3G/4G Mobile Communications Systems

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Chapter II: Basics of Wireless and Mobile Communications

Basics of Wireless and Mobile Communications

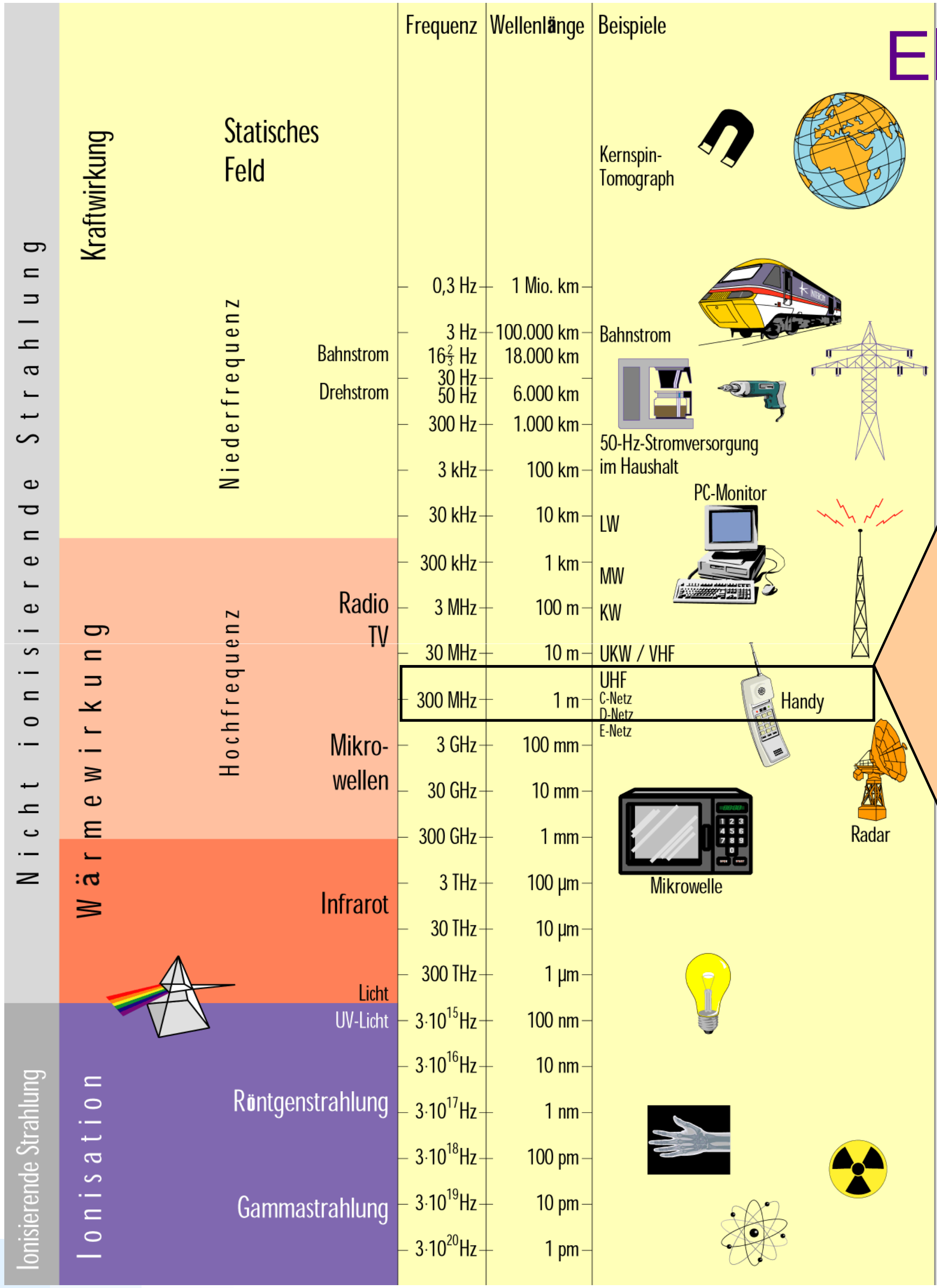
- Frequencies
- Signals
- Signal propagation
- Multiplexing
- Spread spectrum
- Cellular systems
- Communication Links
- Duplex Modes

Mobile Communication Systems – The Issues

- What does it require?
  - Provide telecommunition services
    - Voice (conversation, messaging)
    - Data (fax, SMS/MMS, internet)
    - Video (conversation, streaming, broadcast)

  - Anywhere → Coverage
  - Anytime → Ubiquitous connectivity, reachability
  - Wireless → Without cord/wire
  - Mobile → In motion, on the move (terrestrial)
  - Secure → Integrity, identity, privacy, authenticity, non-repudiation
  - Reliable → Guaranteed quality of service

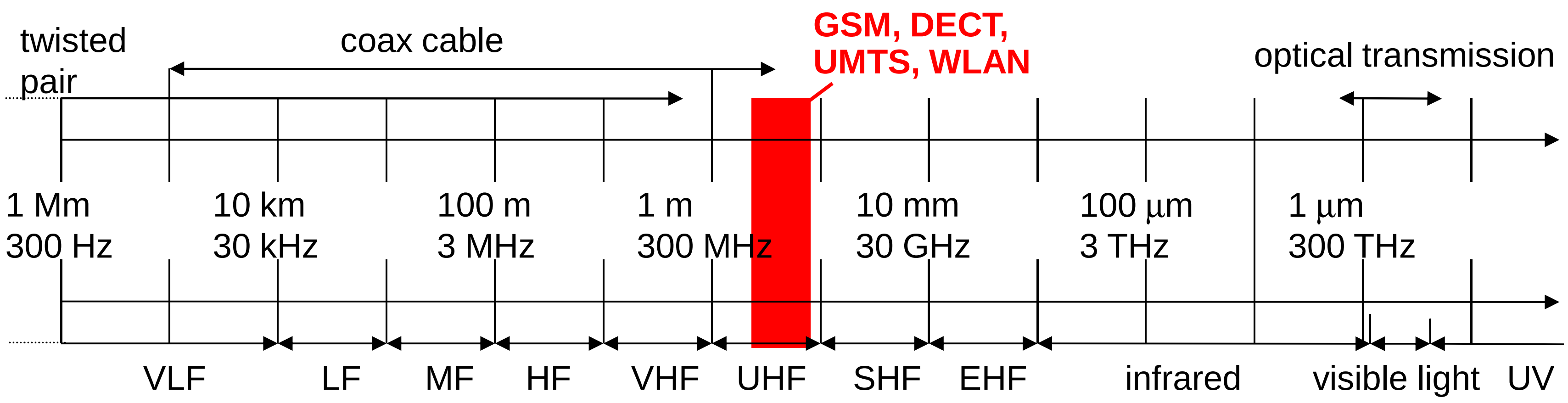
Elektromagnetic Spectrum



- 100 MHz: UKW Radio, VHF TV
- 400 MHz: UHF TV
- 450 MHz: C-Netz
- 900 MHz: GSM900 (D-Netz)
- 1800 MHz: GSM1800 (E-Netz)
- 1900 MHz: DECT (schnurl. Telefon)
- 2000 MHz: UMTS (3G)
- 2400 MHz: WLAN, Bluetooth
- 2450 MHz: Mikrowellenherd

3500 MHz: WiMax

Frequencies for Communication (Spectrum)



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 antennas
  - Good propagation characteristics (limited reflections, small path loss, penetration of walls)
  - Typically used for radio & TV (terrestrial+satellite) broadcast, wireless telecommunication (cordless/mobile phone)
- SHF and higher for directed radio links, satellite communication
  - Small antenna, strong focus
  - Larger bandwidth available
  - No penetration of walls
- Mobile systems and 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 (licensed)	**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 (un-licensed)	**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 (un-licensed)	**IEEE 802.11 b** 2400-2483 **802.11a/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
WiMax (IEEE 802.16, licensed)	2.3GHz, 2.5GHz and **3.5GHz**	2.3GHz, **2.5GHz** and 3.5GHz	**2.3GHz**, 2.5GHz and 3.5GHz

Abbreviations:

AMPS Advanced Mobile Phone System
CDMA Code Division Multiple Access
CT Cordless Telephone
DECT Digital Enhanced Cordless Telecommunications
GSM Global System for Mobile Communications
HIPERLAN High-Performance LAN
IEEE Institute of Electrical and Electronics Engineers
JCT Japanese Cordless Telephone
NMT Nordic Mobile Telephone
PACS Personal Access Communications System
PACS-UB PACS- Unlicensed Band
PDC Pacific Digital Cellular
PHS Personal Handyphone System
TDMA Time Division Multiple Access
WiMAX Worldwide Interoperability for Microwave Access

UMTS Frequency Bands (FDD mode only)

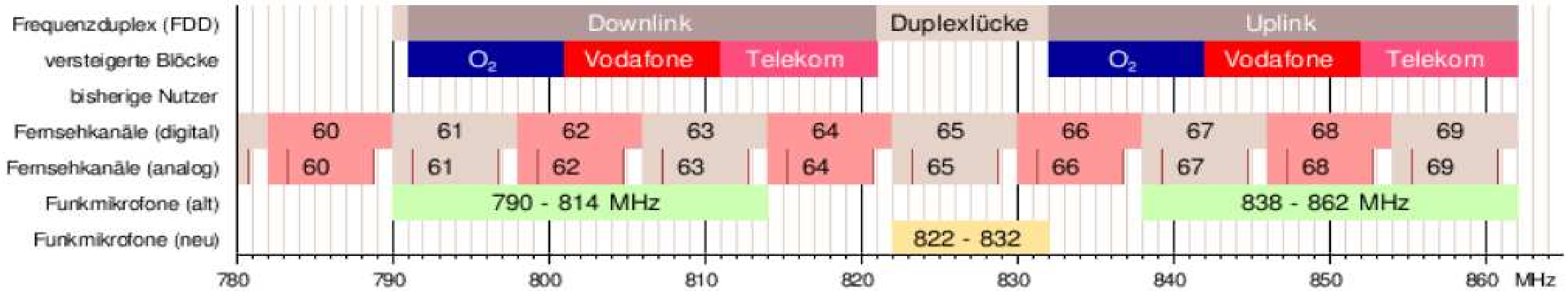
Operating Band	Frequency Band	UL Frequencies UE transmit (MHz)	DL Frequencies UE receive (MHz)	Typically used in region ...
I	2100	1920 - 1980	2110 - 2170	EU, Asia
II	1900	1850 - 1910	1930 - 1990	America
III	1800	1710 - 1785	1805 - 1880	EU (future use,)
IV	1700	1710 - 1755	2110 - 2155	Japan
V	850	824 - 849	869 - 894	America, Australia, Brazil
VI	800	830 - 840	875 - 885	Japan
VII	2600	2500 - 2570	2620 - 2690	„Extension Band“
VIII	900	880 - 915	925 - 960	EU (future use)
IX	1800	1749.9 - 1784.9	1844.9 - 1879.9	Japan
X	1700	1710 - 1770	2110 - 2170	America/US

Frequency Auction 2010 - Germany

800 MHz Bereich (Digitale Dividende)

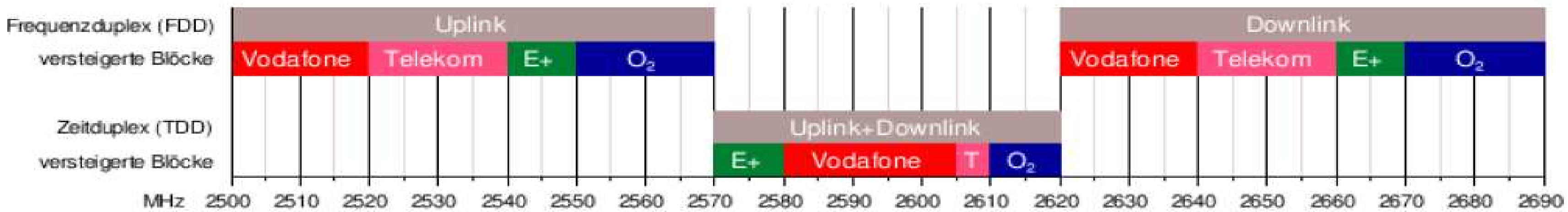
Nutzer	Uplink	Downlink	Preis
Deutsche Telekom	852–862 MHz	811–821 MHz	1,153 Mrd. €
Vodafone	842–852 MHz	801–811 MHz	1,210 Mrd. €
O_2	832–842 MHz	791–801 MHz	1,212 Mrd. €

The amount of spectrum that will be freed up by the switchover from analogue to digital terrestrial TV is known as the **Digital Dividend**



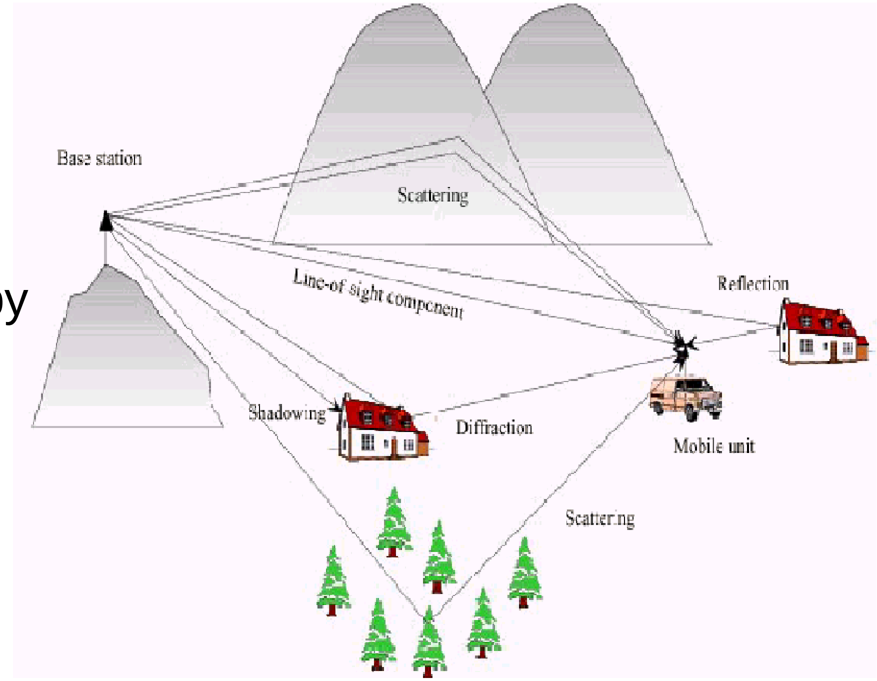
2,6 GHz Bereich

Nutzer	Frequenzduplex (FDD)			Zeitduplex (TDD)	
	Uplink	Downlink	Preis	Uplink+Downlink	Preis
Deutsche Telekom	2520–2540 MHz	2640–2660 MHz	76,228 Mio. €	2605–2610 MHz	8,598 Mio. €
Vodafone	2500–2520 MHz	2620–2640 MHz	73,464 Mio. €	2580–2605 MHz	44,96 Mio. €
E-Plus	2540–2550 MHz	2660–2670 MHz	36,67 Mio. €	2570–2580 MHz	16,502 Mio. €
O2	2550–2570 MHz	2670–2690 MHz	71,415 Mio. €	2610–2620 MHz	16,458 Mio. €

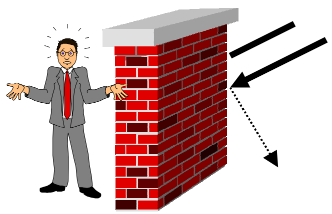


Signal Propagation – Path Loss

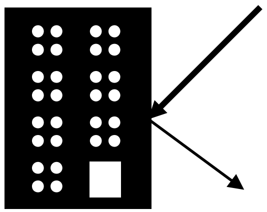
- Propagation in free space always like light (straight line, line of sight)
- Receiving power proportional to
  - **$1 / (d \cdot f/c)^2$ (ideal)**
  - **$1/(d \cdot f/c)^\alpha$ (α=3...4 realistically)**
  - d = distance between sender and receiver
  - f = carrier frequency



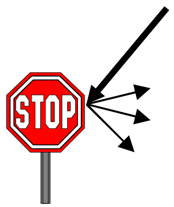
- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - scattering at small obstacles
  - diffraction at edges



shadowing



reflection

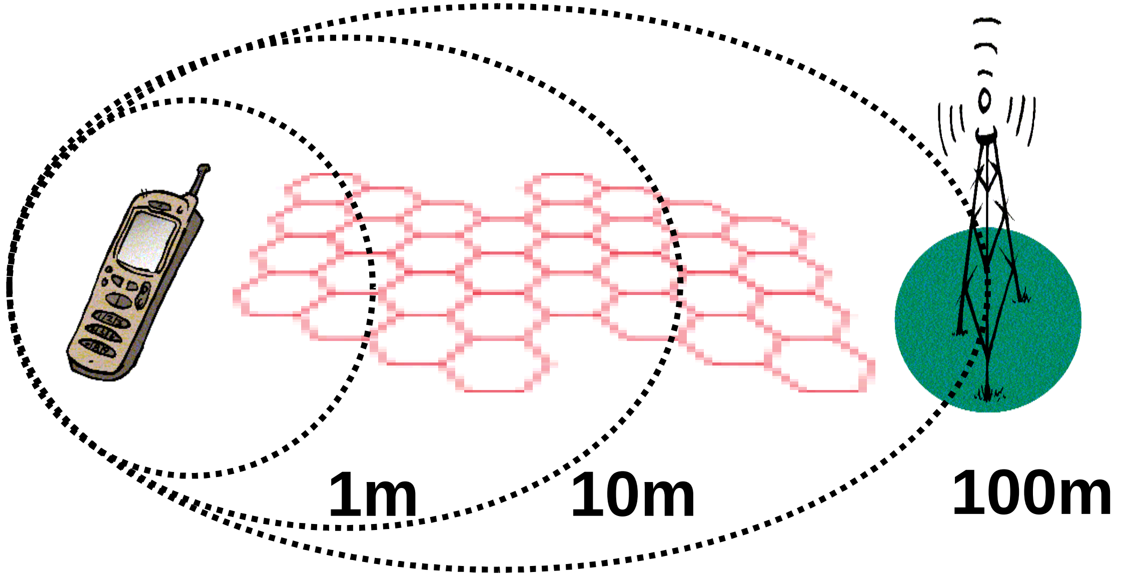


scattering

diffraction

Radio Propagation: Received Power

- The received power decreases with increasing distance
- Typically, the power in watts is converted to dBm
- The differences in received power at distances $d_2 - d_1 = d$
  - Ideal: $-20 \cdot \log_{10}(d)$
  - **Realistic: $-35 \cdot \log_{10}(d)$, $-40 \cdot \log_{10}(d)$**
- The power is reduced by 35 – 40 dB per decade
- Examples:
  - $d_1 = 1m$, $d_2 = 10m$
  - $d_1 = 10m$, $d_2 = 100m$



Quick Exercise: iPhone 4 “AntennaGate”

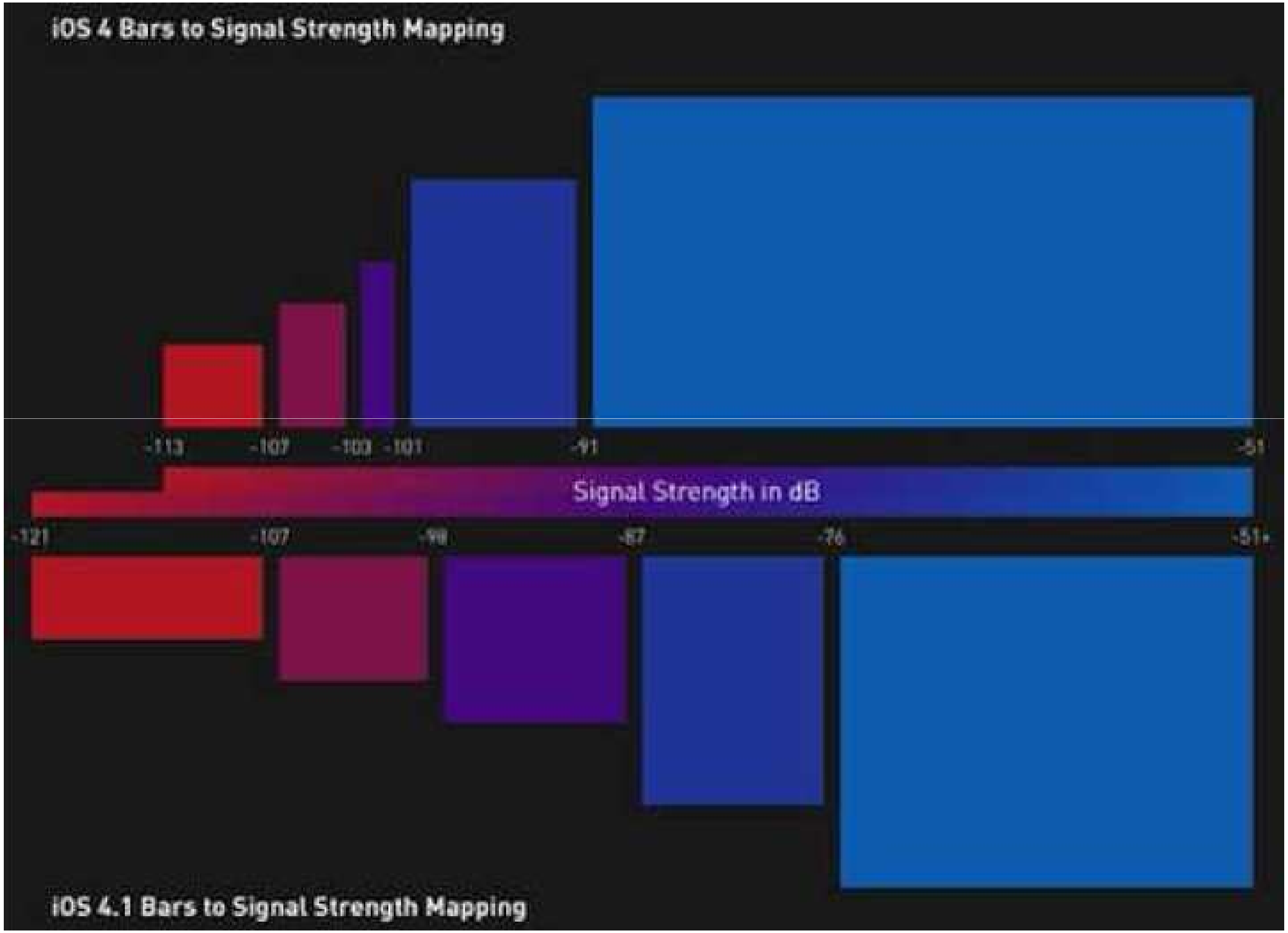
- The received power is reduced by 24dB in case the antenna is capped by the hand of the user

- Let’s assume a typical pathloss model for urban scenarios:

$$PL_{dB} = 128.1 + 36.7 \cdot \log_{10}(d/km)$$

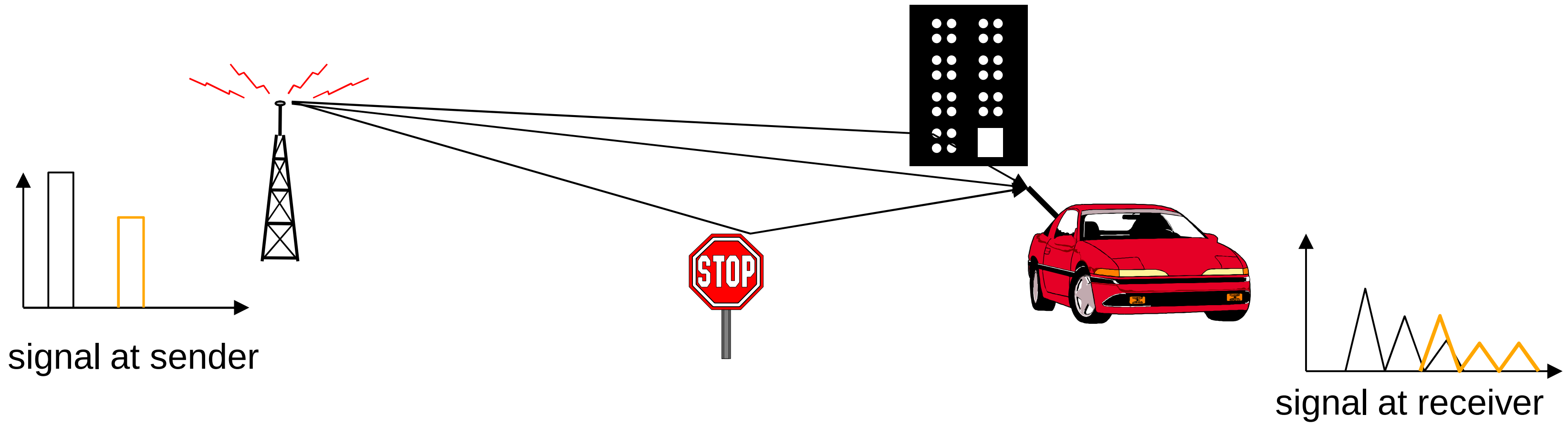
- The Tx power of the base station is assumed to be 43dBm
- Questions:
  - Assume the iPhone 4 user is at a distance of 700m to the base station. What is the received power in case he does not touch his phone?
  - Now he touches his phone. By how many meters has the iPhone 4 user to move towards the base station in order to get the same received power again?

Bars to Signal Strength Mapping in iPhone 4



Multipath Propagation – Inter Symbol Interference

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

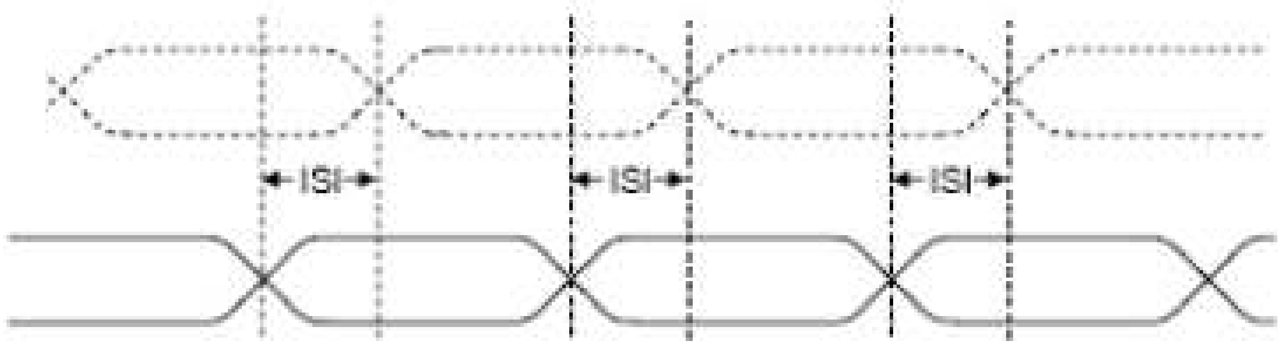


Time dispersion: signal is dispersed over time

➔ Interference with “neighbor” symbols, Inter Symbol Interference (ISI)

Delayed signal received via longer path

Signal received by direct path



Effects of Mobility – Fading

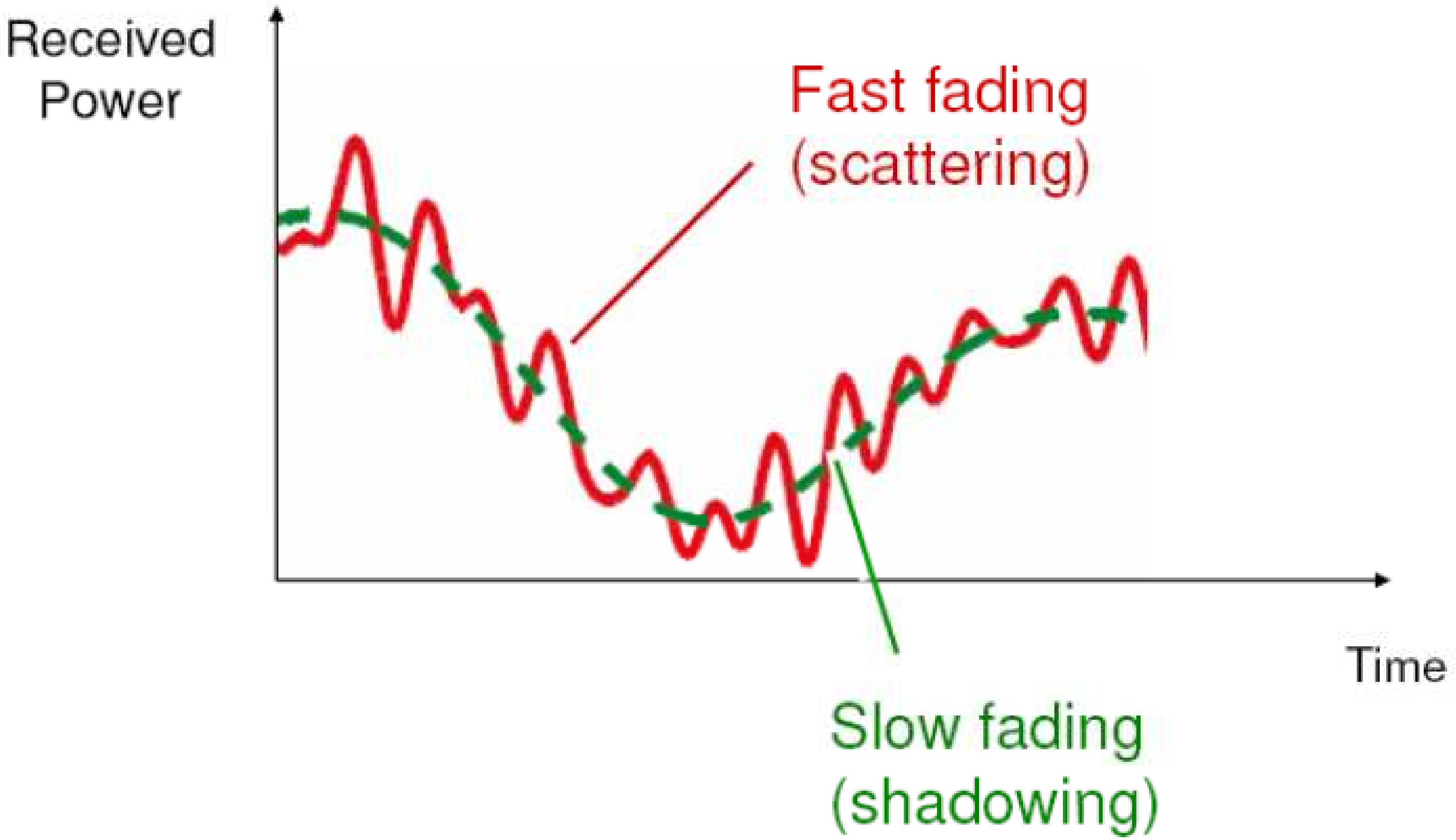
- Channel characteristics change over time and location
  - Signal paths change
  - Different delay variations of different signal parts (frequencies)
  - Different phases of signal parts

➔ Quick changes in the power received (short-term fading or **fast fading**)

- Additional changes in
  - Distance to sender
  - Obstacles further away

➔ Slow changes in the average power
Received (long-term fading, **slow fading, shadow fading**)

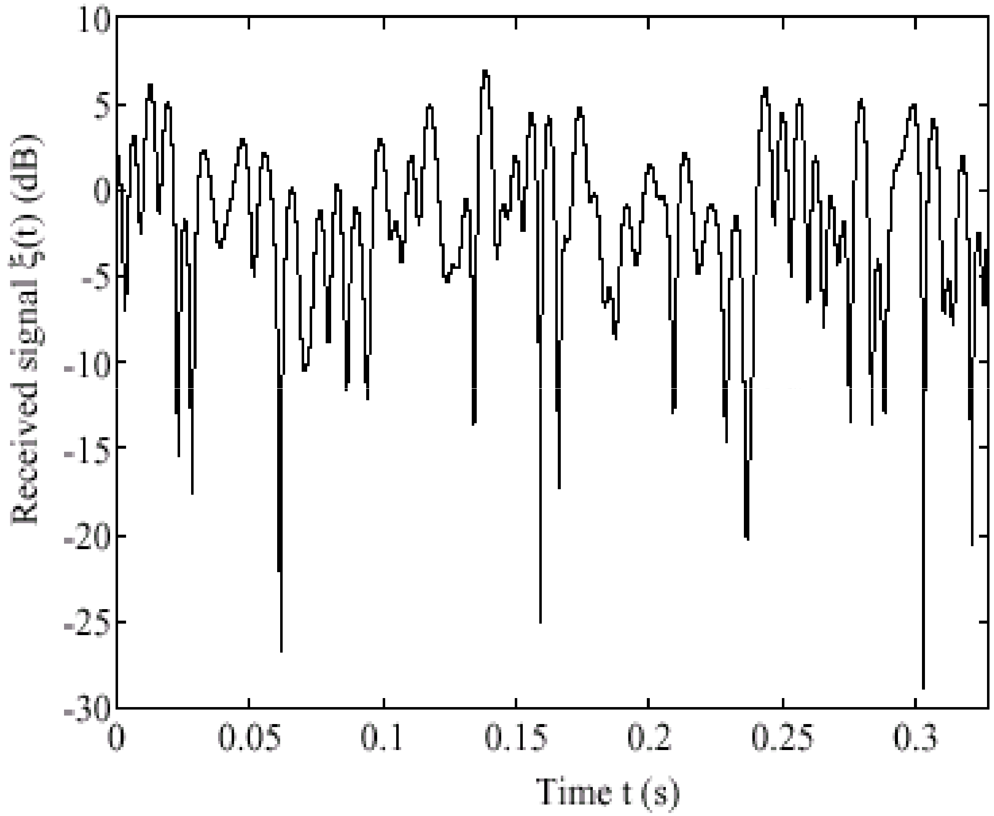
Mobile Radio Channel – Received Power



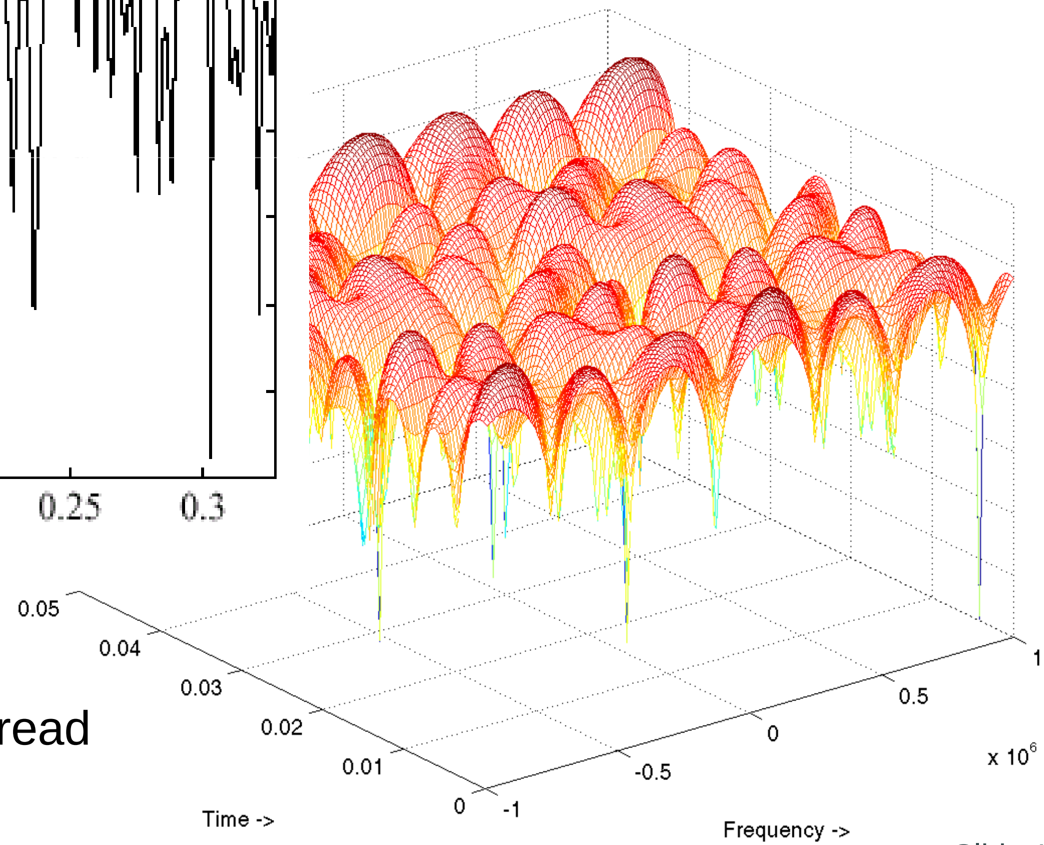
Refer to : P. Jung, Analyse und Entwurf digitaler Mobilfunksysteme, B.G. Teubner, 1997, p. 67, figure 3.5

Fast Fading

- Simulation showing time and frequency dependency of a multipath fading channel



V = 110km/h 900MHz



Coherence time ~ c / (f · v)
Coherence bandwidth ~ 1 / delay spread

Interferences

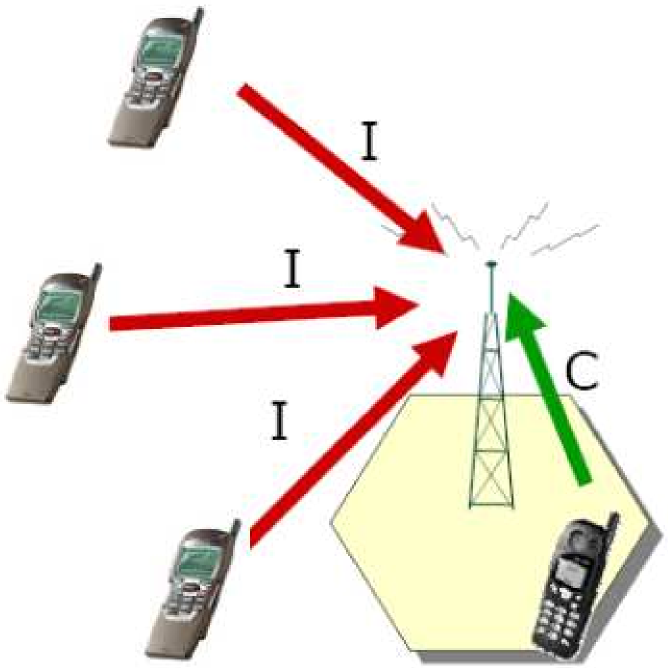
Interference	Problem
Intersymbol Interference (ISI)	Multipath; superposition of same radiated data symbol transmitted via different paths
Multiple Access Interference (MAI)	Different user signals interfere dependent on the access scheme used (T/F/CDMA)
Intra-Cell Interference	Interference caused by users belonging to same cell
Inter-Cell Interference	Interference caused by users belonging to neighbor cells

Carrier to Interference Ratio (CIR, C/I)

- Ratio of Carrier-to-Interference power at the receiver

$$\mathrm{CIR} = \frac{C}{\sum I_j + N}$$

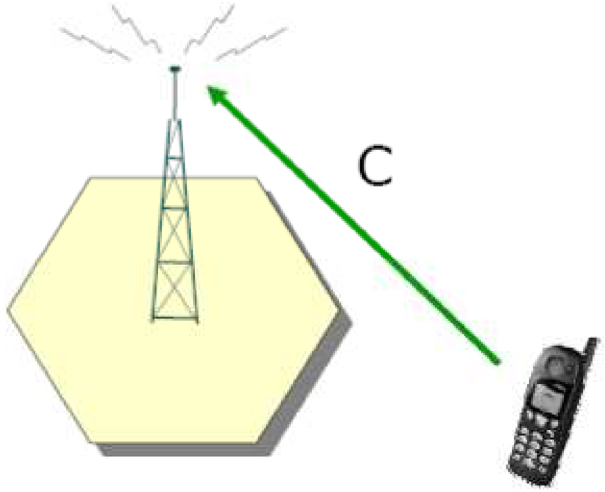
- The minimum required CIR depends on the system and the signal processing potential of the receiver technology



Quelle: B. Walke, M.P. Althoff, P.Seidenberg, UMTS – Ein Kurs, Weil der Stadt 2001,

Coverage Limited Systems (Lack of Coverage)

- Mobile stations located far away from BS (at cell border or even beyond the coverage zone)
- C at the receiver is too low, because the path loss between sender and receiver is too high



➔ **Signal C is too low**

Quelle: B. Walke, M.P. Althoff, P.Seidenberg, UMTS – Ein Kurs, Weil der Stadt 2001

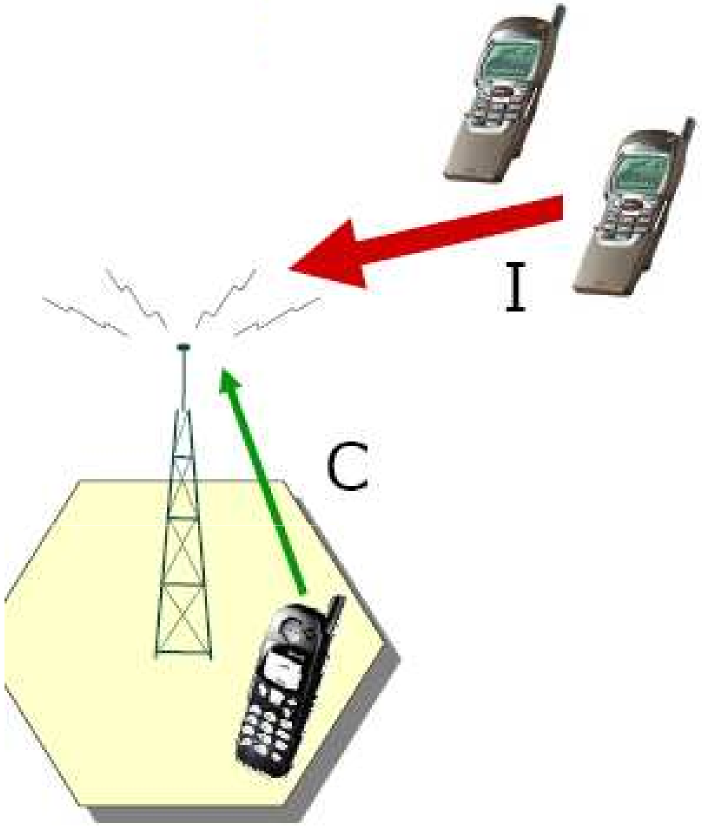
➔ **No signal reception possible**

Interference Limited Systems (Lack of Capacity)

- Mobile station is within coverage zone
- C is sufficient, but too much interference I at the receiver

➔ **Interference I is too large**

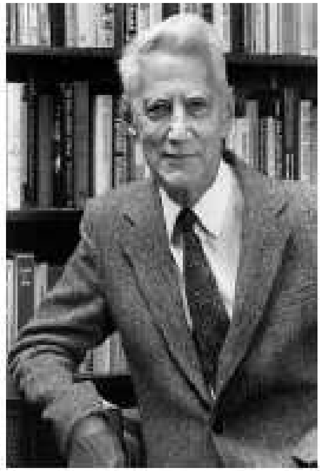
➔ **No more resources / capacity left**



Quelle: B. Walke, M.P. Althoff, P.Seidenberg, UMTS – Ein Kurs, Weil der Stadt 2001

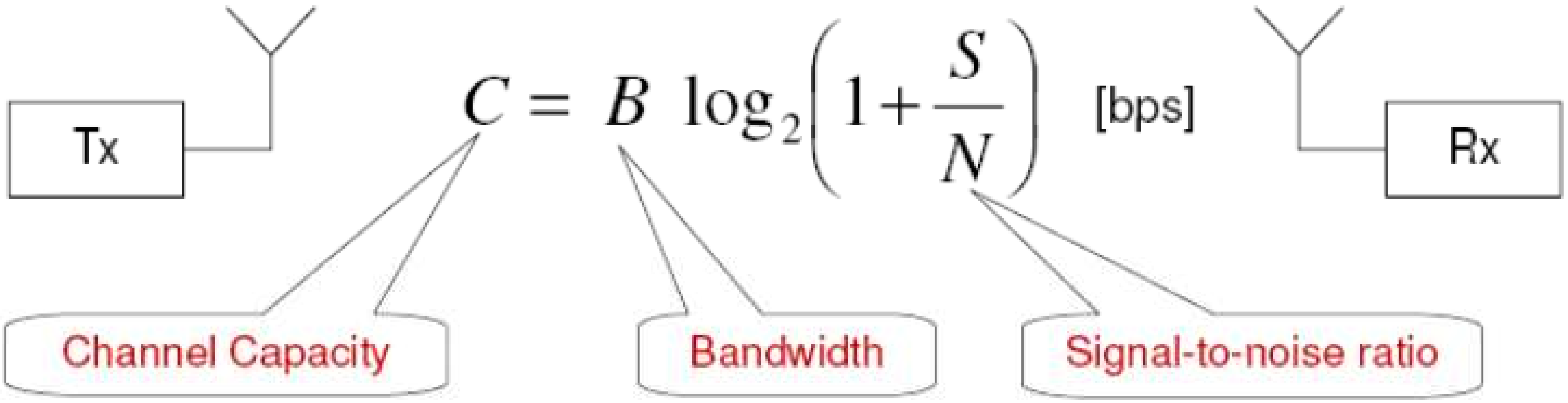
Information Theory: Channel Capacity (1)

- Bandwidth limited Additive White Gaussian Noise (AWGN) channel
- Gaussian codebooks
- Single transmit antenna
- Single receive antenna (SISO)
- Shannon (1950):
  Channel Capacity <= Maximum mutual information between sink and source



C. Shannon
Bell Labs Technical Journal, 1950

$$C = B \log_2\left(1+\frac{S}{N}\right) \quad \text{[bps]}$$



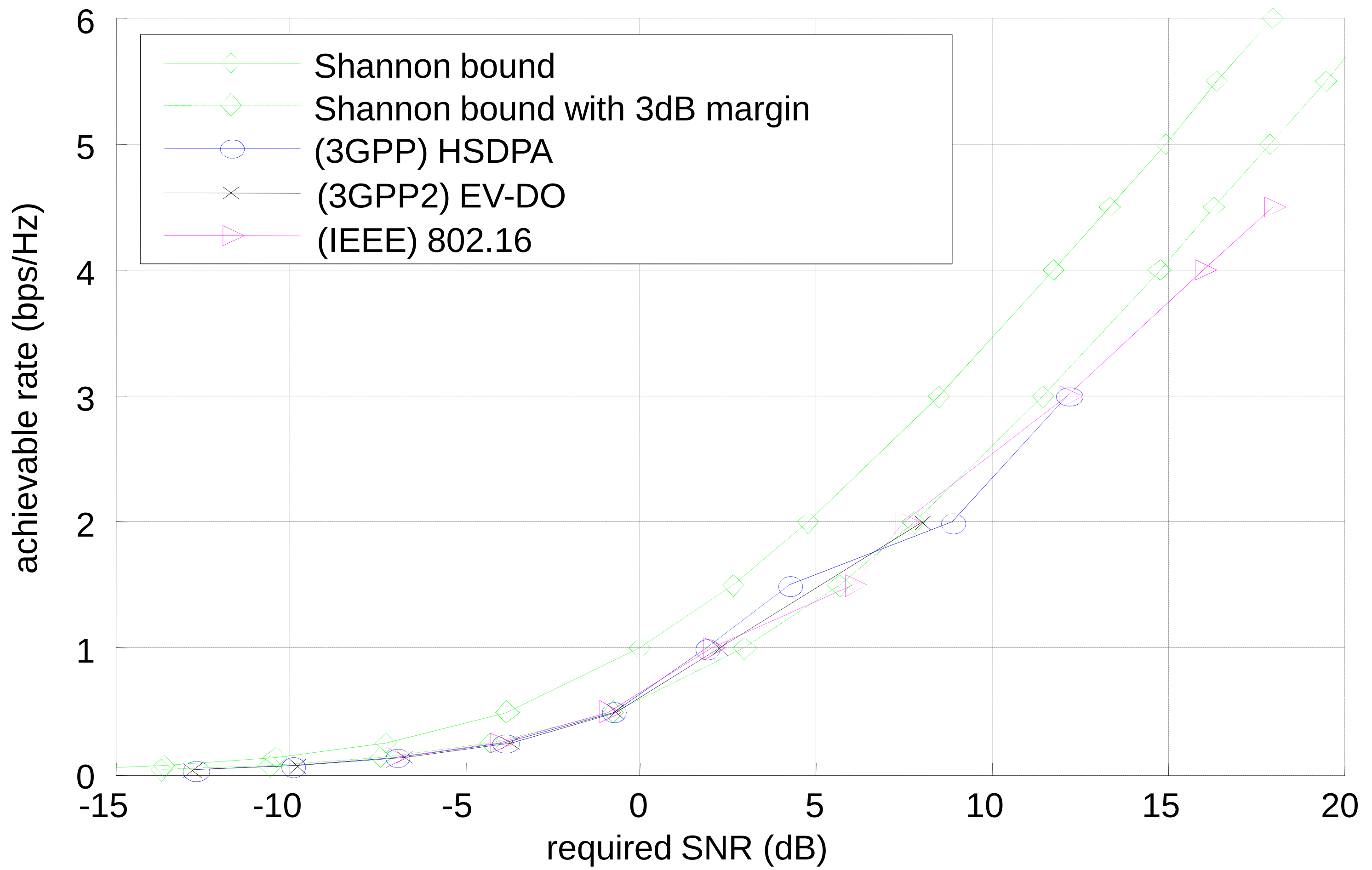
Information Theory: Channel Capacity (2)

- For S/N >>1 (high signal-to-noise ratio), approximate

$$C \approx B \, \frac{1}{3} \, \frac{S}{N}_{dB} \qquad \text{[bps]}$$

- **Observation: Bandwidth and S/N are means to increase capacity**
- Means to increase capacity:
  - With low bandwidth very high data rate is possible provided
    - S/N is high enough
    - Example: Higher order modulation schemes
  - With high noise (low S/N) data communication is possible if
    - Bandwidth is large
    - Example: Spread Spectrum…
  - Shannon channel capacity has been seen as a “unreachable” theoretical limit, for a long time
  - However: Turbo coding (1993) pushes practical systems up to 0.5 dB to Shannon channel bandwidth

Link Capacity for Various Technologies



- The link capacity of current systems is quickly approaching the Shannon limit
- Link Performance of 3G & 4G Systems approaches the Shannon Bound

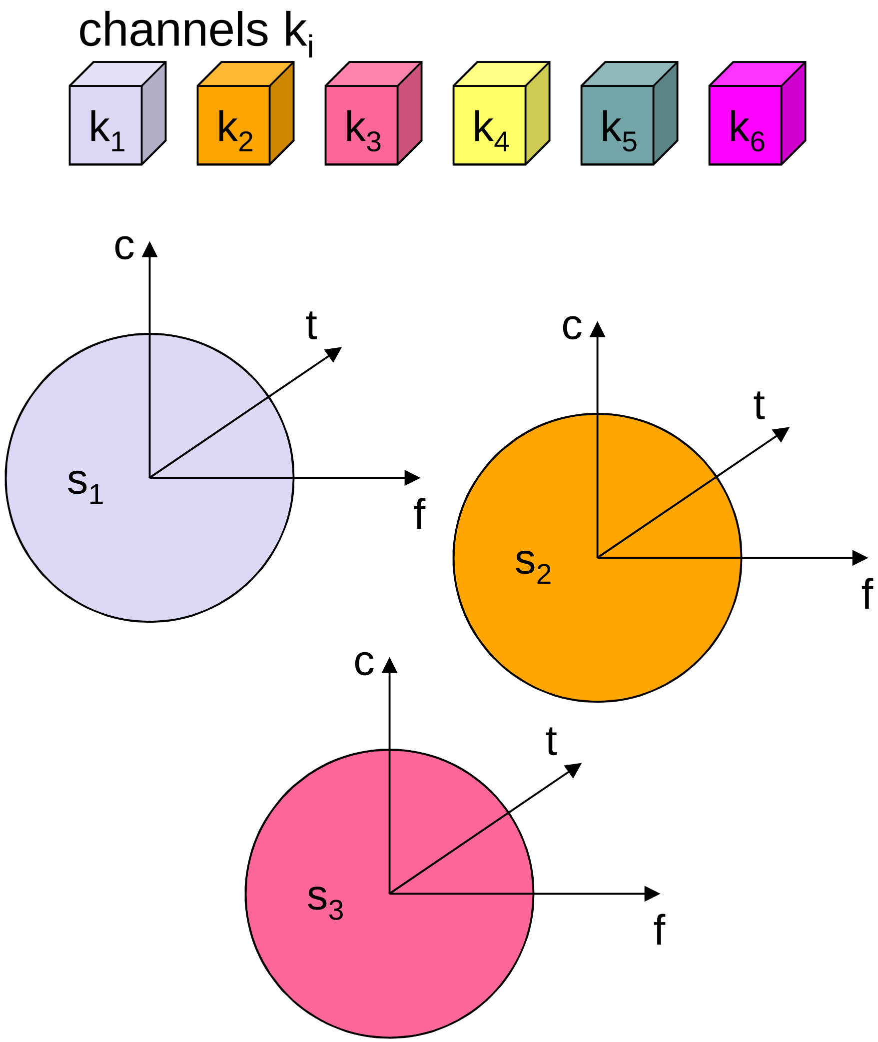
Multiplexing

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

- Multiplexing in 4 dimensions
  - Space (s_i)
  - Time (t)
  - Frequency (f)
  - Code (c)

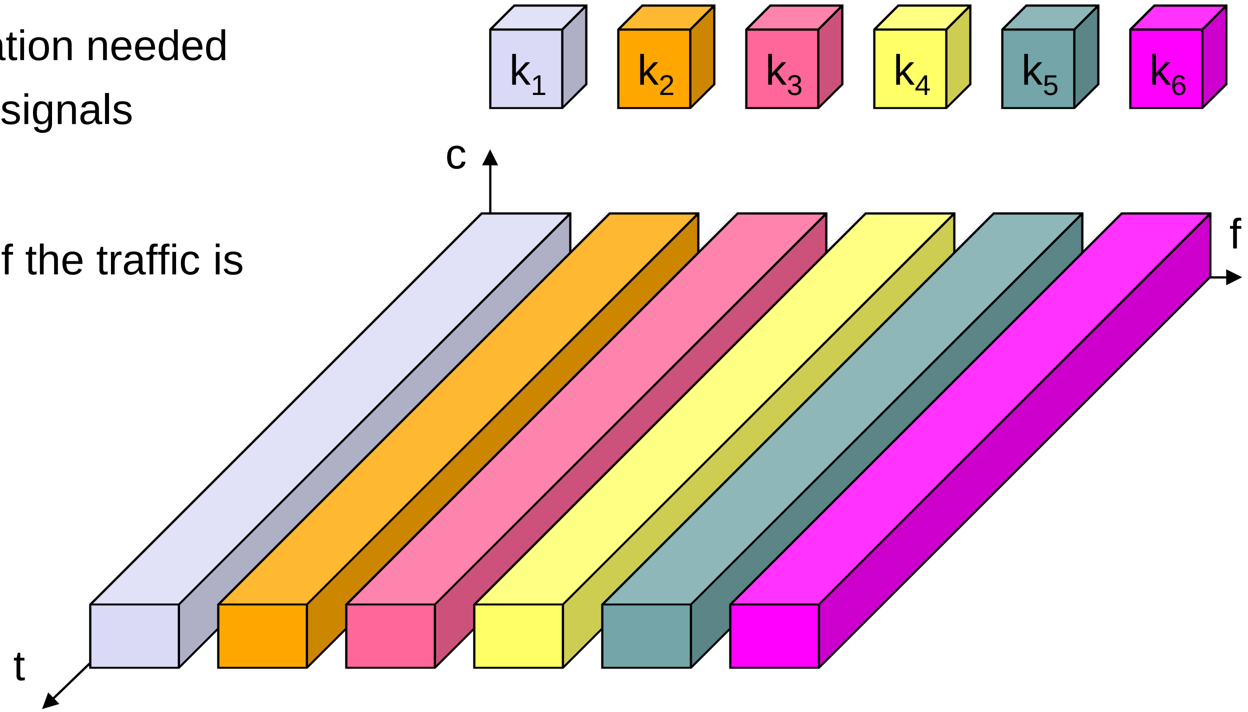
- Multiple use is possible, if resource (channel) is different in at least one dimension

- Important: Guard spaces needed!



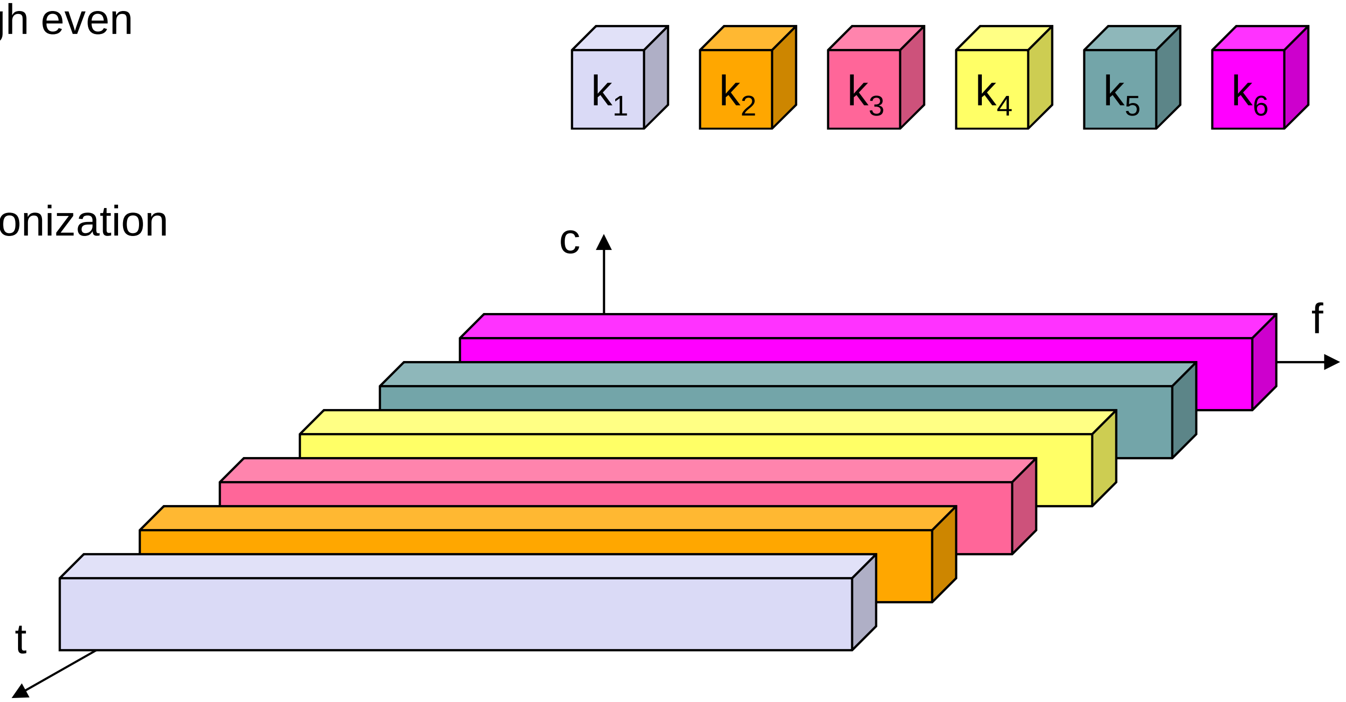
Frequency Multiplex (FDMA)

- 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 needed
  - Applicable to analog signals
- Disadvantages:
  - Waste of bandwidth if the traffic is distributed unevenly
  - Inflexible
  - Guard space



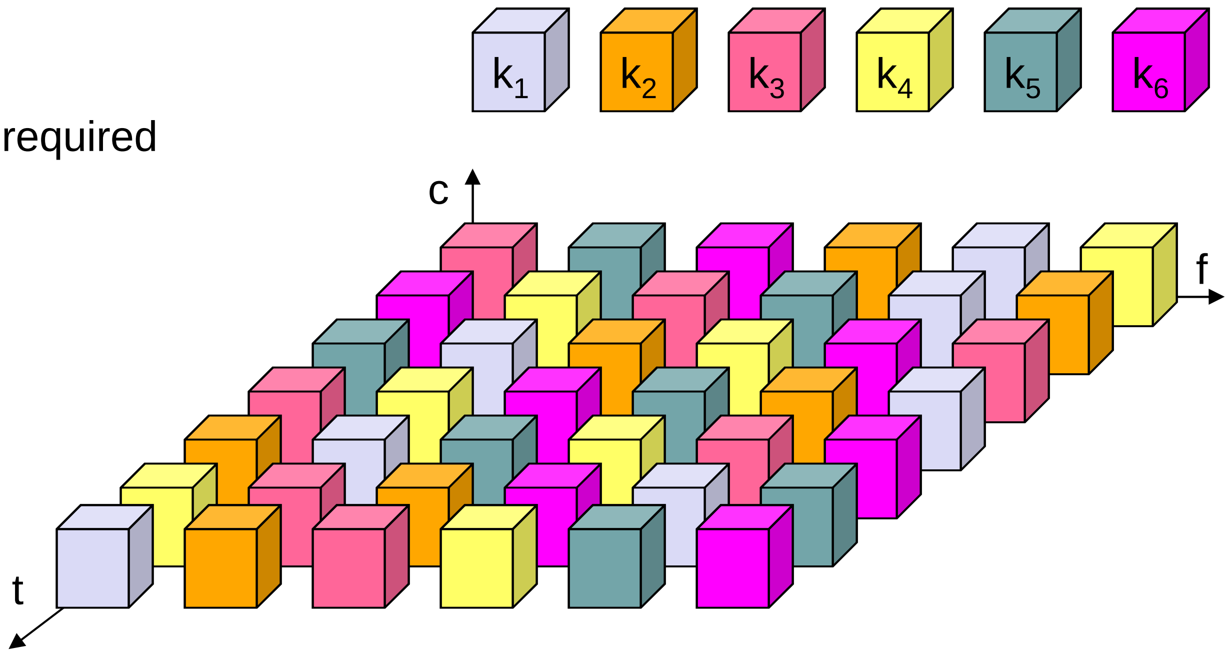
Time Multiplex (TDMA)

- 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 needed



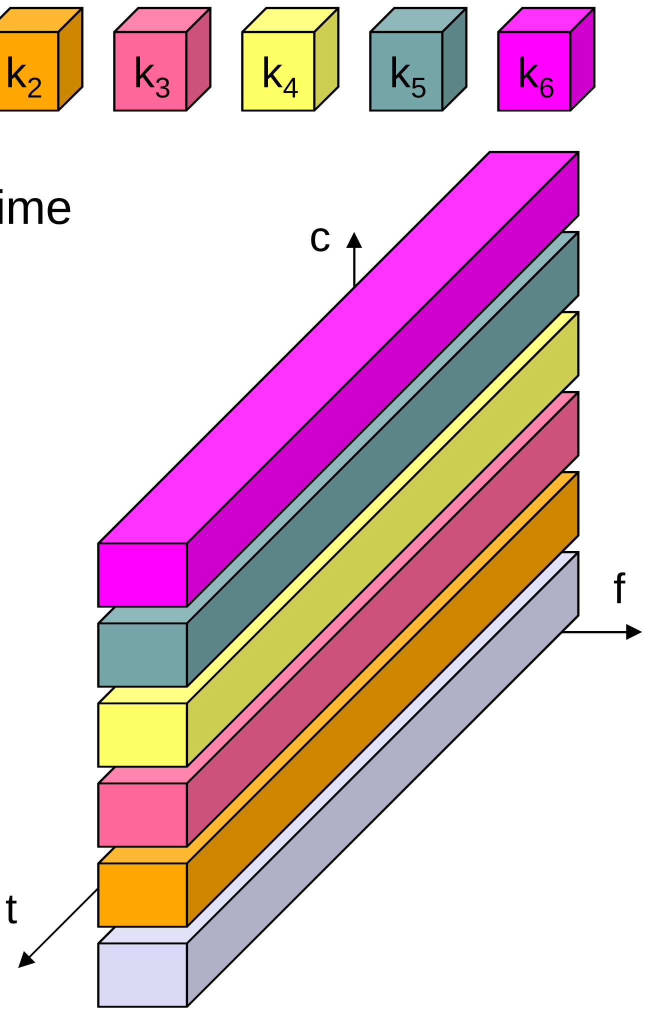
Time and Frequency Multiplex (FDMA/TDMA)

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
  - Example: GSM (frequency hopping)
- Advantages:
  - Protection against frequency selective interference
- Disadvantage
  - Precise coordination required



Code Multiplex (CDMA)

- Each channel has a unique code
  - Example: UMTS
- 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:
  - More complex receivers
  - Intra cell interference



Cellular Systems: Space Division Multiplex

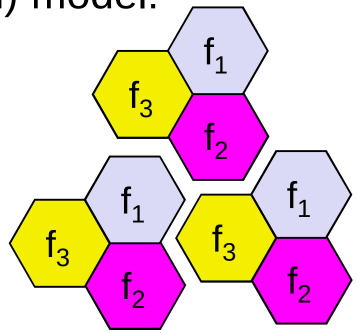
- Cell structure implements **Space Division Multiplex**:
  - Base station covers a certain transmission area (cell)
- Mobile stations communicate only via the base station
- Advantages of cell structures:
  - Higher capacity, higher number of users
  - Less transmission power needed
  - More robust, decentralized
  - Base station deals with interference, transmission area, etc. locally
- Disadvantages:
  - Fixed network needed for the base stations
  - Handover (changing from one cell to another) necessary
  - Interference with other cells
- Cell sizes vary from tens of meters in urban areas to many km in rural areas (e.g. maximum of 35 km radius in GSM)

Cellular Systems: Frequency Planning I

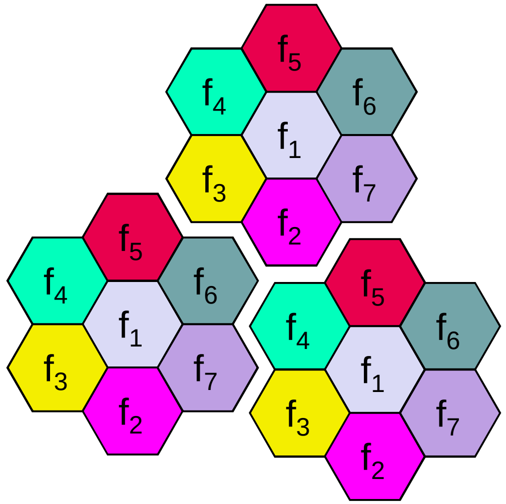
- **Frequency reuse** only with a certain distance between the base stations
  - Applied in GSM, not needed in UMTS, may be applied in early deployments of LTE

Typical (hexagon) model:

Reuse-3 cluster:

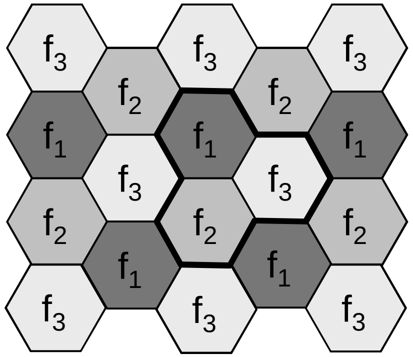


Reuse-7 cluster:



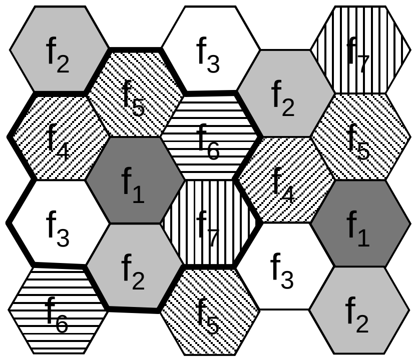
- Fixed frequency assignment:
  - Certain frequencies are assigned to a certain cell
  - Problem: different traffic load in different cells
- Dynamic frequency assignment:
  - Base station chooses frequencies depending on the frequencies already used in neighbor cells
  - Assignment can also be based on interference measurements

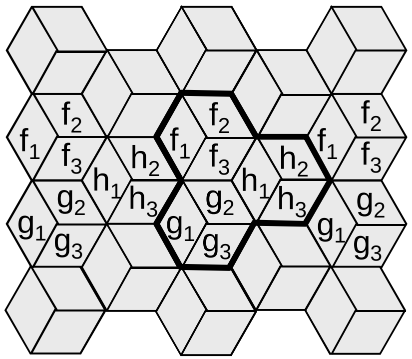
Cellular Systems: Frequency Planning II



3 cell cluster

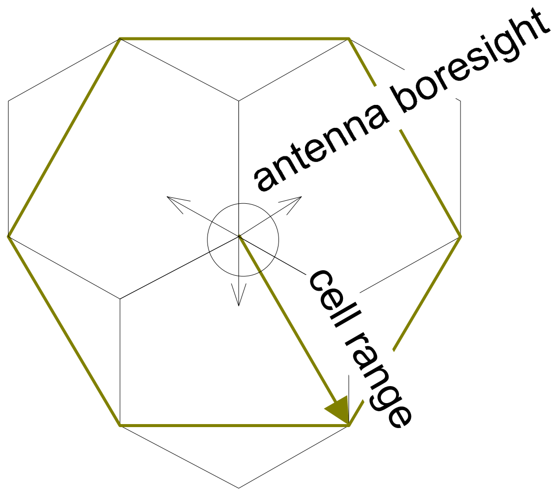
7 cell cluster

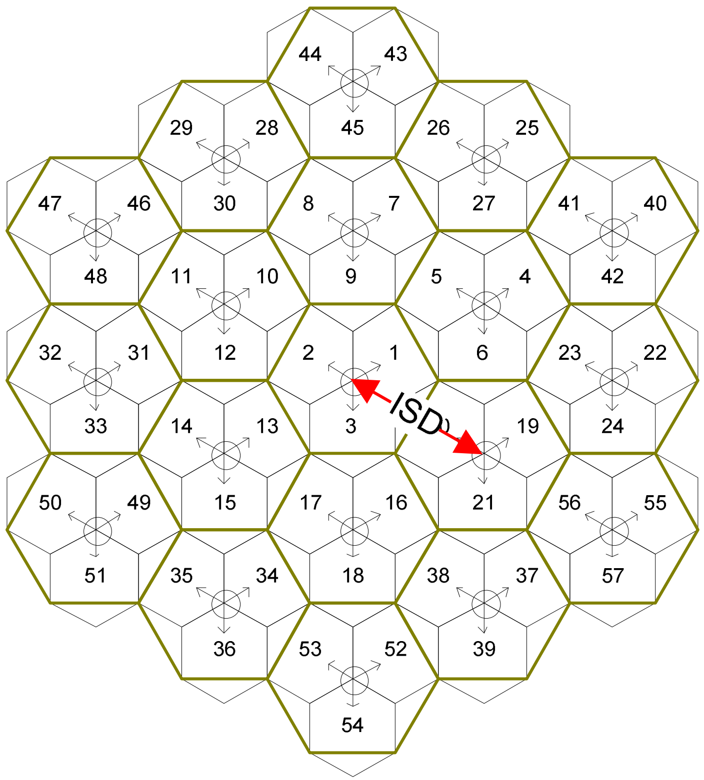




3 cell cluster
with 3 sector antennas

Sectorisation



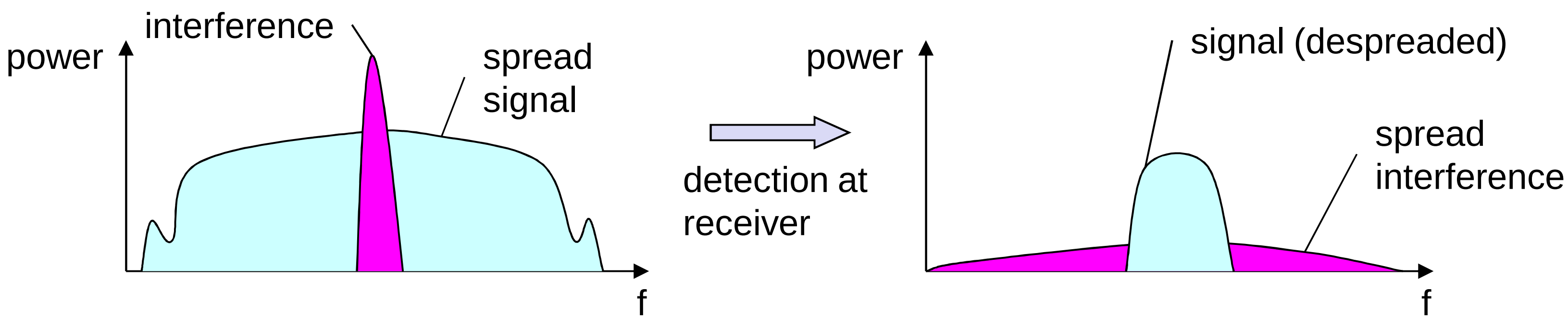


- Directive antennas are usually applied at a site (location of a base station)
- The geographical area is sectorized
  - Protection against intra and inter cell interference
- **A site (≡ base station) typically consists of three, sometimes six sectors (≡ cells)**

Antennas and Sectorisation

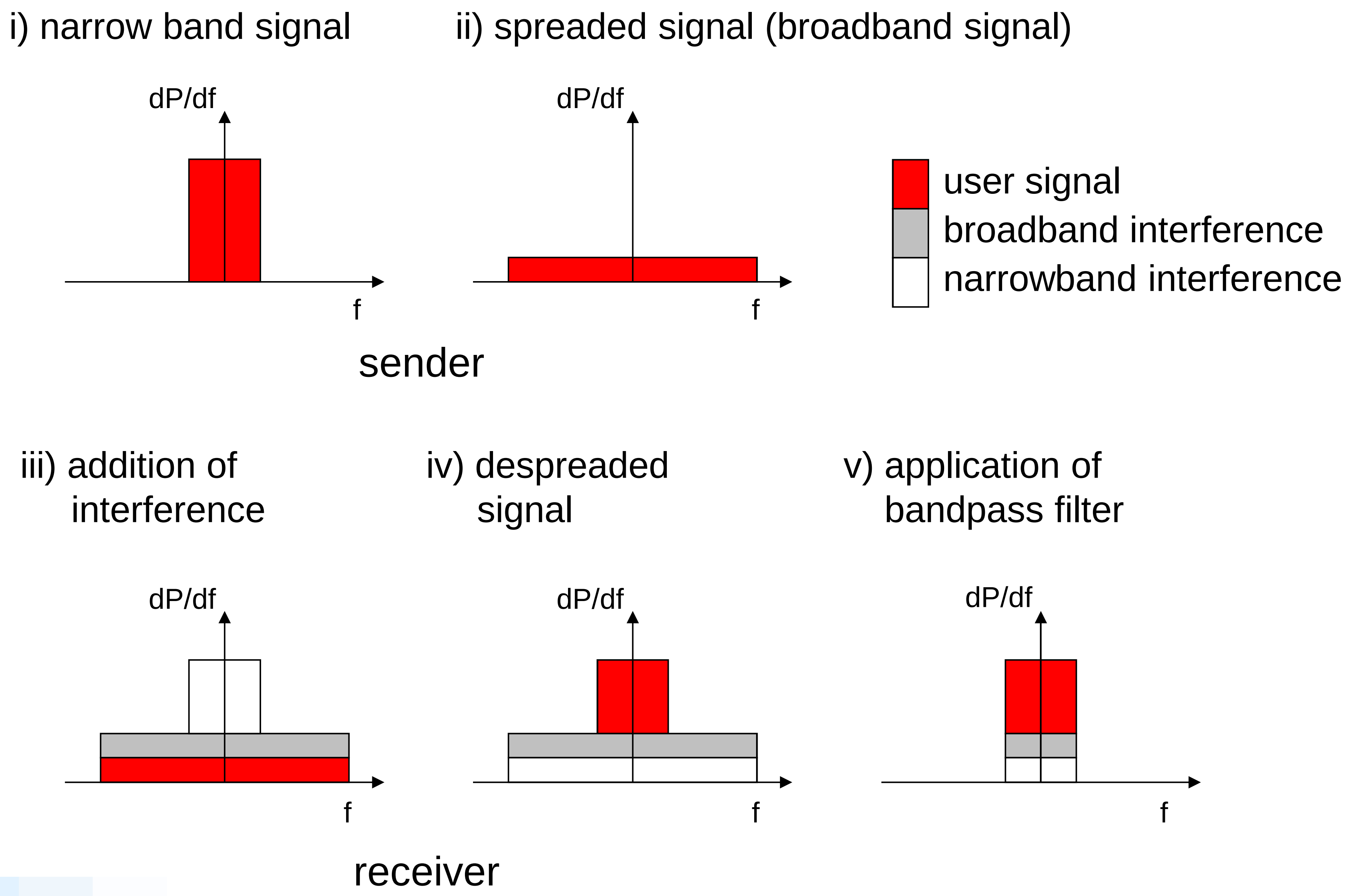
Spread Spectrum Technology

- Problem of radio transmission: Frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
  - ⇒ Protection against narrow band interference

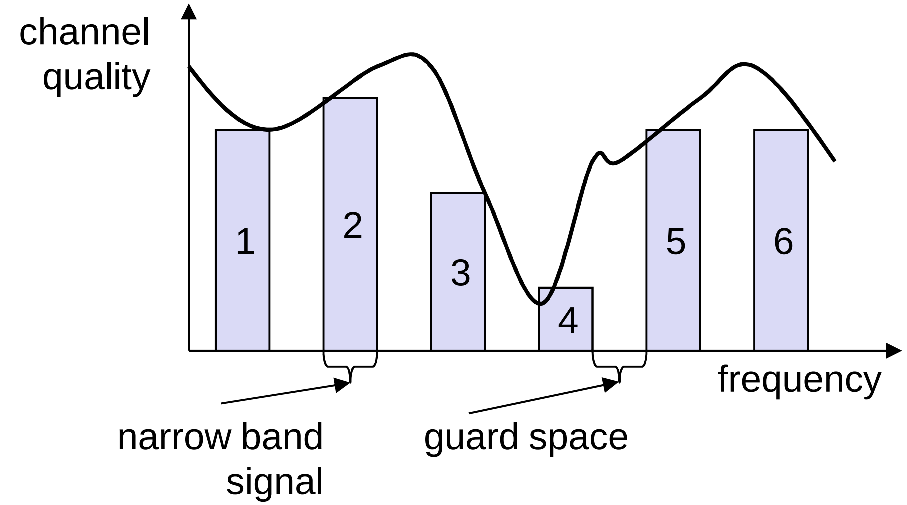


- Side effects:
  - Coexistence of several signals without dynamic coordination
- Alternatives:
  - Direct Sequence (UMTS)
  - Frequency Hopping (slow FH: GSM, fast FH: Bluetooth)

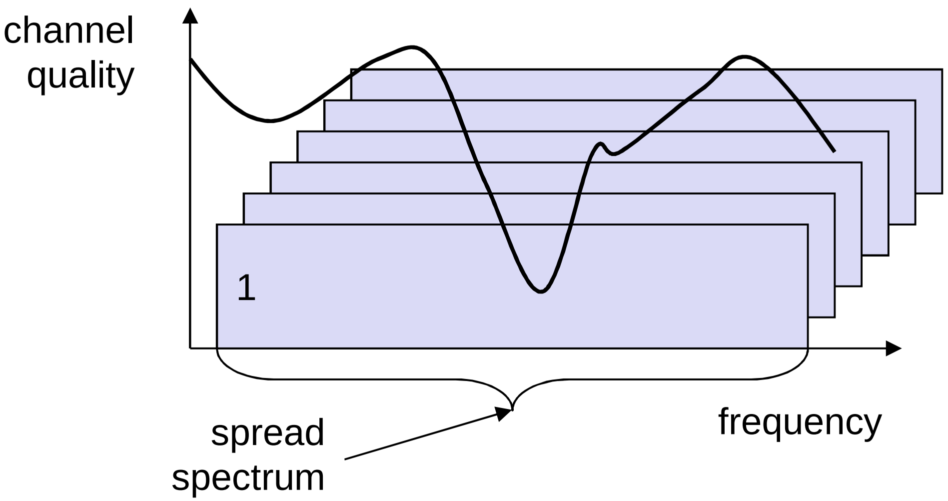
Effects of Spreading and Interference



Spreading and Frequency Selective Fading



narrowband signals can suffer from deep fades

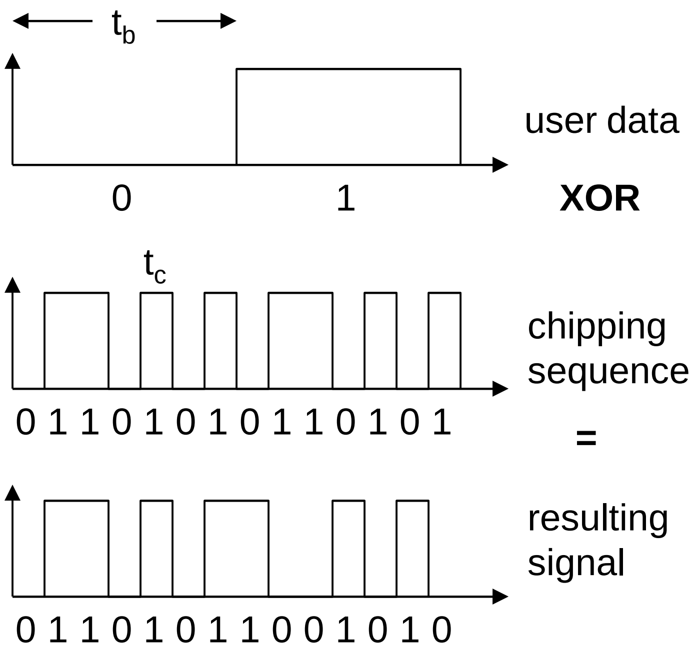


spread signal more robust against frequency selective fading

Direct Sequence Spread Spectrum – I/II

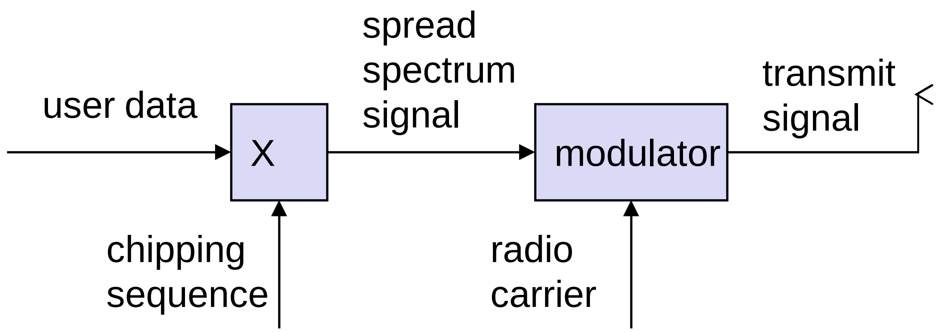
- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal

- Advantages
  - 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 needed
  - Relatively large bandwdth needed
    - UMTS applies 3.84 Mcps $\rightarrow$ 5 MHz bandwidth needed

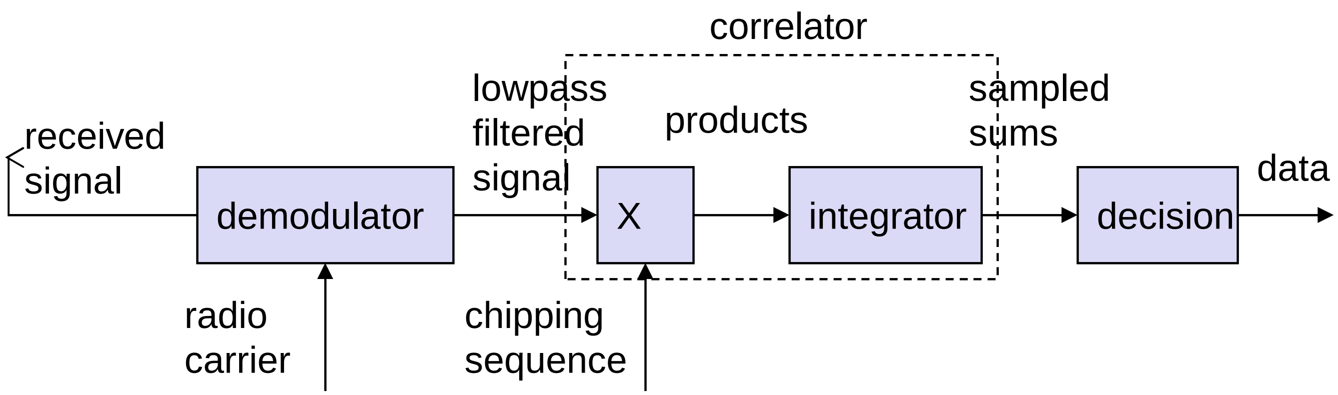


t_b: bit period
t_c: chip period

Direct Sequence Spread Spectrum – II/II



transmitter

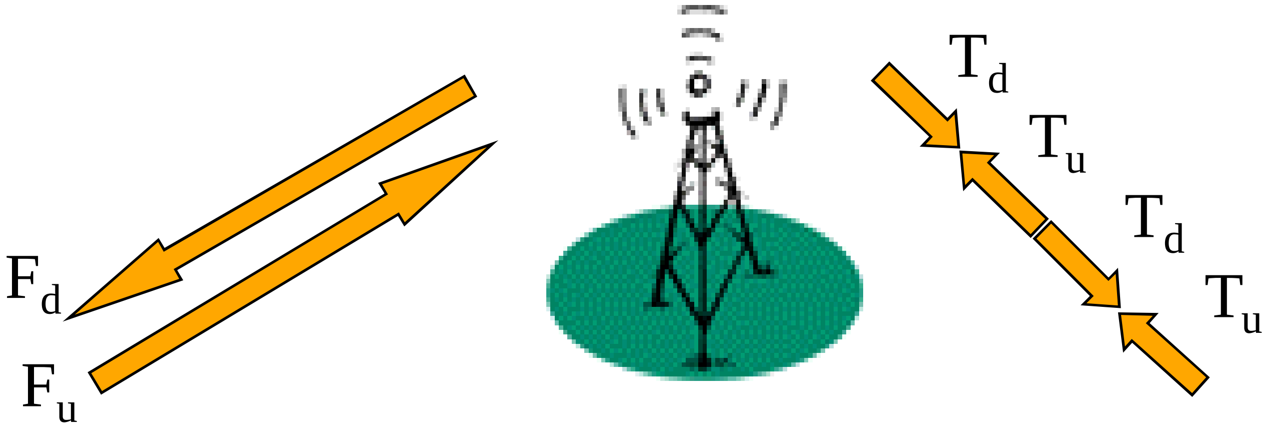


receiver

Communication Link Types

- Each terminal needs an uplink and a downlink
- Types of communication links:
  - Simplex
    - unidirectional link transmission
  - Half Duplex
    - Bi-directional (but not simultaneous)
  - Duplex
    - simultaneous bi-directional link transmission, two types:
      - Frequency division duplexing (FDD)
      - Time division duplexing (TDD)

Duplex Modes



- **Frequency Division Duplex (FDD)**
  - Separate frequency bands for up- and downlink

Examples:

GSM, IS-95, UMTS (FDD), LTE(FDD)

- **Time Division Duplex (TDD)**
  - Separation of up- and downlink traffic on time axis

Examples:

DECT, UMTS (TDD), LTE (TDD)