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Dipartimento di Scienze dell'Informazione
Corso di Laurea Specialistica in Scienze di Internet (SdI) e Informatica (Inf)

Sistemi e Reti Wireless (2)

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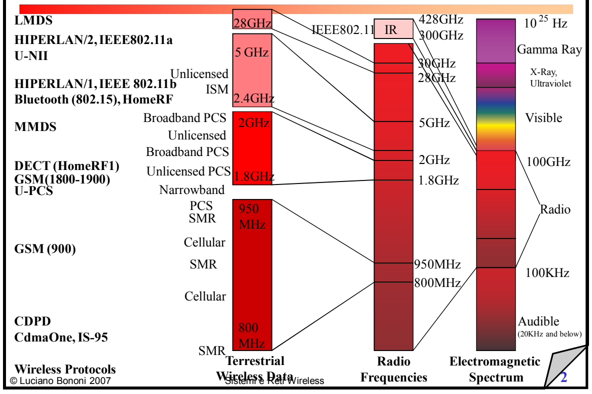
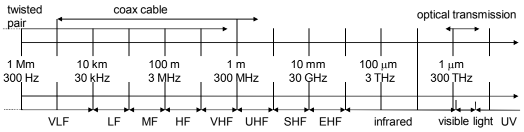
Figure-credits: some figures have been taken from slides published on the Web, by the following authors (in alfabethical order):
J.J. Garcia Luna Aceves (ucsc), James F. Kurose & Keith W. Ross, Jochen Schiller (fub), Nitin Vaidya (uiuc)

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
- UHF = Ultra High Frequency
- SHF = Super High Frequency
- EHF = Extra High Frequency
- UV = Ultraviolet Light
- Frequency and wave length:
- $\lambda = c/f$
- wave length λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f

Frequencies for mobile communication

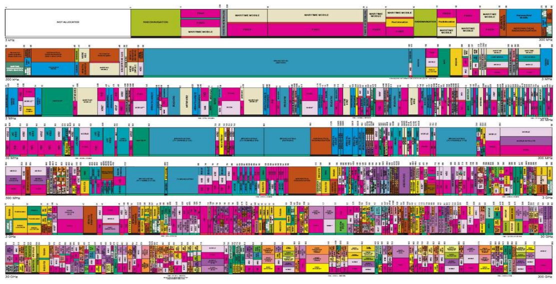
- VHF/UHF ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, large bandwidth available
- Wireless LANs use frequencies in UHF to SHF spectrum
  - 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



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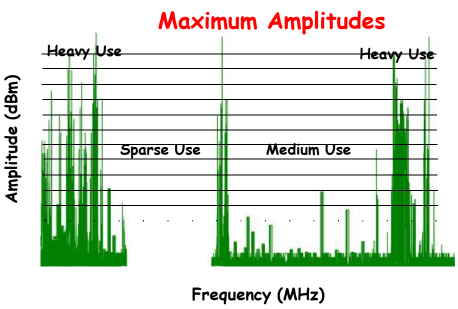
Fixed spectrum utilization



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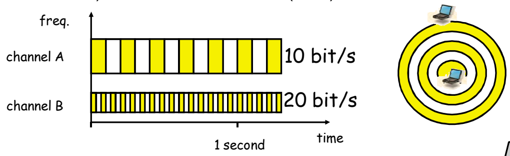
Wireless networks Bandwidth and Spectrum

- **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)

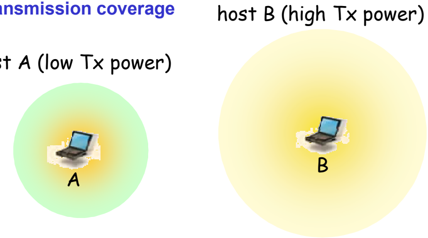


Wireless networks' technology

- **Radio transmission coverage**

host B (high Tx power)

host A (low Tx power)

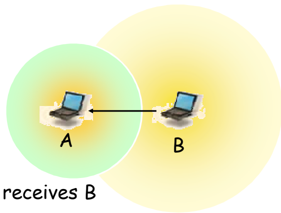


"...is there anybody outhere?"

both isolated

Wireless networks' technology

- **Radio transmission coverage**



A receives B

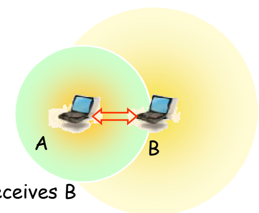
B cannot receive A

unidirectional(*) link

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

Wireless networks' technology

- **Radio transmission coverage**



A receives B

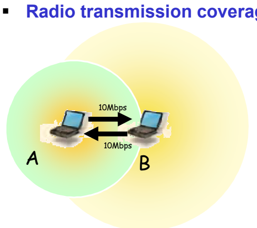
B receives A

bidirectional(*) link

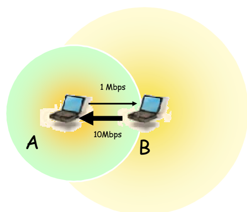
(*) sometimes improperly referred to as "symmetric link"

Wireless networks' technology

- **Radio transmission coverage**



bidirectional symmetric link



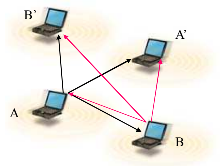
bidirectional asymmetric link

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)

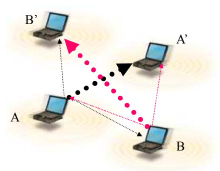
Wireless networks' technology

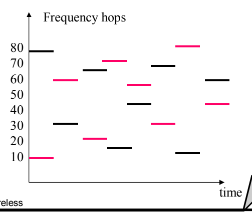
- **Narrowband radio system**
  - transmit/receive using a single, licensed, as narrow as possible radio frequency
  - undesired cross-talk between channels requires coordination and license for each site
  - low data-rates
  - e.g. ⟶ frequency X
  - e.g. ⟶ frequency Y



Wireless networks' technology

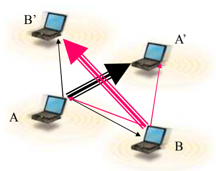
- **Frequency Hopping Spread Spectrum**
  - narrow band carrier changes frequency in a pattern known by both transmitter and receiver (single logical channel)
  - to unintended receiver FHSS appears as impulse noise

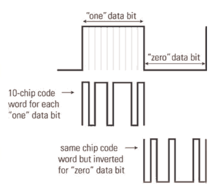




Wireless networks' technology

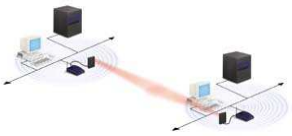
- **Direct Sequence Spread Spectrum**
  - redundant bit pattern (chipping code) spreaded over a large spectrum. Long chips increase probability of recovering the original bit (with no retransmission)
  - to unintended receiver DSSS appears as low power wideband noise





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



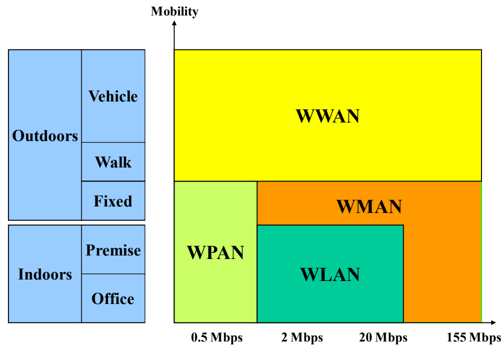
Transmission Technique Comparison

	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

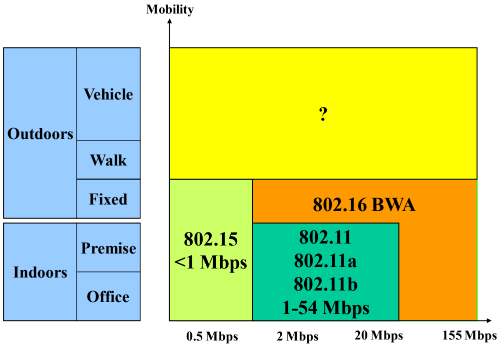
Wireless networks' coverage classification

- **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

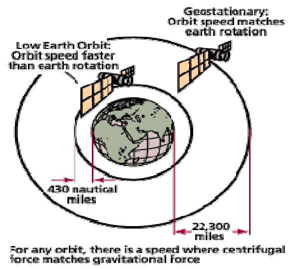


IEEE 802 Wireless standards



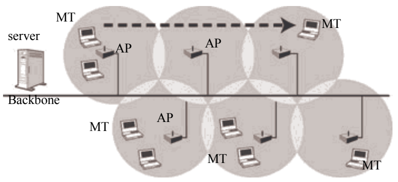
Wireless network structures

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



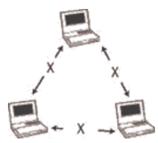
Wireless network structures

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

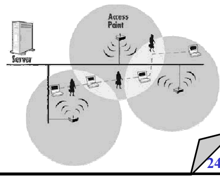


Wireless network structures

- **WLAN:**
  - Ad-Hoc:
    - peer-to-peer (P2P) "on the fly" communication
    - the network "is" the set of computers
    - no administration, no setup, no cost?

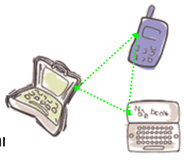


  - Infrastructure:
    - Centralized control unit (Access Point, local server)
    - Roaming between cells
    - resource sharing and backbone connection



Wireless network structures

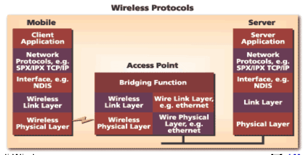
- **WPAN:**
  - cable connection alternative for in-home/office/workspace device connection
  - common technology and protocols required (e.g. HomeRF, Bluetooth)



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

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

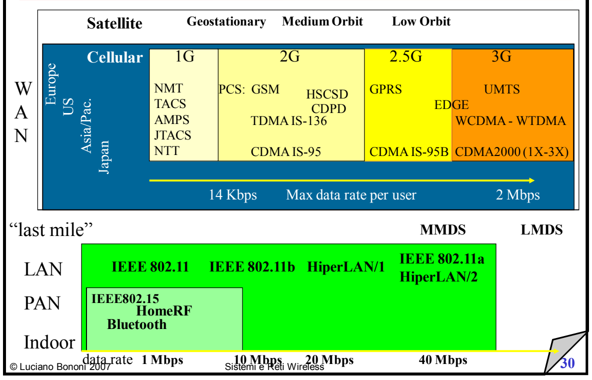
Wireless vs. Wired

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.

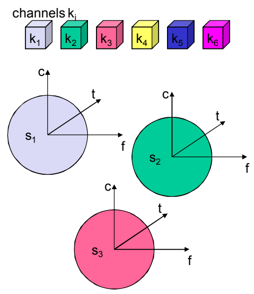
Wireless drawbacks

- **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

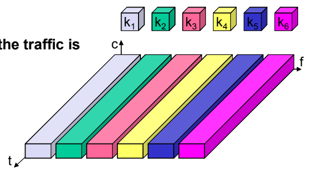
Multiplexing: multiple use of shared medium

- **Multiplexing in 4 dimensions**
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)
- **Goal: multiple use of a shared medium**
- **Important: guard spaces needed!**



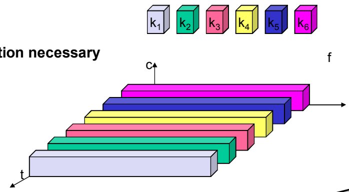
Frequency multiplex

- 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



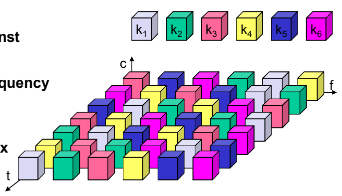
Time multiplex

- 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



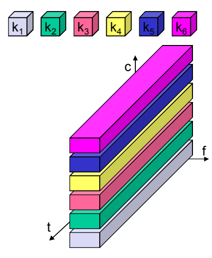
Time and frequency multiplex

- 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

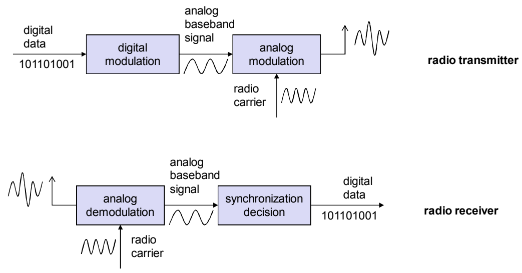
- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages:
  - lower user data rates
  - more complex signal regeneration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



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., λ/4)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

Modulation and demodulation



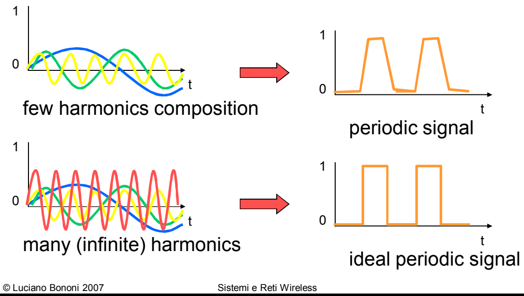
Signals I

- 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:

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

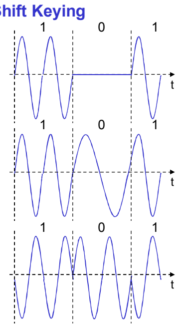
Fourier representation of periodic signals

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



Digital modulation

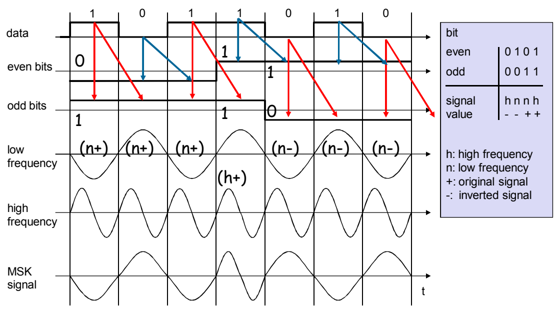
- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - more complex
  - robust against interference



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

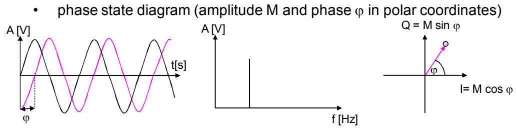
Example of MSK



No phase shifts!

Signals II

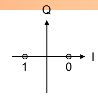
- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

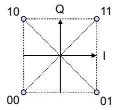


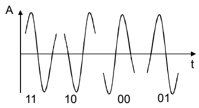
- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

Advanced Phase Shift Keying

- **BPSK (Binary Phase Shift Keying):**
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used e.g. in satellite systems
- **QPSK (Quadrature Phase Shift Keying):**
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex
- **Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)**



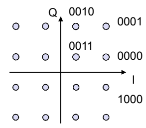




Quadrature Amplitude Modulation

- **Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation**
- **it is possible to code n bits using one symbol**
- **2^n discrete levels, n=2 identical to QPSK**
- **bit error rate increases with n, but less errors compared to comparable PSK schemes**

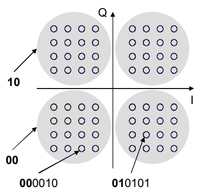
Example: 16-QAM (4 bits = 1 symbol)



- **Symbols 0011 and 0001 have the same phase, but different amplitude. 0000 and 1000 have different phase, but same amplitude.**
- **➔ used in standard 9600 bit/s modems, Digital TV, in Wi-max OFDM…**
- **Simulation example:** http://www.inue.uni-stuttgart.de/german/lehre/lesungen/uet2/applet/QAM16e.html

Hierarchical Modulation

- **modulates two separate data streams onto a single stream**
- **High Priority (HP) embedded within a Low Priority (LP) stream**
- **Multi carrier system, about 2000 or 8000 carriers**
- **QPSK, 16 QAM, 64QAM**
- **Example: 64QAM**
  - good reception: resolve the entire 64QAM constellation
  - poor reception, mobile reception: resolve only QPSK portion
  - 6 bit per QAM symbol, 2 most significant determine QPSK
  - HP service coded in QPSK (2 bit), LP uses remaining 4 bit

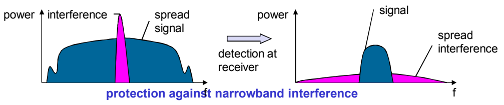


Multi-carrier Modulation (MCM)

- **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
  - Coded Orthogonal Frequency Division Multiplexing (COFDM)
  - E.g. Digital Audio Broadcasting (DAB): 192 – 1536 subcarriers
- **ISI interference mitigation (few subcarriers affected by selective fading)**
  - Delay spread of direct and main reflected signals between symbols x and x+1 must be below a certain threshold:
    - <500 nanoseconds or <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!
- **Orthogonal carriers reduce error probability**

Spread spectrum technology

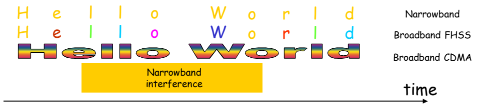
- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- CDMA: spread narrowband signal into broadband signal using special code
- protection against narrow band interference



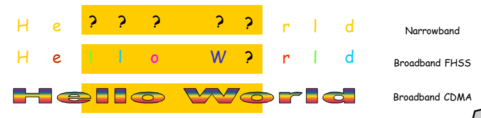
- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof (cannot be detected without knowing the code)
- Alternatives: Direct Sequence, Frequency Hopping

Spread spectrum technology

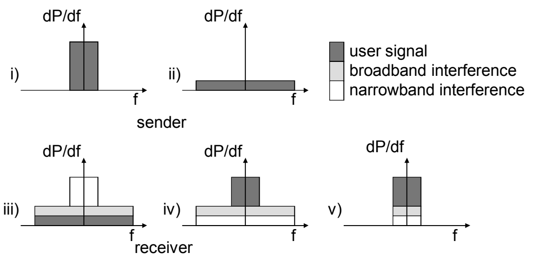
- intuitive example: narrowband interference effect on transmission:
  - transmit “Hello World” coded using narrowband “yellow” frequency and broadband “many colors” frequencies



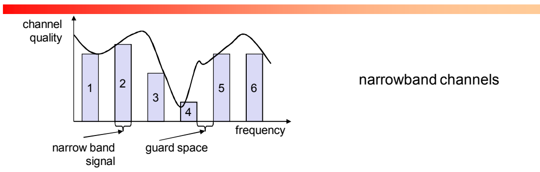
  - a burst of yellow interference adds to the signal for a significant time: what is the result at the receiver?

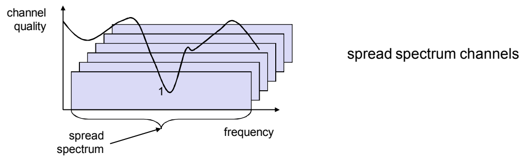


Effects of spreading and interference



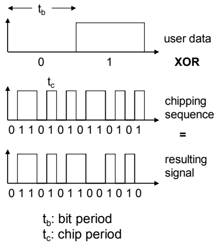
Spreading and frequency selective fading



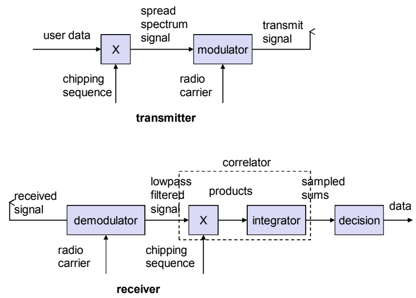


DSSS (Direct Sequence Spread Spectrum) I

- **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 necessary



DSSS (Direct Sequence Spread Spectrum) II



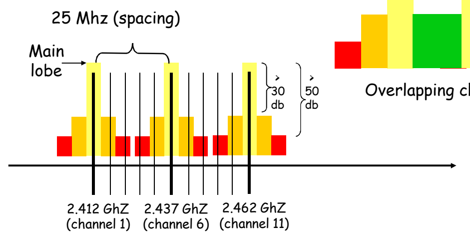
DSSS (Direct Sequence Spread Spectrum) III

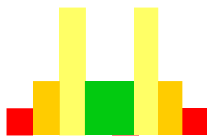
DSSS channel frequency assignment

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

DSSS channel frequency rule



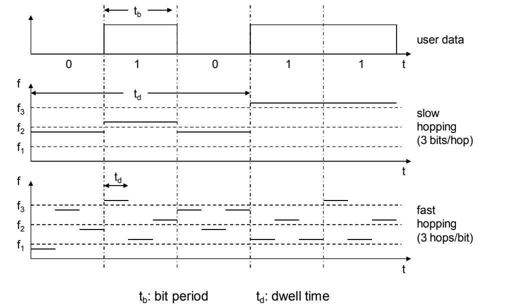


Overlapping channels

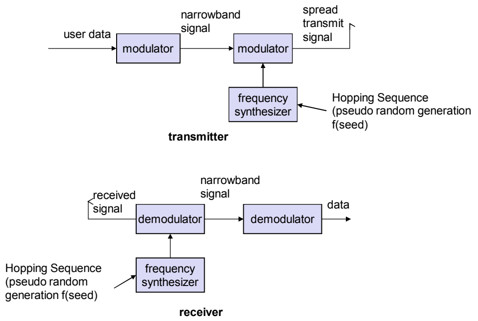
FHSS (Frequency Hopping Spread Spectrum) I

- **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



FHSS (Frequency Hopping Spread Spectrum) III



OFDM

- **Very accurate adjacent communication channels**
  - Transmit data concurrently in parallel subcarriers
  - Harmonics cancelation
  - Convolution coding (error correction with redundant information)
    - More or less similar to: one subcarrier transmits “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!

Summary of OFDM

- OFDM encoding

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

- Assumptions:
  - Channel noise free
  - "if the rate of signal transmission is 2B then a signal with frequency not greater than B is sufficient to carry the data rate"
  - Given M symbols that can be coded on the channel by using carrier with frequency B

$$C = 2B \log_2 M$$

That is, by doubling the carrier bandwidth could duble the bitrate

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 = 24 dB = 10 log10(SNR) => SNR = 251

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

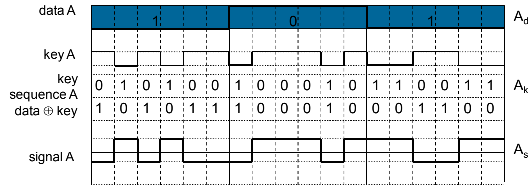
Access method CDMA

- CDMA (Code Division Multiple Access)
  - all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
  - each sender has a unique random number, the sender XORs the signal with this random number
  - the receiver can "tune" into this signal if it knows the pseudo random number, tuning is done via a correlation function
- Disadvantages:
  - higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
  - all signals should have the same strength at a receiver
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g. 2^{32}) compared to frequency space
  - interferences (e.g. white noise) is not coded
  - forward error correction and encryption can be easily integrated

CDMA in theory

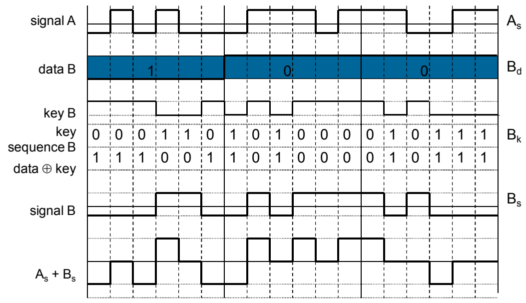
- **Sender A**
  - sends $A_d = 1$, key $A_k = 010011$ (assign: „0"= -1, „1"= +1)
  - sending signal $A_s = A_d * A_k = (-1, +1, -1, -1, +1, +1)$
- **Sender B**
  - sends $B_d = 0$, key $B_k = 110101$ (assign: „0"= -1, „1"= +1)
  - sending signal $B_s = B_d * B_k = (-1, -1, +1, -1, +1, -1)$
- **Both signals superimpose in space**
  - interference neglected (noise etc.)
  - $A_s + B_s = (-2, 0, 0, -2, +2, 0)$
- **Receiver wants to receive signal from sender A**
  - apply key A_k bitwise (inner product)
    - $A_e = (-2, 0, 0, -2, +2, 0) \bullet A_k = 2 + 0 + 0 + 2 + 2 + 0 = 6$
    - result greater than 0, therefore, original bit was „1"
  - receiving B
    - $B_e = (-2, 0, 0, -2, +2, 0) \bullet B_k = -2 + 0 + 0 - 2 - 2 + 0 = -6$, i.e. „0"

CDMA on signal level I

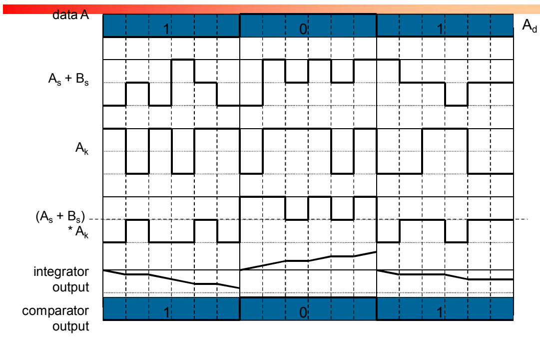


Real systems use much longer keys resulting in a larger distance between single code words in code space.

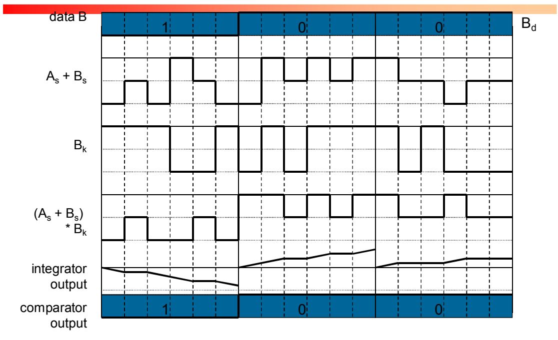
CDMA on signal level II



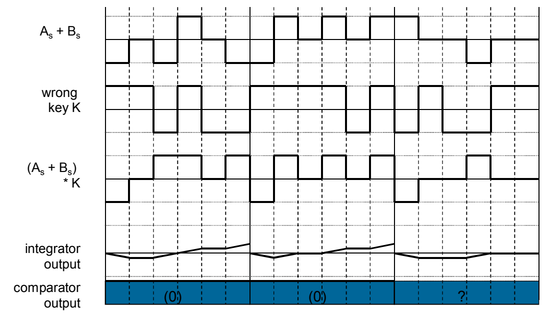
CDMA on signal level III



CDMA on signal level IV



CDMA on signal level V

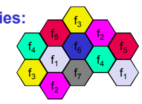


Space division mux: cell structure

- 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

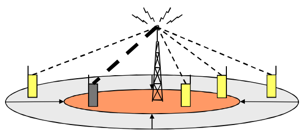
- Frequency reuse only with a certain distance between the base stations
- Standard model using 7 frequencies:



- 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



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