SCHOOL OF INNOVATIVE TECHNOLOGIES & ENGINEERING

Module Information Pack 2

BEng (Hons.) Telecommunications

BTEL v1.2

Wireless Communications

TELC2103

Academic Year 2013/2014

Wireless Communications

- Wireless Frequencies
- Signal Propagation
- Multiplexing

Wireless communication frequencies

- 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, focusing
  - 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 etc.

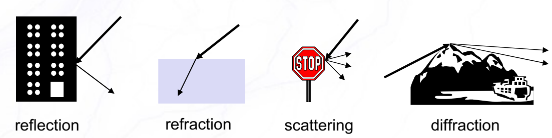
Frequencies and Regulations

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

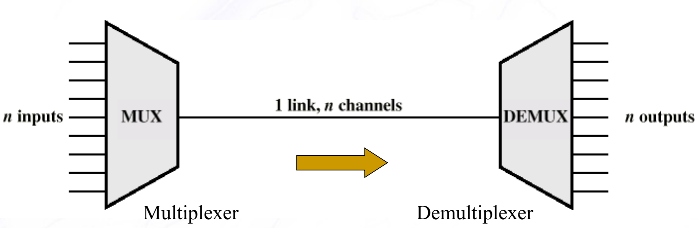
Signal propagation

- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$ (d = distance between sender and receiver)
- Receiving power additionally influenced by
- reflection at large obstacles (>> λ)
- refraction depending on the density of a medium
- scattering at small obstacles (< λ)
- diffraction at edges



Multiplexing

- Multiplexing: A generic term used when more than multiple source share the capacity of one link
- Objective is to achieve better utilization of the link bandwidth (channel capacity)



Motivation

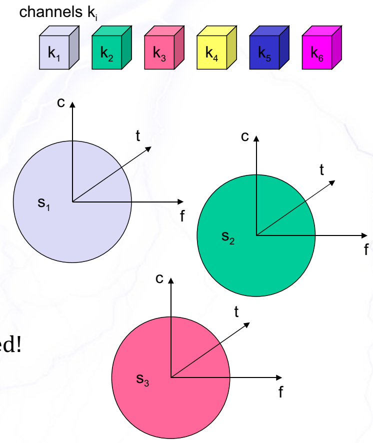
- High capacity (data rate) links are cost effective. i.e. it is more economical to go for large capacity links
- But requirements of individual users are usually fairly modest…e.g. 9.6 to 64 kbps for non intensive (graphics, video) applications
- Solution: Let a number of such users share the high capacity channel (Multiplexing)
- Example: Long haul trunk traffic:
  - High capacity links: Optical fiber, terrestrial microwaves, etc. carrying large number of channels between cities over large distances

Multiplexing

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

Goal: multiple use of a shared medium

Important: guard spaces needed!



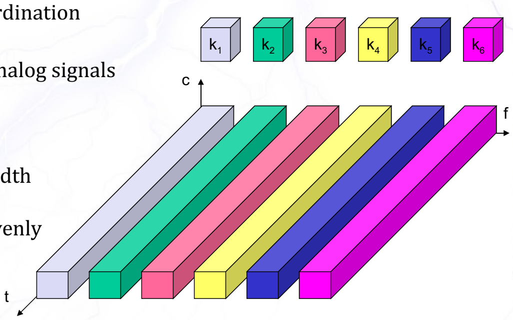
Frequency Division Multiplexing

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

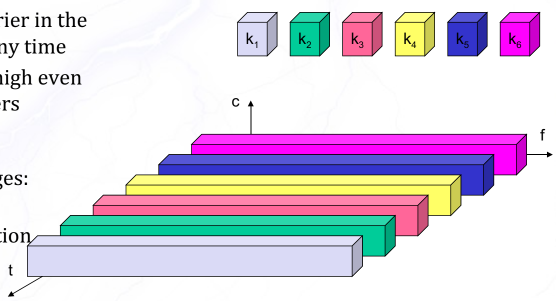


Time Division Multiplexing

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 & Frequency Division Multiplexing

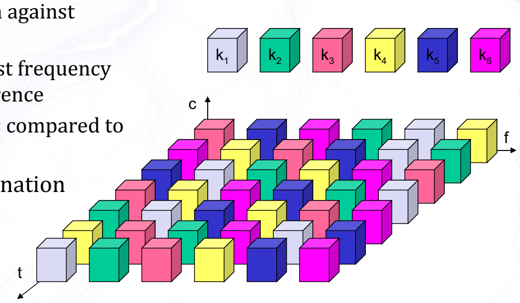
Combination of both methods

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 multiplex

but: precise coordination required



Code Division Multiplexing

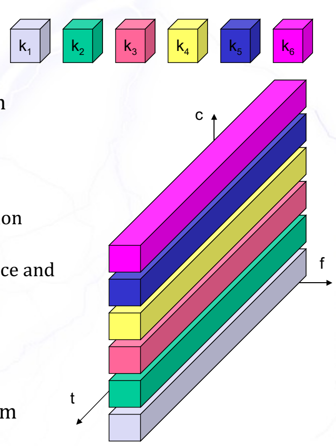
Each channel has a unique code

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



Wireless Communications

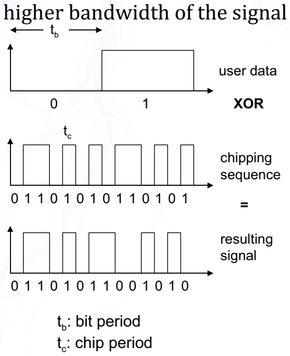
- Spread Spectrum Techniques
- Frequency Planning

DSSS (Direct Sequence Spread Spectrum)

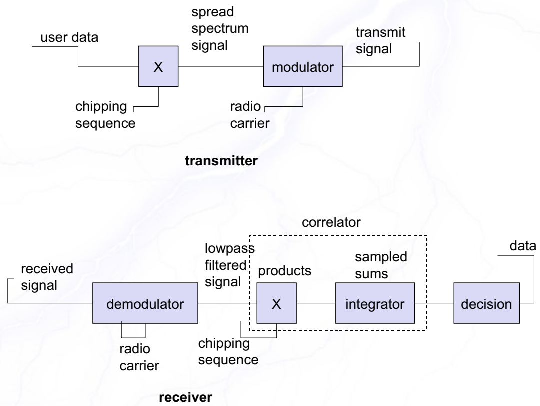
XOR of the signal with pseudo-random number (chipping sequence)
- many chips per bit (e.g., 128) result in higher bandwidth of the signal

Advantages
- 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 (synchronization)



DSSS (Direct Sequence Spread Spectrum)



FHSS (Frequency Hopping Spread Spectrum)

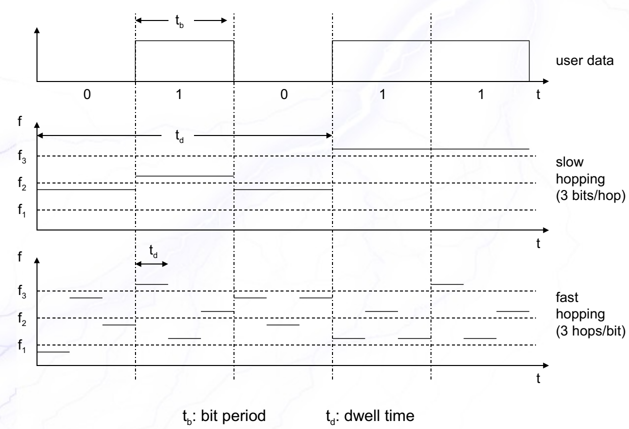
Discrete changes of carrier frequency
- The total bandwidth is split into many channels of smaller bandwidth. Transmitter and receiver stay on one of these channels for a certain time and hop to another channel.
- This system implements FDM and TDM.
- The pattern of channel usage is called the **hopping sequence**, the time spent on a channel with a certain frequency is called the **dwell time**.
- sequence of frequency changes determined via pseudo random number sequence

Two versions
- Fast Hopping: several frequencies per user bit
- Slow Hopping: several user bits per frequency

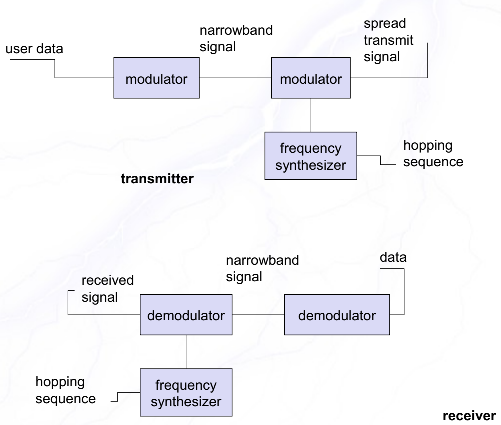
Advantages
- Interference limited to short period
- simple implementation
- uses only small portion of spectrum at any time

Disadvantages
- not as robust as DSSS
- simpler to detect

FHSS (Frequency Hopping Spread Spectrum)



FHSS (Frequency Hopping Spread Spectrum)



Cell structure

Implements space division multiplex: base station covers a certain transmission area (cell)

Mobile stations communicate only via the base station

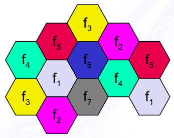
Advantages of cell structures:
- higher capacity, higher number of users
- less transmission power needed
- more robust, decentralized
- base station deals with interference, transmission area etc. locally

Problems:
- Infrastructure needed: fixed network needed for the base stations
- Handover needed: handover (changing from one cell to another) necessary
- Frequency planning: 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

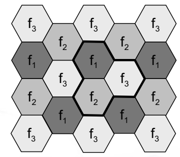
Frequency reuse only with a certain distance between the base stations
Standard model using 7 frequencies:



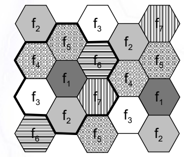
Fixed frequency assignment - Fixed channel allocation (FCA):
- certain frequencies are assigned to a certain cell
- problem: different traffic load in different cells

Dynamic frequency assignment – Dynamic channel allocation (DCA):
- 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

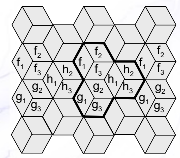
Frequency Planning



3 cell cluster



7 cell cluster



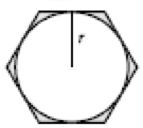
3 cell cluster
with 3 sector antennas

Frequency Planning

The number of cells required for a given area is given by:

$$N = A/a$$

where
- *N = number of cells*
- *A = total area to be covered*
- *a = area of one cell*



This assumes that all cells are of equal size and that there is no overlap between cells, but it serves as a reasonably good estimate.
If hexagonal cells are used, there need be no overlap, at least in theory. (In practice, the cells will not be perfectly hexagonal.) The area of a regular hexagon (one with all six sides equal) is given by:

$$A = 3.464r^2$$

where
- *A = the area of the hexagon*
- *r = the radius of a circle inscribed in the hexagon*

Frequency Planning

In a sectored cell, the total number of users supported per cell obtained by multiplying the number of users per sector by 360/*x* degrees where *x* is the antenna sector angle.

The total data capacity *C* in bps of a network is given by the formula:

$$C = n * S_{eff} * (360/x) * B$$

where
- S_{eff} *= the spectral efficiency of the modulation scheme in bits/Hz*
- *n = the total number of cells in the network*
- *B = the total bandwidth available in Hz*
- *x = the antenna sector angle in degrees.*

Wireless Communications

- Wireless LAN
- Bluetooth

Characteristics of wireless LANs

Advantages
- **Flexibility**: very flexible within the reception area
- **Planning**: Ad-hoc networks without previous planning possible
- **Design**: (almost) no wiring difficulties (e.g. historic buildings, firewalls)
- **Robustness**: more robust against disasters like, e.g., earthquakes, fire - or users pulling a plug
- **Cost**: Adding additional users to a wireless network will not increase the cost.

Disadvantages
- **QoS**: typically low bandwidth compared to wired networks (1-54 Mbit/s)
- **Proprietary solutions**: many proprietary solutions, especially for higher bit-rates, standards take their time (e.g. IEEE 802.11). Now, 802.11g is a popular solution.
- **Restrictions**: products must follow many national restrictions if working wireless, it takes a long time to establish global solutions like, e.g., IMT-2000
- **Safety and security**: Precautions have to be taken to prevent safety hazards. Secrecy and integrity must be assured.

Design goals for wireless LANs

- **Global operation**
- **Low power** for battery use
- **License-free operation**: no special permissions or licenses needed to use the LAN
- **Robust transmission technology**
- **Simplified spontaneous cooperation** at meetings
- **Easy to use** for everyone, simple management
- **Protection of investment** in wired networks
- **Safety and security**: security (no one should be able to read my data), privacy (no one should be able to collect user profiles), safety (low radiation)
- **Transparency for applications**: transparency concerning applications and higher layer protocols, but also location awareness if necessary

Infra-red vs. Radio transmission

Infrared
- uses IR (Infra-Red) diodes, diffuse light, multiple reflections (walls, furniture etc.)

Advantages
- simple, cheap, available in many mobile devices
- no licenses needed
- simple shielding possible

Disadvantages
- interference by sunlight, heat sources etc.
- many things shield or absorb IR light
- low bandwidth

Example
- IrDA (Infrared Data Association) interface available everywhere

Radio
- typically using the license free ISM (Industrial, Scientific, Medical) band at 2.4 GHz

Advantages
- experience from wireless WAN and mobile phones can be used
- coverage of larger areas possible (radio can penetrate walls, furniture)

Disadvantages
- very limited license free frequency bands
- shielding more difficult, interference with other electrical devices

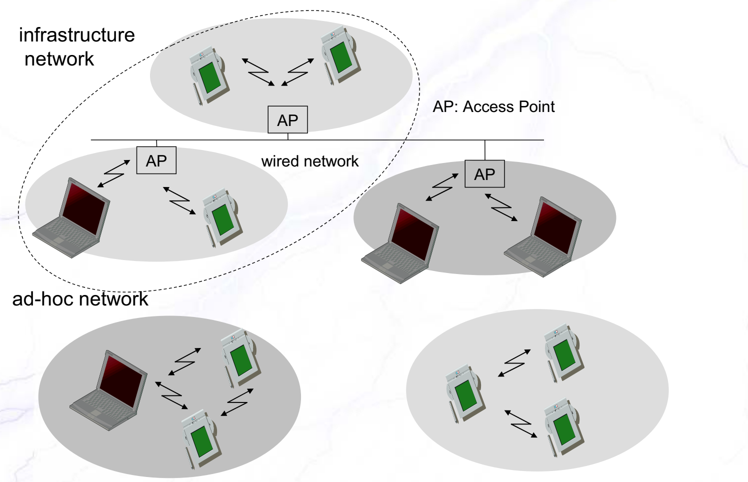
Example
- WLAN, Bluetooth

Infrastructure vs. Ad-hoc networks

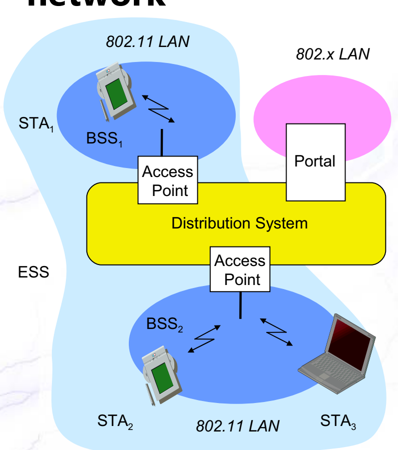
Infrastructure networks
- Provide access to other networks
- Include forwarding functions
- Medium access control

Ad-hoc networks is a group of computers each with wireless adapters, connected as an independent wireless LAN.
- Each node can communicate with other nodes

Infrastructure vs. Ad-hoc networks



802.11 - Architecture of an infrastructure network



Station (STA)
- terminal with access mechanisms to the wireless medium and radio contact to the access point

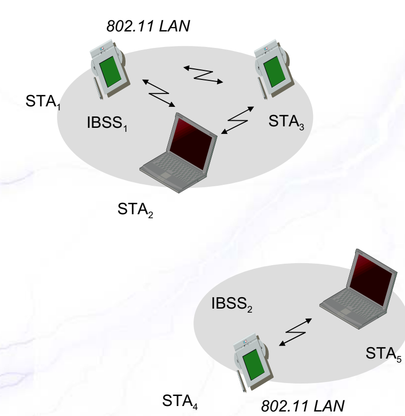
Basic Service Set (BSS)
- group of stations using the same radio frequency

Access Point (AP)
- station integrated into the wireless LAN and the distribution system

Portal
- bridge to other (wired) networks

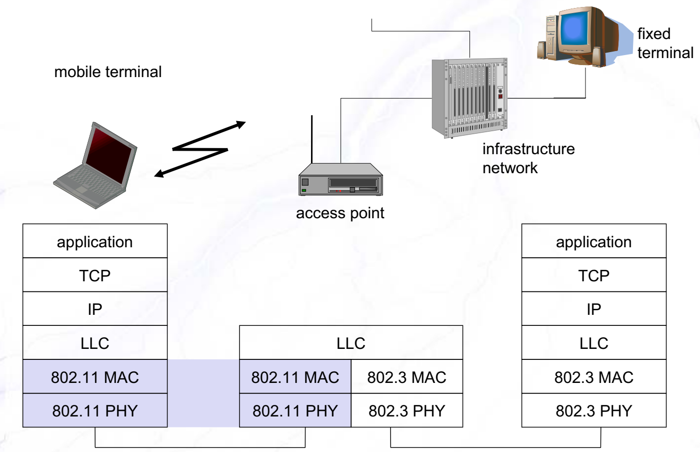
Distribution System
- interconnection network to form one logical network (EES: Extended Service Set) based on several BSS

802.11 - Architecture of an ad-hoc network



Direct communication within a limited range
- Station (STA): terminal with access mechanisms to the wireless medium
- Independent Basic Service Set (IBSS): group of stations using the same radio frequency

IEEE standard 802.11



802.11 - Layers and functions

MAC
- access mechanisms, fragmentation, encryption

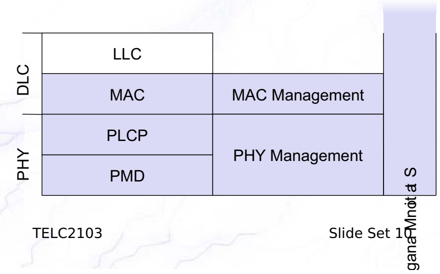
MAC Management
- synchronization, roaming, MIB (Management Information Base), power management

PLCP Physical Layer Convergence Protocol
- clear channel assessment signal (carrier sense)

PMD Physical Medium Dependent
- modulation, coding

PHY Management
- channel selection, MIB

Station Management
- coordination of all management functions



802.11 Physical Layers

Infrared – 1 Mbps and 2 Mbps
- 850-950 nm, infra-red light, typical 10 m range

FHSS (Frequency Hopping Spread Spectrum) uses 79 channels, each 1 MHz wide, starting in the 2.4 GHz band.
- A pseudo-random number generator is used to produce the sequence of frequencies hopped to.
- The amount of time spent at each frequency, dwell time, is adjustable.
- spreading, de-spreading, signal strength, typical 1 Mbit/s
- min. 2.5 frequency hops/s (USA), 2-level GFSK modulation, 4-level GFSK for 2Mbit/s

802.11 - Physical layer

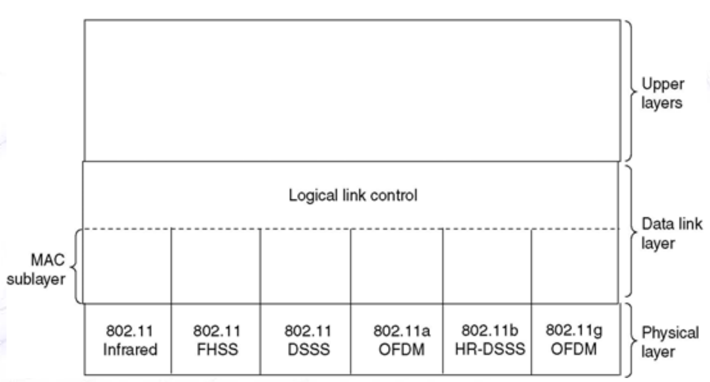
DSSS (Direct Sequence Spread Spectrum) delivers 1 or 2 Mbps in the 2.4 GHz band.
- DBPSK modulation for 1 Mbit/s (Differential Binary Phase Shift Keying), DQPSK for 2 Mbit/s (Differential Quadrature PSK)
- preamble and header of a frame is always transmitted with 1 Mbit/s, rest of transmission 1 or 2 Mbit/s
- chipping sequence: +1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1 (Barker code)
- max. radiated power 1 W (USA), 100 mW (EU), min. 1mW

802.11a uses OFDM (Orthogonal Frequency Division Multiplexing) to deliver up to 54 Mbps in the 5 GHz band.

802.11b uses HR-DSSS (High Rate Direct Sequence Spread Spectrum) to achieve 11 Mbps in the 2.4 GHz band.

802.11g uses OFDM to achieve 54 Mbps in the 2.4 GHz band.

The 802.11 Protocol Stack



Wireless LAN Standards

Standard	Modulation	Spectrum	Max physical Rate	Working distance
802.11	WDM, FHSS DSSS	2.4 GHz	2 Mbps	≈100 m
802.11a	OFDM	5 GHz	54 Mbps	≈ 50 m
802.11b	HR-DSSS	2.4 GHz	11 Mbps	≈ 200 m
802.11g	OFDM	2.4 GHz	54 Mbps	≈ 200 m

Wireless LANS Devices

wireless router

wireless network card

802.11x - Frame format

Types
- control frames, management frames, data frames

Sequence numbers
- important against duplicated frames due to lost ACKs

Addresses
- receiver, transmitter (physical), BSS identifier, sender (logical)

Miscellaneous
- sending time, checksum, frame control, data

bytes	2	2	6	6	6	2	6	0-2312	4
	Frame Control	Duration/ ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	Data	CRC

bits	2	2	4	1	1	1	1	1	1	1	1
	Protocol version	Type	Subtype	To DS	From DS	More Frag	Retry	Power Mgmt	More Data	WEP	Order

MAC address format

scenario	to DS	from DS	address 1	address 2	address 3	address 4
ad-hoc network	0	0	DA	SA	BSSID	-
infrastructure network, from AP	0	1	DA	BSSID	SA	-
infrastructure network, to AP	1	0	BSSID	SA	DA	-
infrastructure network, within DS	1	1	RA	TA	DA	SA

DS: Distribution System
AP: Access Point
DA: Destination Address
SA: Source Address

BSSID: Basic Service Set Identifier
RA: Receiver Address
TA: Transmitter Address

- Ad-hoc network: packet exchanged between two wireless nodes without a distribution system
- Infrastructure network, from AP: a packet sent to the receiver via the access point
- Infrastructure network, to AP: a station sends a packet to another station via the access point
- Infrastructure network, within DS: packets transmitted between two access points over the distribution system.

Special Frames: ACK, RTS, CTS

Acknowledgement

ACK bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

Request To Send

RTS bytes	2	2	6	6	4
	Frame Control	Duration	Receiver Address	Transmitter Address	CRC

Clear To Send

CTS bytes	2	2	6	4
	Frame Control	Duration	Receiver Address	CRC

802.11 - MAC management

Synchronization
- try to find a LAN, try to stay within a LAN
- Synchronize internal clocks and generate beacon signals

Power management
- periodic sleep, frame buffering, traffic measurements
- sleep-mode without missing a message

Association/Reassociation
- integration into a LAN
- roaming, i.e. change networks by changing access points
- scanning, i.e. active search for a network

MIB - Management Information Base
- All parameters representing the current state of a wireless station and an access point are stored in a MIB.
- A MIB can be accessed via SNMP.

WLAN: IEEE 802.11b

Data rate
- 1, 2, 5.5, 11 Mbit/s, depending on SNR
- User data rate max. approx. 6 Mbit/s

Transmission range
- 300m outdoor, 30m indoor
- Max. data rate ~10m indoor

Frequency
- Free 2.4 GHz ISM-band

Security
- Limited, WEP insecure, SSID

Cost
- 100€ adapter, 250€ base station, dropping

Availability
- Many products, many vendors

Connection set-up time
- Connectionless/always on

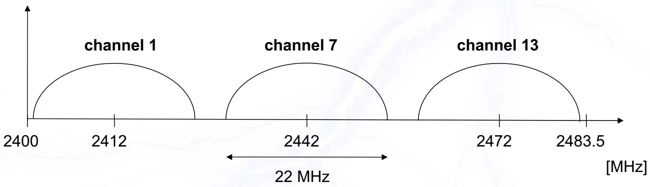
Quality of Service
- Typ. Best effort, no guarantees (unless polling is used, limited support in products)

Manageability
- Limited (no automated key distribution, sym. Encryption)

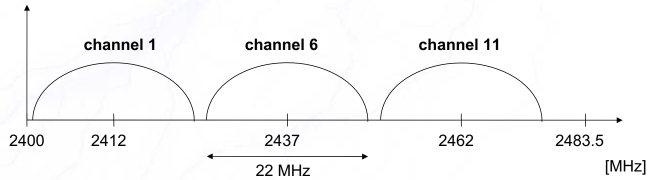
Special Advantages/Disadvantages
- Advantage: many installed systems, lot of experience, available worldwide, free ISM-band, many vendors, integrated in laptops, simple system
- Disadvantage: heavy interference on ISM-band, no service guarantees, slow relative speed only

Channel selection (3 non-overlapping)

Europe (ETSI)



US (FCC)/Canada (IC)



WLAN: IEEE 802.11a

Data rate
- 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s, depending on SNR
- User throughput (1500 byte packets): 5.3 (6), 18 (24), 24 (36), 32 (54)
- 6, 12, 24 Mbit/s mandatory

Transmission range
- 100m outdoor, 10m indoor
  - E.g., 54 Mbit/s up to 5 m, 48 up to 12 m, 36 up to 25 m, 24 up to 30m, 18 up to 40 m, 12 up to 60 m

Frequency
- Free 5.15-5.25, 5.25-5.35, 5.725-5.825 GHz ISM-band

Security
- Limited, WEP insecure, SSID

Cost
- 280€ adapter, 500€ base station

Availability
- Some products, some vendors

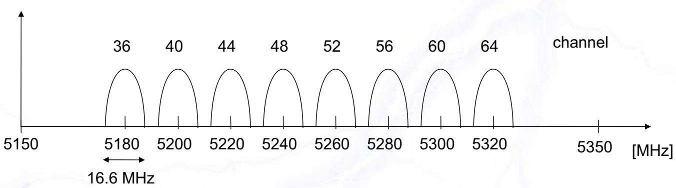
Connection set-up time
- Connectionless/always on

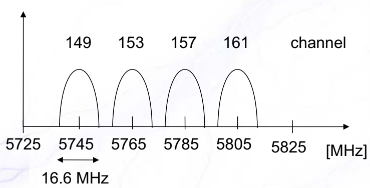
Quality of Service
- Typ. best effort, no guarantees (same as all 802.11 products)

Manageability
- Limited (no automated key distribution, sym. Encryption)

Special Advantages/Disadvantages
- Advantage: fits into 802.x standards, free ISM-band, available, simple system, uses less crowded 5 GHz band
- Disadvantage: stronger shading due to higher frequency, no QoS

Operating channels for 802.11a

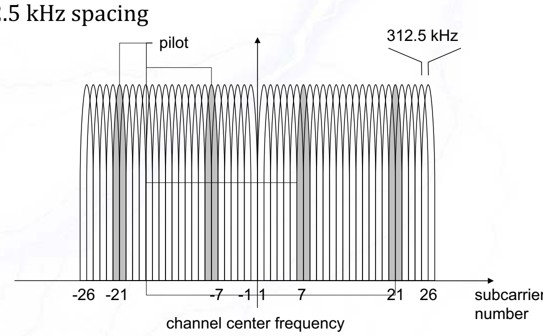




center frequency =
5000 + 5*channel number [MHz]

OFDM in IEEE 802.11a

OFDM with 52 used subcarriers (64 in total)
- 48 data + 4 pilot
- (plus 12 virtual subcarriers)
- 312.5 kHz spacing



WLAN: IEEE 802.11g

Data rate
- OFDM: 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s CCK: 1, 2, 5.5, 11 Mbit/s
- User throughput (1500 byte packets): 5.3 (6), 18 (24), 24 (36), 32 (54)
- 6, 12, 24 Mbit/s mandatory

Transmission range
- 300m outdoor, 30m indoor
  - E.g., 54 Mbit/s up to 5 m, 48 up to 12 m, 36 up to 25 m, 24 up to 30m, 18 up to 40 m, 12 up to 60 m

Frequency
- Free 2.4 – 2.497 GHz ISM-band

Security
- Limited, WEP insecure, SSID

Cost
- Check market for the price of adapter, base station

Availability
- more products, more vendors

Connection set-up time
- Connectionless/always on

Quality of Service
- Typ. best effort, no guarantees (same as all 802.11 products)

Manageability
- Limited (no automated key distribution, sym. Encryption)

Special Advantages/Disadvantages
- Advantage: fits into 802.x standards, free ISM-band, available, simple system
- Disadvantage: heavy interference on ISM-band, no service guarantees

WLAN: IEEE 802.11 – future developments

802.11d: Regulatory Domain Update – completed

802.11e: MAC Enhancements – QoS – ongoing
- Enhance the current 802.11 MAC to expand support for applications with Quality of Service requirements, and in the capabilities and efficiency of the protocol.

802.11f: Inter-Access Point Protocol – ongoing
- Establish an Inter-Access Point Protocol for data exchange via the distribution system.

802.11g: Data Rates > 20 Mbit/s at 2.4 GHz; 54 Mbit/s, OFDM – complete

802.11h: Spectrum Managed 802.11a (DCS, TPC) – ongoing

802.11i: Enhanced Security Mechanisms – ongoing
- Enhance the current 802.11 MAC to provide improvements in security.

Study Groups
- 5 GHz (harmonization ETSI/IEEE) – closed
- Radio Resource Measurements – started
- High Throughput – started

Bluetooth (802.15.x)

Idea
- Universal radio interface for ad-hoc wireless connectivity
- Interconnecting computer and peripherals, handheld devices, PDAs, cell phones – replacement of IrDA
- Embedded in other devices, goal: 5€/device (2002: 50€/USB bluetooth)
- Short range (10 m), low power consumption, license-free 2.45 GHz ISM
- Voice and data transmission, approx. 1 Mbit/s gross data rate

One of the first modules (Ericsson).

Bluetooth

History
- 1994: Ericsson (Mattison/Haartsen), "MC-link" project
- Renaming of the project: Bluetooth according to Harald "Blåtand" Gormsen [son of Gorm], King of Denmark in the 10th century
- 1998: foundation of Bluetooth SIG. (was: Bluetooth)
- 1999: erection of a rune stone at Ercisson/Lund ;-)
- 2001: first consumer products for mass market, spec. version 1.1 released

Special Interest Group
- Original founding members: Ericsson, Intel, IBM, Nokia, Toshiba
- Added promoters: 3Com, Agere (was: Lucent), Microsoft, Motorola
- > 2500 members
- Common specification and certification of products

IEEE founded IEEE 802.15 for Wireless Personal Area Networks (WPAN)

Bluetooth™

Characteristics

2.4 GHz ISM band, 79 (23) RF channels, 1 MHz carrier spacing
- Channel 0: 2402 MHz … channel 78: 2480 MHz
- G-FSK modulation, 1-100 mW transmit power

FHSS and TDD
- Frequency hopping with 1600 hops/s
- Hopping sequence in a pseudo random fashion, determined by a master
- Time division duplex for send/receive separation

Voice link – SCO (Synchronous Connection Oriented)
- FEC (forward error correction), no retransmission, 64 kbit/s duplex, point-to-point, circuit switched

Data link – ACL (Asynchronous ConnectionLess)
- Asynchronous, fast acknowledge, point-to-multipoint, up to 433.9 kbit/s symmetric or 723.2/57.6 kbit/s asymmetric, packet switched

Topology
- Overlapping piconets (stars) forming a scatternet

Piconet

Collection of devices connected in an ad hoc fashion

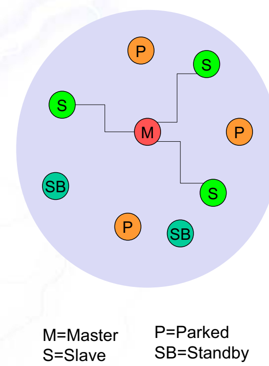
One unit acts as master and the others as slaves for the lifetime of the piconet

Master determines hopping pattern, slaves have to synchronize

Each piconet has a unique hopping pattern

Participation in a piconet = synchronization to hopping sequence

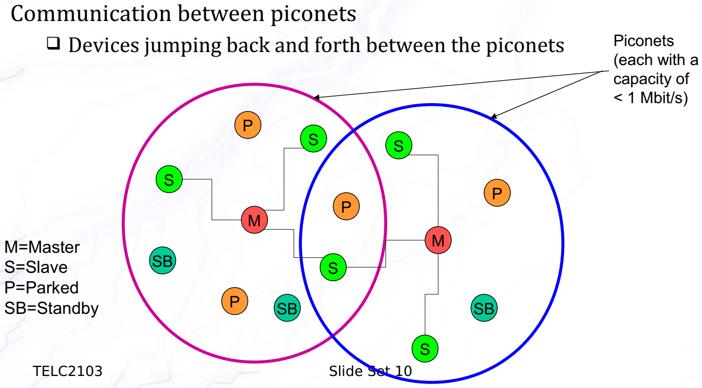
Each piconet has one master and up to 7 simultaneous slaves (> 200 could be parked)



Scatternet

Linking of multiple co-located piconets through the sharing of common master or slave devices
- Devices can be slave in one piconet and master of another
  - As soon as a master leaves a piconet, all traffic within this piconet is suspended until the master returns.

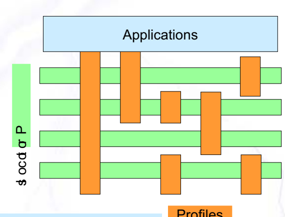
Communication between piconets
- Devices jumping back and forth between the piconets



Profiles

Represent default solutions for a certain usage model
- Vertical slice through the protocol stack
- Basis for interoperability

Generic Access Profile
Service Discovery Application Profile
Cordless Telephony Profile
Intercom Profile
Serial Port Profile
Headset Profile
Dial-up Networking Profile
Fax Profile
LAN Access Profile
Generic Object Exchange Profile
Object Push Profile
File Transfer Profile
Synchronization Profile



Additional Profiles
Advanced Audio Distribution
PAN
Audio Video Remote Control
Basic Printing
Basic Imaging
Extended Service Discovery
Generic Audio Video Distribution
Hands Free
Hardcopy Cable Replacement

WPAN: IEEE 802.15 v. 1

Data rate
- Synchronous, connection-oriented: 64 kbit/s
- Asynchronous, connectionless
  - 433.9 kbit/s symmetric
  - 723.2 / 57.6 kbit/s asymmetric

Transmission range
- POS (Personal Operating Space) up to 10 m
- with special transceivers up to 100 m

Frequency
- Free 2.4 GHz ISM-band

Security
- Challenge/response (SAFER+), hopping sequence

Cost
- 50€ adapter, drop to 5€ if integrated

Availability
- Integrated into some products, several vendors

Connection set-up time
- Depends on power-mode
- Max. 2.56s, avg. 0.64s

Quality of Service
- Guarantees, ARQ/FEC

Manageability
- Public/private keys needed, key management not specified, simple system integration

Special Advantages/Disadvantages
- Advantage: already integrated into several products, available worldwide, free ISM-band, several vendors, simple system, simple ad-hoc networking, peer to peer, scatternets
- Disadvantage: interference on ISM-band, limited range, max. 8 devices/network&master, high set-up latency

WPAN: IEEE 802.15 v. 2.x+EDR, 3.0+HS

802.15.2: Coexistance
- Coexistence of Wireless Personal Area Networks (802.15) and Wireless Local Area Networks (802.11), quantify the mutual interference

802.15.3: High-Rate
- Standard for high-rate (20Mbit/s or greater) WPANs, while still low-power/low-cost
- Data Rates: 11, 22, 33, 44, 55 Mbit/s
- Quality of Service isochronous protocol
- Ad hoc peer-to-peer networking
- Security
- Low power consumption
- Low cost
- Designed to meet the demanding requirements of portable consumer imaging and multimedia applications

WPAN: IEEE 802.15 v.4

802.15.4: Low-Rate, Very Low-Power
- Low data rate solution with multi-month to multi-year battery life and very low complexity
- Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation
- Data rates of 20-250 kbit/s, latency down to 15 ms
- Master-Slave or Peer-to-Peer operation
- Support for critical latency devices, such as joysticks
- CSMA/CA channel access (data centric), slotted (beacon) or unslotted
- Automatic network establishment by the PAN coordinator
- Dynamic device addressing, flexible addressing format
- Fully handshaked protocol for transfer reliability
- Power management to ensure low power consumption
- 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz US ISM band and one channel in the European 868 MHz band

ISM band interference

Many sources of interference
- Microwave ovens, microwave lightning
- 802.11, 802.11b, 802.11g, 802.15,...
- Even analog TV transmission, surveillance
- Unlicensed metropolitan area networks
- …

Levels of interference
- Physical layer: interference acts like noise
  - Spread spectrum tries to minimize this
  - FEC/interleaving tries to correct
- MAC layer: algorithms not harmonized
  - E.g., Bluetooth might confuse 802.11

Satellite Communications

- History
- Basics
- Path Loss
- Summary

History of satellite communication

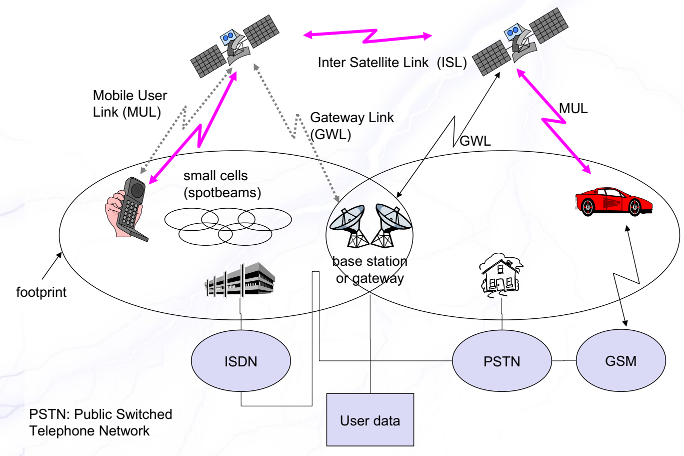
1945 Arthur C. Clarke publishes an essay about "Extra Terrestrial Relays"
1957 first satellite SPUTNIK
1960 first reflecting communication satellite ECHO
1963 first geostationary satellite SYNCOM
1965 first commercial geostationary satellite Satellit „Early Bird" (INTELSAT I): 240 duplex telephone channels or 1 TV channel, 1.5 years lifetime
1976 three MARISAT satellites for maritime communication
1982 first mobile satellite telephone system INMARSAT-A
1988 first satellite system for mobile phones and data communication INMARSAT-C
1993 first digital satellite telephone system
1998 global satellite systems for small mobile phones

Applications

- Traditionally
  - weather satellites
  - radio and TV broadcast satellites
  - military satellites
  - satellites for navigation and localization (e.g., GPS)
- Telecommunication
  - global telephone connections } replaced by fiber optics
  - backbone for global networks
  - connections for communication in remote places or underdeveloped areas
  - global mobile communication

➔ satellite systems to extend cellular phone systems (e.g., GSM or AMPS)

Classical satellite systems



Basics

Satellites in circular orbits

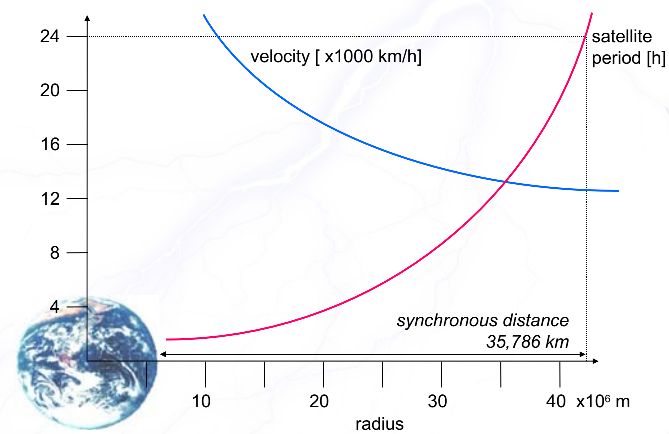
- attractive force $F_g = m\,g\,(R/r)^2$
- centrifugal force $F_c = m\,r\,\omega^2$
- m: mass of the satellite
- R: radius of the earth (R = 6370 km)
- r: distance to the center of the earth
- g: acceleration of gravity ($g = 9.81\ m/s^2$)
- ω: angular velocity ($\omega = 2\,\pi\,f$, f: rotation frequency)

Stable orbit

- $F_g = F_c$

$$r = \sqrt[3]{\frac{gR^2}{(2\pi\ f)^2}}$$

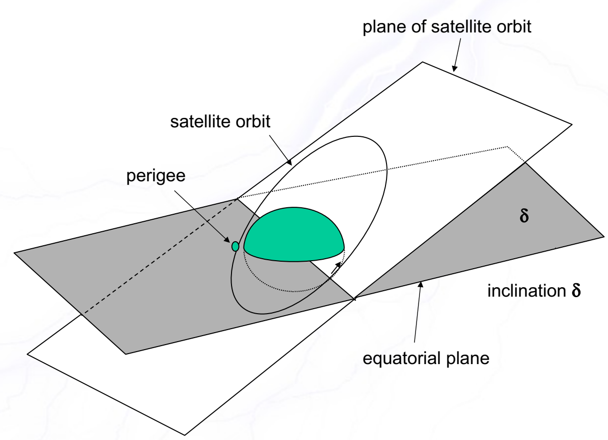
Satellite period and orbits



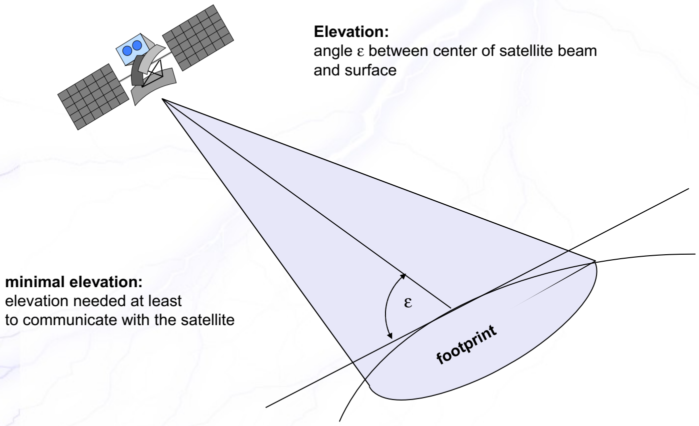
Basics

- elliptical or circular orbits
- complete rotation time depends on distance satellite-earth
- inclination: angle between orbit and equator
- elevation: angle between satellite and horizon
- LOS (Line of Sight) to the satellite necessary for connection
  ➔ high elevation needed, less absorption due to e.g. buildings
- Uplink: connection base station - satellite
- Downlink: connection satellite - base station
- typically separated frequencies for uplink and downlink
  - transponder used for sending/receiving and shifting of frequencies
  - transparent transponder: only shift of frequencies
  - regenerative transponder: additionally signal regeneration

Inclination



Elevation



Free Space Attenuation (Path Loss)

$$Pr = Pt + Gt + Gr - (32.44 + 20 \log d + 20 \log f)$$

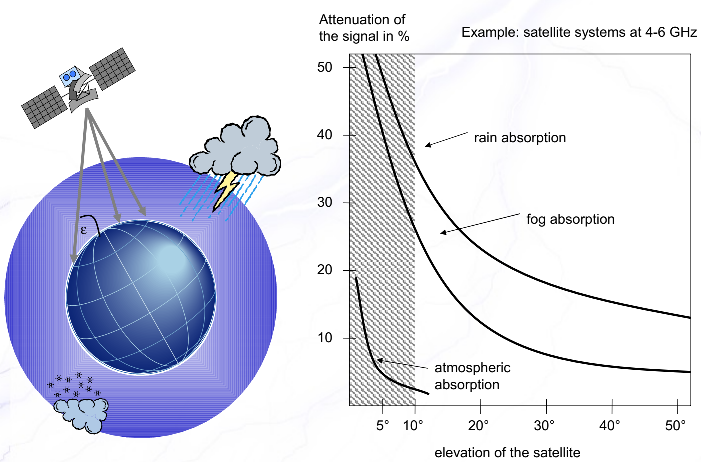
where

Pr = received power in dBm
Pt = transmitted power in dBm
Gt = transmitting antenna gain in dBi
Gr = receiving antenna gain in dBi
d = distance between transmitter and receiver, in km
f = frequency in MHz

it is usually convenient to have an expression for free-space attenuation, often called path loss L_{fs}, that is independent of antenna gain:

$$L_{fs} = 32.44 + 20 \log d + 20 \log f$$

Atmospheric attenuation

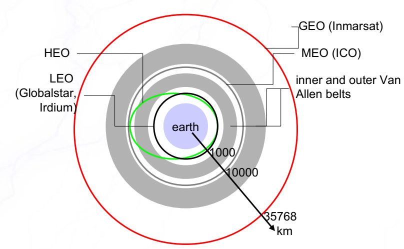


Orbits

Four different types of satellite orbits can be identified depending on the shape and diameter of the orbit:

- GEO: geostationary orbit, about 36000 km above earth surface
- LEO (Low Earth Orbit): about 500 - 1500 km
- MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit): about 6000 - 20000 km
- HEO (Highly Elliptical Orbit) elliptical orbits.

Van-Allen-Belts:
ionized particles
2000 - 6000 km and
15000 - 30000 km
above earth surface



Geostationary satellites

Orbit 35,786 km distance to earth surface, orbit in equatorial plane (inclination 0°)

➔ complete rotation exactly one day, satellite is synchronous to earth rotation

- fix antenna positions, no adjusting necessary
- satellites typically have a large footprint (up to 34% of earth surface!), therefore difficult to reuse frequencies
- bad elevations in areas with latitude above 60° due to fixed position above the equator
- high transmit power needed
- high latency due to long distance (ca. 275 ms)

➔ not useful for global coverage for small mobile phones and data transmission, typically used for radio and TV transmission

LEO systems

Orbit ca. 500 - 1500 km above earth surface

- visibility of a satellite ca. 10 - 40 minutes
- global radio coverage possible
- latency comparable with terrestrial long distance connections, ca. 5 - 10 ms
- smaller footprints, better frequency reuse
- but now handover necessary from one satellite to another
- many satellites necessary for global coverage
- more complex systems due to moving satellites

Examples:

Iridium (start 1998, 66 satellites)

- Bankruptcy in 2000, deal with US DoD (free use, saving from "deorbiting")

Globalstar (start 1999, 48 satellites)

- Not many customers (2001: 44000), low stand-by times for mobiles

MEO systems

Orbit ca. 5000 - 12000 km above earth surface

comparison with LEO systems:

- slower moving satellites
- less satellites needed
- simpler system design
- for many connections no hand-over needed
- higher latency, ca. 70 - 80 ms
- higher sending power needed
- special antennas for small footprints needed

Example:

ICO (Intermediate Circular Orbit, Inmarsat) start ca. 2000

- Bankruptcy, planned joint ventures with Teledesic, Ellipso – canceled again, start planned for 2003

Summary of LEO/MEO systems

	Iridium	Globalstar	ICO	Teledesic
# satellites	66 + 6	48 + 4	10 + 2	288
altitude (km)	780	1414	10390	ca. 700
coverage	global	± 70° latitude	global	global
min. elevation	8°	20°	20°	40°
frequencies [GHz (circa)]	1.6 MS 29.2 ↑ 19.5 ↓ 23.3 ISL	1.6 MS ↑ 2.5 MS ↓ 5.1 ↑ 6.9 ↓	2 MS ↑ 2.2 MS ↓ 5.2 ↑ 7 ↓	19 ↓ 28.8 ↑ 62 ISL
access method	FDMA/TDMA	CDMA	FDMA/TDMA	FDMA/TDMA
ISL	yes	no	no	yes
bit rate	2.4 kbit/s	9.6 kbit/s	4.8 kbit/s	64 Mbit/s ↓ 2/64 Mbit/s ↑
# channels	4000	2700	4500	2500
Lifetime [years]	5-8	7.5	12	10
cost estimation	4.4 B$	2.9 B$	4.5 B$	9 B$