0 1 1
signal value	h n n h - - + +

h: high frequency
n: low frequency
+: original signal
-: inverted signal

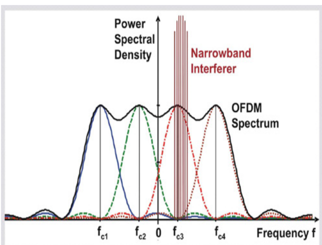
No phase shifts!

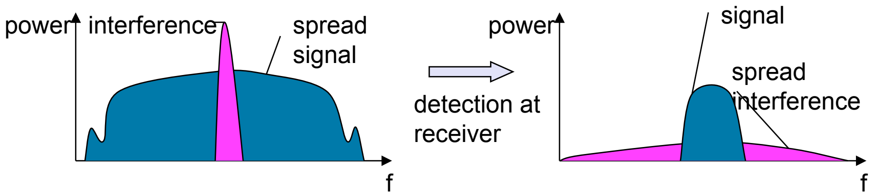
Multi-carrier Modulation (MCM)

- **modulates one high rate data stream onto many low rate bit streams each one modulated on a separate sub-carrier**
  - Orthogonal Frequency Division Multiplexing (OFDM)
    - Is not literally a spread spectrum technology, but it is functionally equivalent
    - Multiple narrowband carriers (with low symbol-rate=strong) modulation (QAM, PSK) = high aggregate symbol rate in the same total bandwidth but more resistant to interference
  - E.g. Digital Audio Broadcasting (DAB): 192 – 1536 subcarriers
- **ISI interference mitigation (few subcarriers affected by selective fading)**
  - Requirements: delay spread of direct and main reflected signals between symbols x and x+1 must be below a certain threshold:
    - <65 nanoseconds in 802.11b (depending on technology) N.B. This is DSSS!
    - <150 nanoseconds in 802.11g (54 Mpbs) N.B. This is OFDM! (better tolerance)
- **Orthogonal carriers reduce error probability**

Spread spectrum technology

- **Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference**
- **E.g. DSSS modulation and correspondent CDMA access technique spread narrowband signal into a broadband signal using special code**
- **protection against narrow band interference**

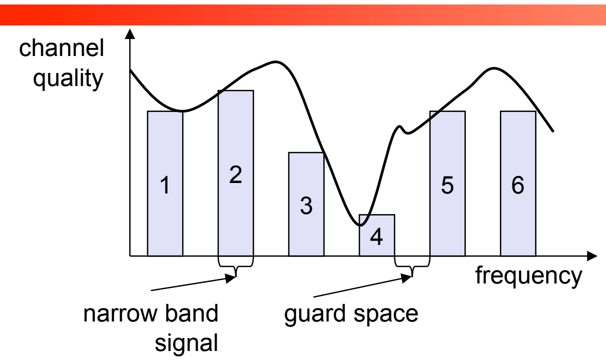




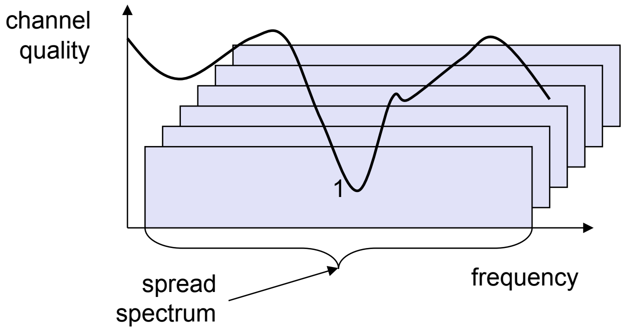
protection against narrowband interference

- **Side effects:**
  - coexistence of several signals without dynamic coordination
  - tap-proof (cannot be detected without knowing the code)
- **Spread spectrum modulation Alternatives: Direct Sequence, Frequency Hopping**

Spreading and frequency selective fading



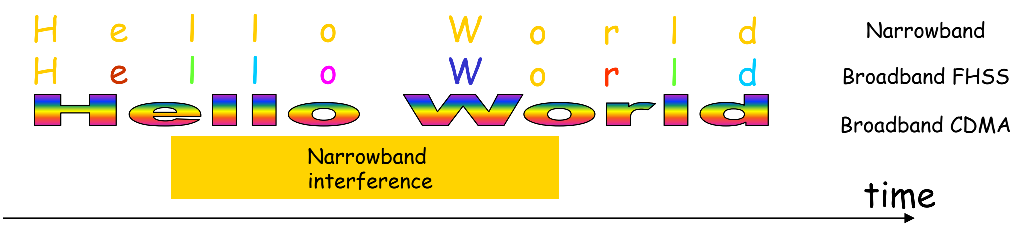
narrowband channels



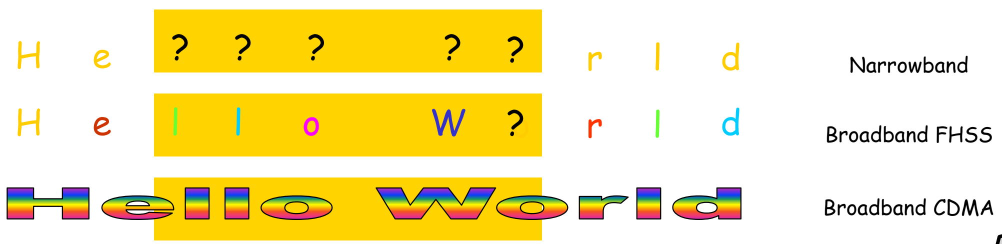
spread spectrum channels

Spread spectrum technology

- **intuitive example: narrowband interference effect on transmission:**
  - transmit “Hello World” coded using narrowband “yellow” frequency and broadband “many colors” frequencies

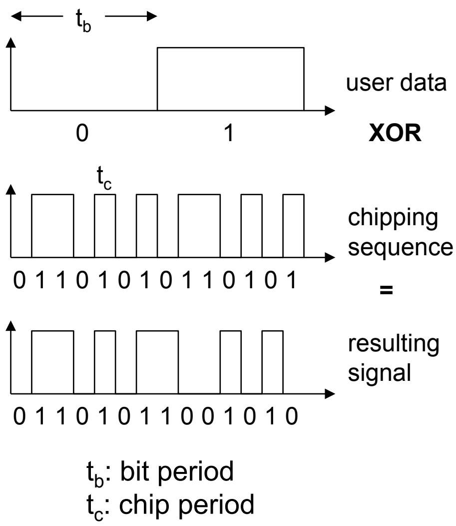


  - a burst of yellow interference adds to the signal for a significant time: what is the result at the receiver?



DSSS (Direct Sequence Spread Spectrum) I

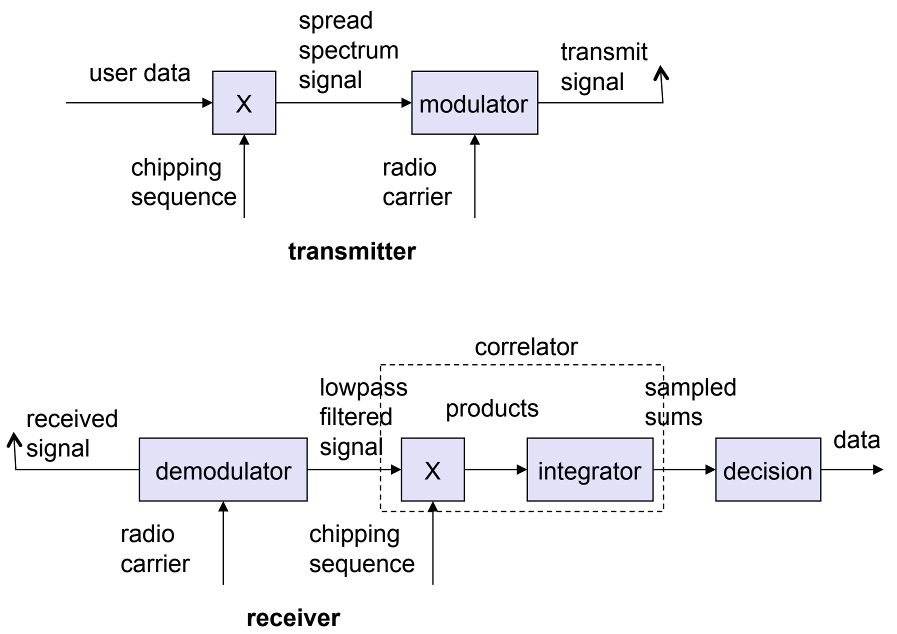
- **XOR of the signal with pseudo-random number (chipping sequence, or Barker sequence)**
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal (low throughput)
- **Advantages**
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover
- **Disadvantages**
  - precise power control and synchronization necessary



DSSS (Direct Sequence Spread Spectrum) IB

- **Resulting signal resemble white noise, but correlation can be exploited by knowing the code (chipping sequence)**
- **Need for strong synchronization between transmitters**
  - Advantage: many transmitters mutually synchronized can achieve a global synchronization (relative timing) which in turn can be used for positioning (e.g. GPS, Galileo)
- **Long chipping sequences for each bit produce high processing gain on the receiver (in dB, similar to using more power). Using a wrong sequence (or no sequence) translates in zero gain (white noise effect). This is the key for implementing the multiple channel access technique based on DSSS: CDMA.**

DSSS (Direct Sequence Spread Spectrum) II

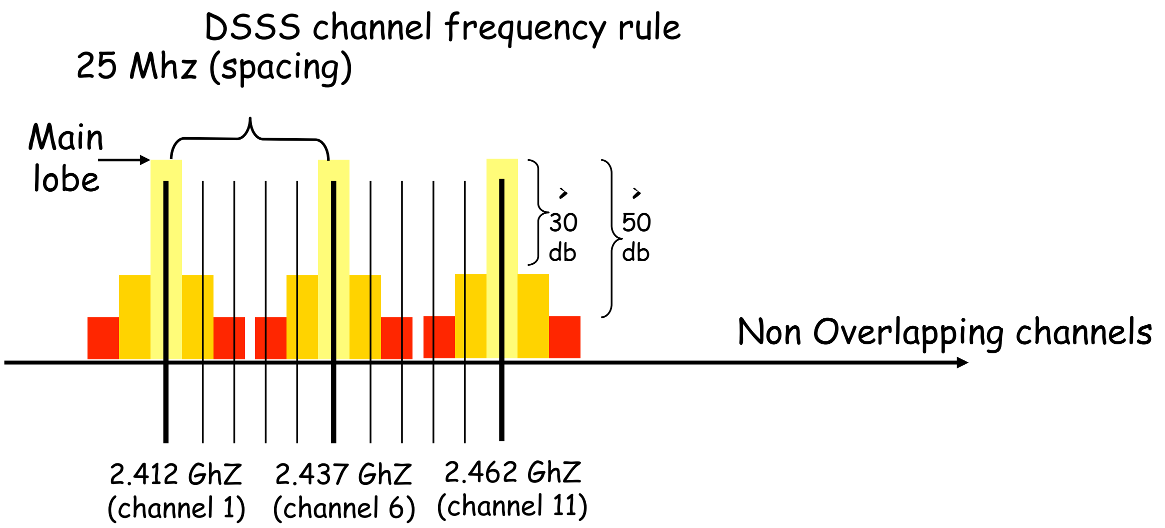


DSSS (Direct Sequence Spread Spectrum) III

IEEE 802.11b DSSS channel frequency assignment

Channel ID	Channel (center) frequencies (GhZ)	USA and Canada	Europe (ETSI)	Spain	Japan	France
1	2.412	Yes	Yes		Yes	
2	2.417	Yes	Yes		Yes	
3	2.422	Yes	Yes		Yes	
4	2.427	Yes	Yes		Yes	
5	2.432	Yes	Yes		Yes	
6	2.437	Yes	Yes		Yes	
7	2.442	Yes	Yes		Yes	
8	2.447	Yes	Yes		Yes	
9	2.452	Yes	Yes		Yes	
10	2.457	Yes	Yes	Yes	Yes	Yes
11	2.462	Yes	Yes	Yes	Yes	Yes
12	2.467		Yes		Yes	Yes
13	2.472		Yes		Yes	Yes
14	2.484				*	

DSSS (Direct Sequence Spread Spectrum) III



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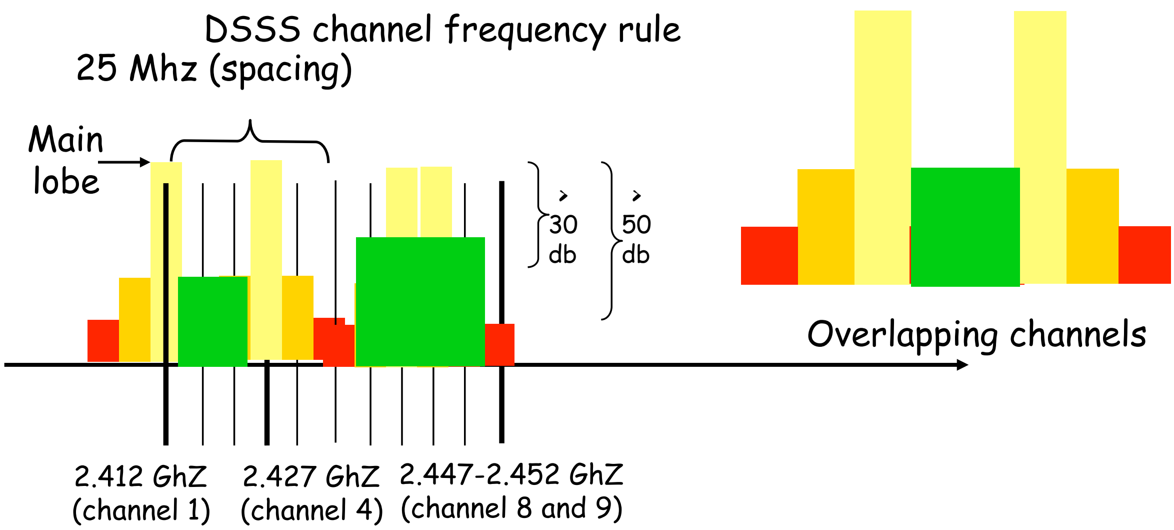


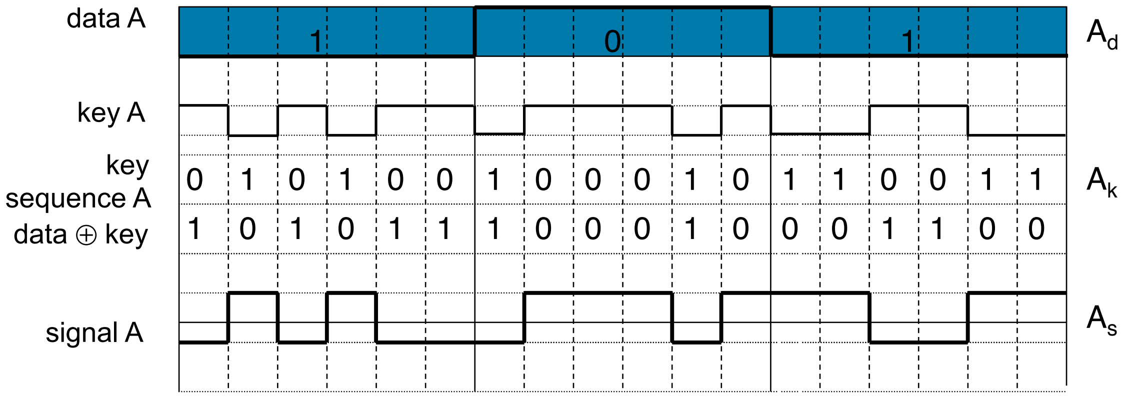
Multiple Access techniques: OFDMA and CDMA

- **Orthogonal Frequency Division Multiple Access (OFDMA)**
  - different subsets of OFDM sub-channels assigned to different users
  - Allows QoS management via subset management, and simple MAC
  - Used in WiMAX (IEEE 802.16)
- **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 pseudo-random number (PRN), and XORs the signal with this random number
  - the receiver can "tune" into this signal via a correlation function, if it knows the PRN
- **Disadvantages:**
  - higher complexity of a receiver
  - 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

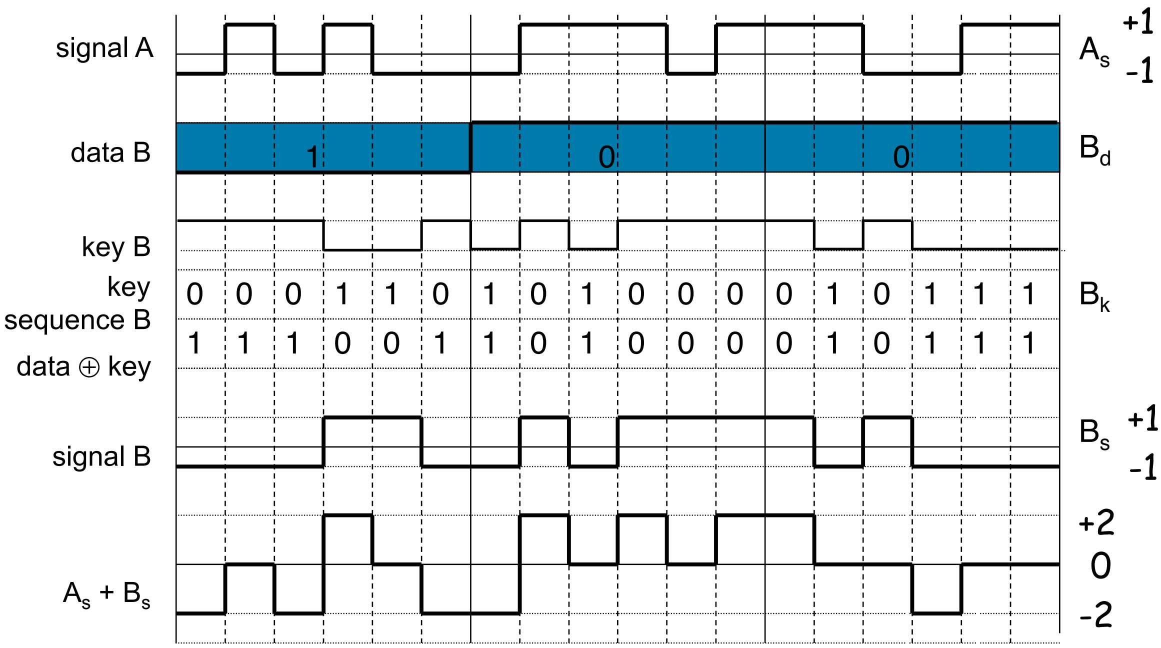
- **Sender A**
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0"= -1, „1"= +1) = (-1, +1, -1, -1, +1, +1)
  - sending signal $A_s = A_d * A_k$ = (-1, +1, -1, -1, +1, +1)
- **Sender B**
  - sends $B_d = 0$, key $B_k = 110101$ (assign: „0"= -1, „1"= +1) = (+1, +1, -1, +1, -1, +1)
  - sending signal $B_s = B_d * B_k$ = (-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) • 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) • B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6, i.e. „0"

CDMA on signal level I

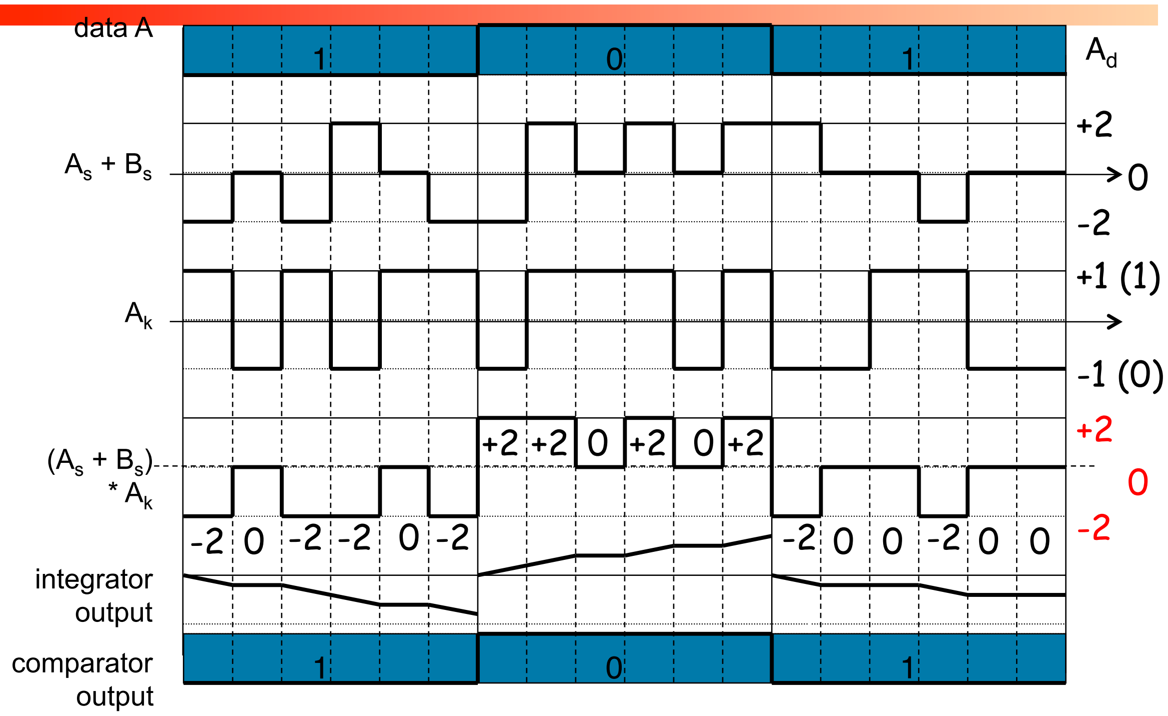


Real systems use much longer keys resulting in a larger distance between single code words in code space.

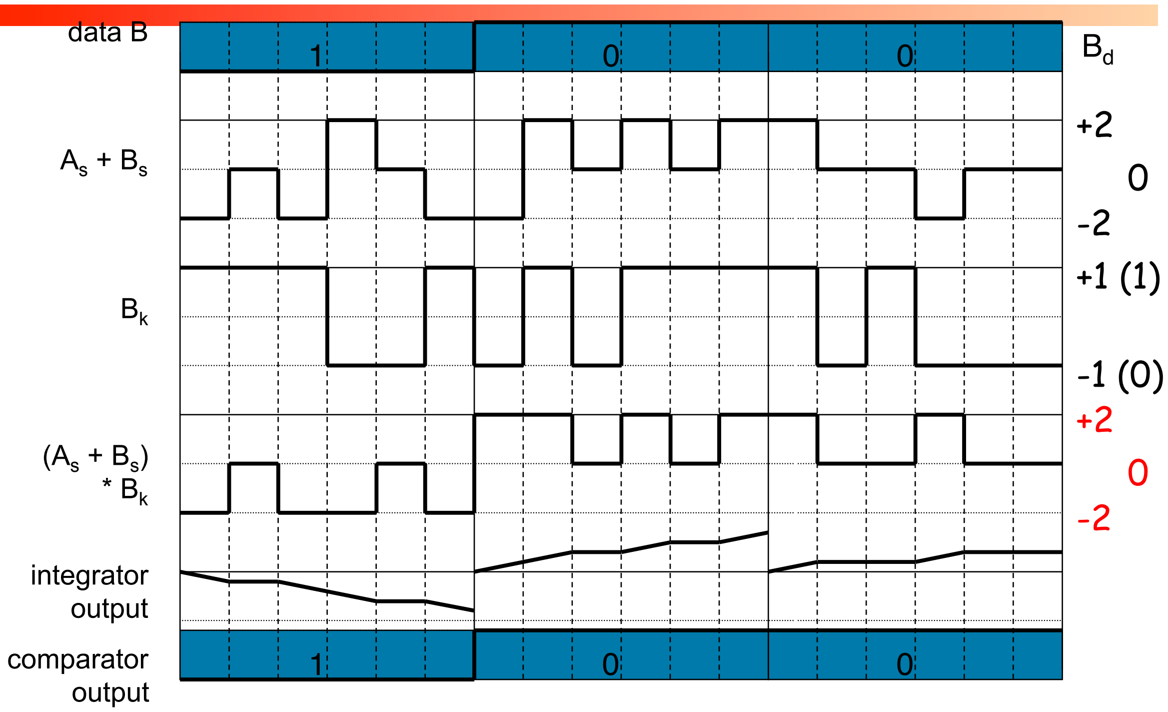
CDMA on signal level II



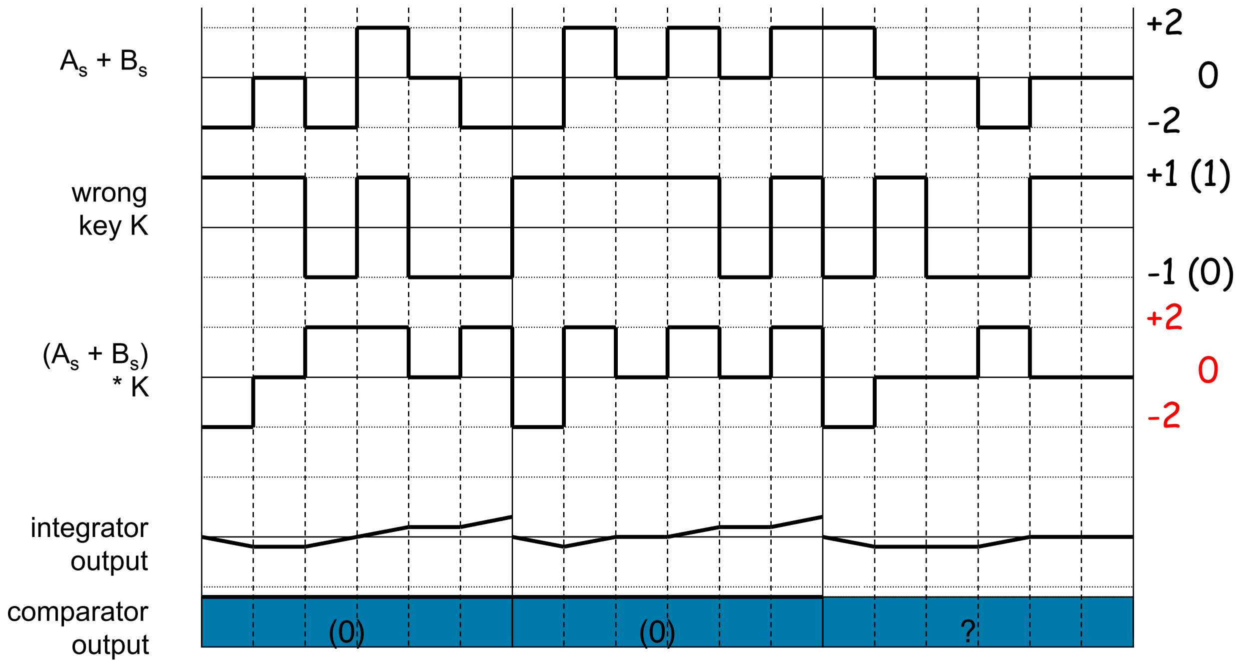
CDMA on signal level III



CDMA on signal level IV



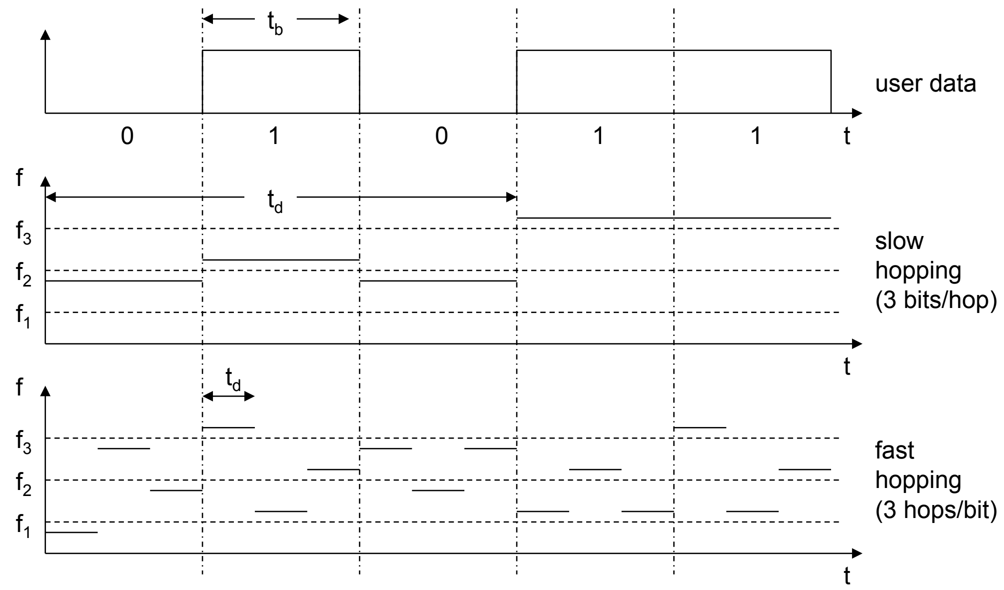
CDMA on signal level V



FHSS (Frequency Hopping Spread Spectrum) I

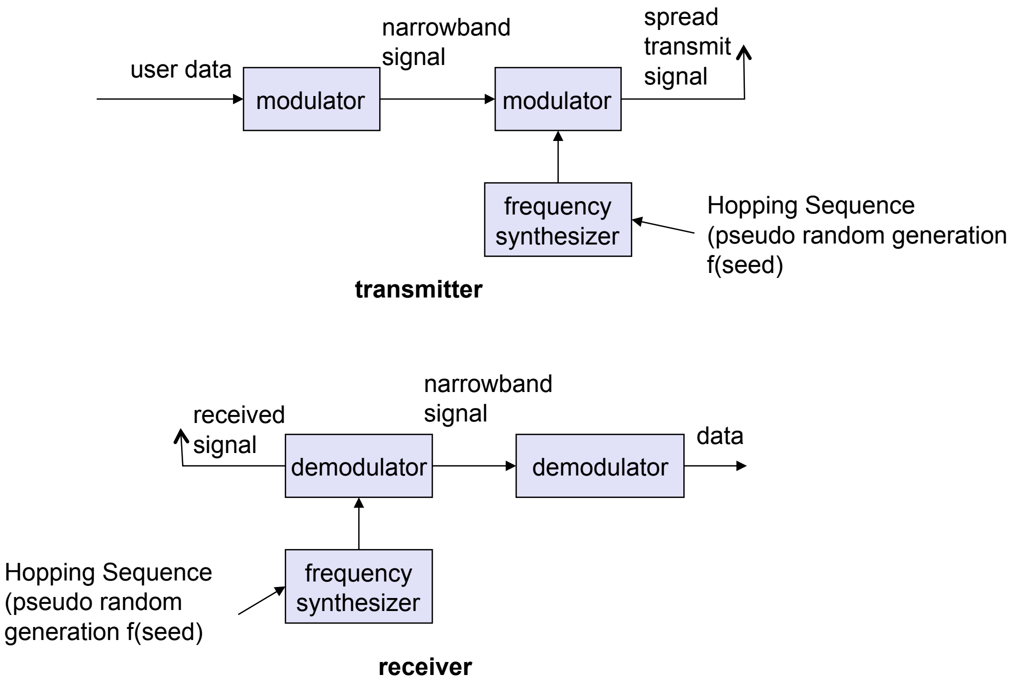
- **Discrete changes of carrier frequency**
  - sequence of frequency changes determined via pseudo random number sequence (e.g. seed = f(host identifier in Bluetooth))
- **Two versions**
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- **Advantages**
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- **Disadvantages**
  - not as robust as DSSS
  - simpler to detect

FHSS (Frequency Hopping Spread Spectrum) II



t_b: bit period t_d: dwell time

FHSS (Frequency Hopping Spread Spectrum) III



OFDM

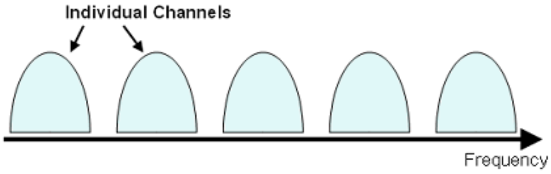
- **Very accurate adjacent communication channels**
  - Transmit data concurrently in parallel subcarriers
    - No need for separate filter for each sub-channel (like in FDM)
    - High bandwidth efficiency (see Nyquist rate formula)
    - Problem: doppler shift (at high speed) of subcarrier frequencies
  - Harmonics cancelation, low cost Fast Fourier Transform chips
  - Convolution coding (error correction with redundant information)
    - More or less similar to: subcarriers transmit "parity bit"
  - OFDM channels: 20 Mhz divided in 52 sub-carriers (300 Khz)
    - 4 subcarriers used as pilot (management)
    - 48 subcarriers used for data (symbols coding = 1 symbol per subcarrier at a time) = 48 concurrent symbols
  - OFDM in 802.11g is not compatible with DSSS in 802.11b!

OFDM

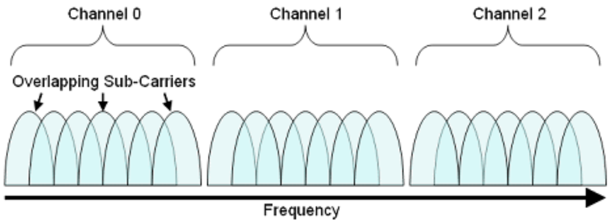
- **Wireless technologies adopting OFDM:**
  - **Ultra Wide Band (UWB) WPAN:**
    - **IEEE 802.15.3a**
  - **WLAN:**
    - **IEEE 802.11 a, g, n and HIPERLAN/2**
  - **Digital radio and TV:**
    - **DAB (EU std), DAB+, HD radio,**
    - **digital Multimedia broadcasting (T-DMB) vs. Digital Video Broadcasting – handheld (DVB-H) in Europe, Digital Video Broadcasting – Terrestrial (DVB-T)**
  - **WMAN:**
    - **IEEE 802.16 (WiMAX), HIPERMAN (3.5 Ghz [2-11 Ghz], ETSI std. Vs. Wi-MAX/ WiBRO)**
  - **Mobile broadband wireless access (MBWA):**
    - **IEEE 802.20, IEEE 802.16e(Mobile WiMAX), WiBRO (Korean Wi-MAX)**

OFDM

- Reprise: Frequency division multiplexing (FDM)
  - non overlapping channels



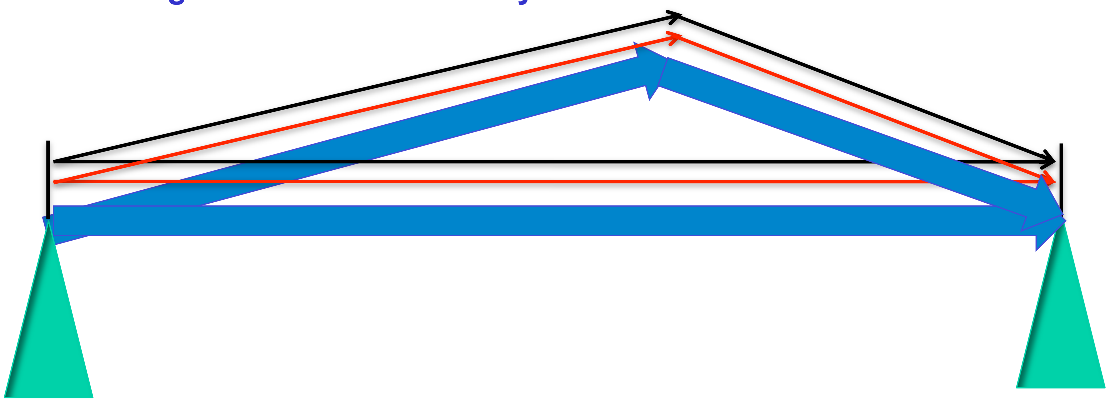
- OFDM: frequency division multiplexing in which a single channel utilizes multiple sub-carriers on adjacent overlapping frequencies



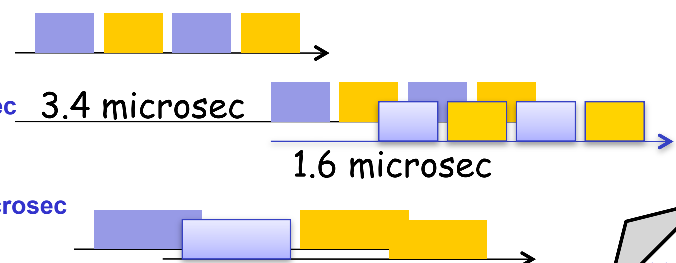
- Spectral efficiency (no guard space)
- Better symbol rate

OFDM

- Advantage of OFDM w.r.t. Intersymbol Interference



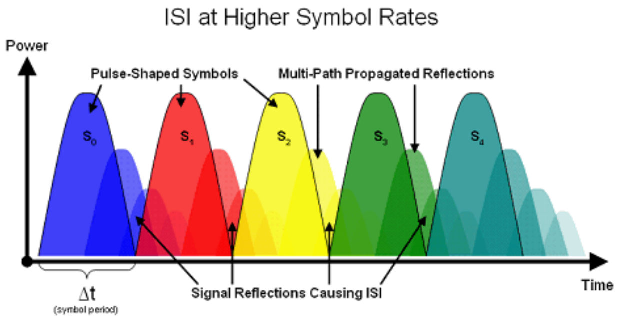
- 1 Msymbol/sec = 1 symbol / microsec
- 1 km distance +- 500 m = 3.4+1.6 microsec



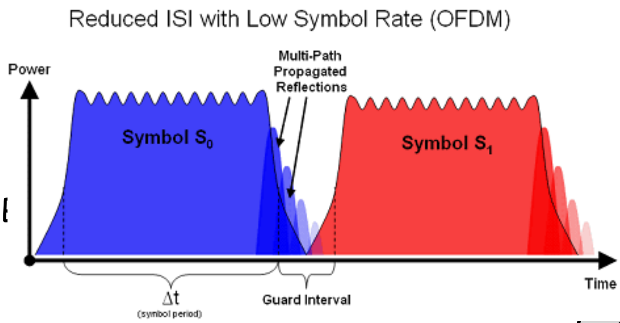
- 10 x 100Ksymbol/sec = 1 symbol / 10 microsec

OFDM

- Advantage of OFDM w.r.t. Intersymbol Interference
- high symbol/rate FDM carriers

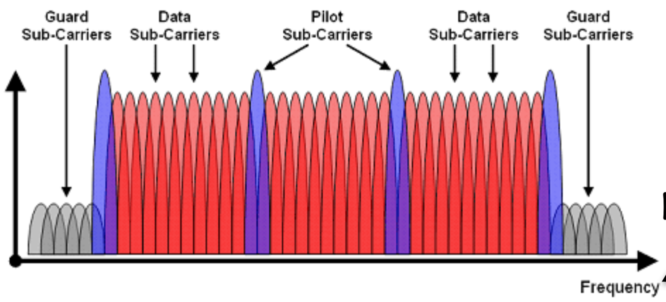


- Low symbol rate OFDM carriers
  BPSK, QPSK, 16-QAM, 64-QAM I



e.g. OFDM

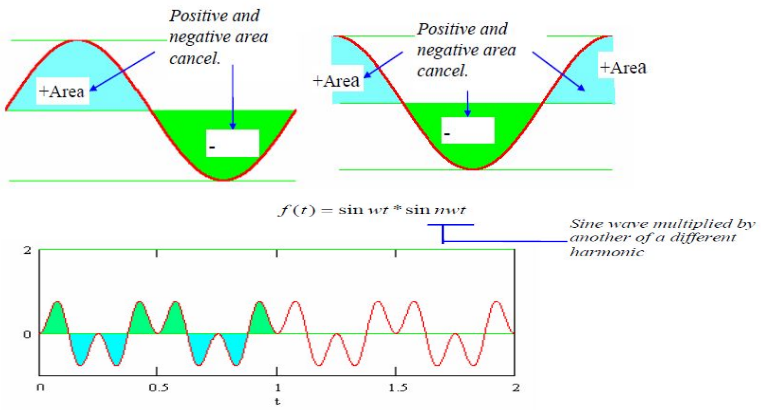
- E.g. IEEE 802.16 (WiMAX): internet access across long wireless communications links (up to 30 miles)
- 1 OFDM channel = 128 to 2048 sub-carriers
  - 1 sub-carrier bandwidth: 9.76 Khz (11.16 kHz in practice)
    - In 1.25 MHz there is space up to 128 subcarriers
    - …Up to 20 MHz (2048 subcarriers)
  - BPSK, QPSK, 16-QAM, or 64-QAM modulation



N.B. Frequency

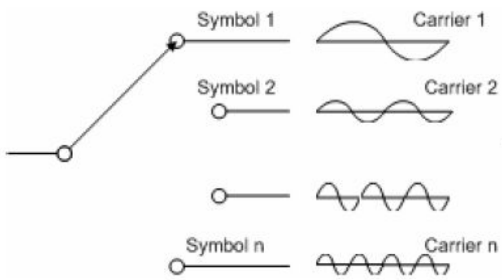
How OFDM works

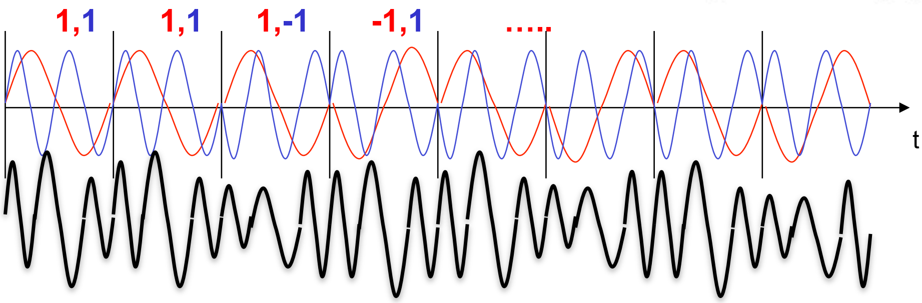
- 1- The importance of orthogonal subcarriers
  - Sin(x) * Sin(kx) = orthogonal signal (Harmonics orthogohality)
  - Cos(x) * Cos(kx) = orthogonal signal
  - In general, all sin(mx), sin(nx), cos(nx), cos(mx) are orthogonal
  - Orthogonal means that integral of signal (t) is zero over period T. This allows simultaneous transmissions on different carriers with no interference



How OFDM works

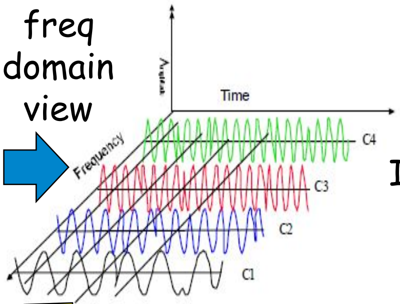
- E.g. OFDM with 4 carriers, 1 symbol per second (total for 4 carriers)
- Bit stream to be modulated (replace 0 with -1): 1 1 -1 -1 1 1 1 -1 1 -1….
- Split the bit sequence in 4 sub-sequences
  - C1 (1 Hz): 1 1 1 -1 1 -1 1 -1…
  - C2 (2 Hz): 1 1 -1 1 -1 -1 -1 1….
  - C3 (3 Hz): -1 1 1 1 1 -1 -1 1….
  - C4 (4 Hz): -1 -1 1 -1 -1 1 1 -1 ….





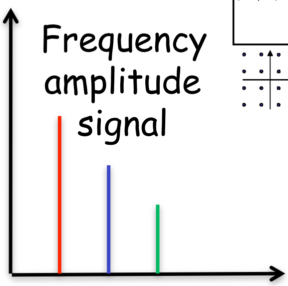
How OFDM works

freq domain view



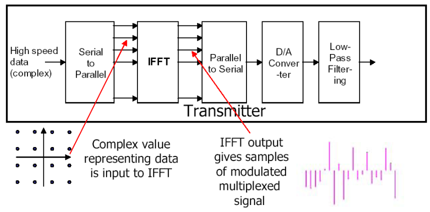
time domain view

IFFT / FFT



Frequency amplitude signal

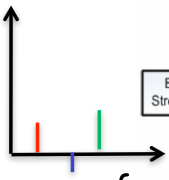
freq



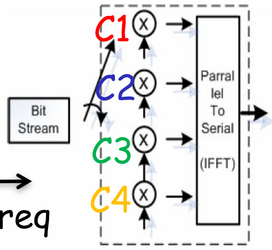
Now think at C1, C2… bits like if they are variable amplitudes of frequencies…

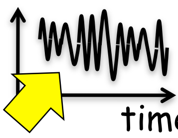
…and apply the IFFT to transform it in a time domain signal:

1 -1 1….



freq





time domain signal

…and viceversa!

Summary of OFDM

- OFDM encoding: ≈ 250.000 phase modulations per second

Data Rate (Mbps)	modulation	Bits coded per phase transition	R = fraction of carriers used for convolution	Length of 1 symbol at the given data rate (#subcarriers * bits coded per symbol)	Data bits encoded in 1 symbol
6	DBPSK	1	1/2	48	24
9	DBPSK	1	3/4	48	36
12	DQPSK	2	1/2	96	48
18	DQPSK	2	3/4	96	72
24	16-QAM	4	1/2	192	96
36	16-QAM	4	3/4	192	144
48	64-QAM	6	2/3	288	192
54	64-QAM	6	3/4	288	216

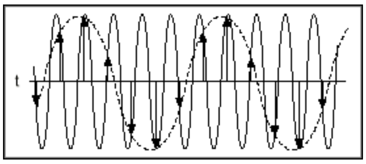
Nyquist Bandwidth and Nyquist rate

- Assumptions:
  - noise free Channel
  - Many possible interpretations:
  - "if the MAX frequency of signal used for transmission is B, then a sampling rate of 2B is needed to re-construct it, (and a signal with symbol rate not greater than 2B can be transmitted)"
  - "Given M symbols that can be coded on the channel by using carrier bandwidth B, the maximum capacity C in bits is:"

$$C = 2B \log_2 M$$

That is, doubling the carrier bandwidth you could double the bitrate

Counter-example: A signal at K Mhz sampled at K+1 Mhz appears as K/5 Mhz



Shannon Capacity Formula

- If the signal to noise ratio is
  - SNR_{dB} = 10 $\log_{10}$(signal power/noise power)
- Then the maximum (error free) channel capacity in bits/second is

$$C = B \log_2(1+SNR)$$

- E.g. channel between 3 Mhz and 4 Mhz and SNR = 24 dB

  B = 4 – 3 Mhz = 1 Mhz

  SNR (in dB) = 24 dB = 10 log10(SNR) => SNR = 251 / 1

By applying Shannon: C = 10E+6 * log2(1+251) = 8 Mbps (ideal scenario)

By applying Nyquist: C = 2B log2 M => 8 Mbps = 2*(10E+6) * log2 M

4 = log2M => M = 16

Network protocols: the glue for integration

- **Networks deal with:**
  - computer hardware, software, operating systems, transmission technology, services defined over it...
    how is it glued?
    and how to glue the existing with the wireless world?
- Communication protocols
  - implemented in software or hardware, transform otherwise isolated machines into **a society of computers**
  - specify how processes in different machines can interact to provide a given service (at different layers)

Communication Protocols

- A set of rules governing the interaction of concurrent processes in a system
- A protocol has mainly five parts:
  - The service it provides
  - The assumptions about the environment where it executes, including the services it enjoys
  - The vocabulary of messages used to implement it
  - The format of each message in the vocabulary
  - The procedure rules (algorithms) guarding the consistency of message exchanges and the integrity of the service provided

Communication Protocols

- **A protocol always involves at least two processes**
  - i.e. Phone call
- **Distributed algorithms**
  - i.e. to define and evaluate the “(wireless) hosts society” behavior
- *Correctness:*
  - The protocol provides the desired service indefinitely, provided operational assumptions are valid.
- *Performance:*
  - Because information and behavior of network are random, we focus on average behavior
- **A protocol must provide its intended service (efficiently)**
  - design choices and protocol definition