Principles in Mobile Communications

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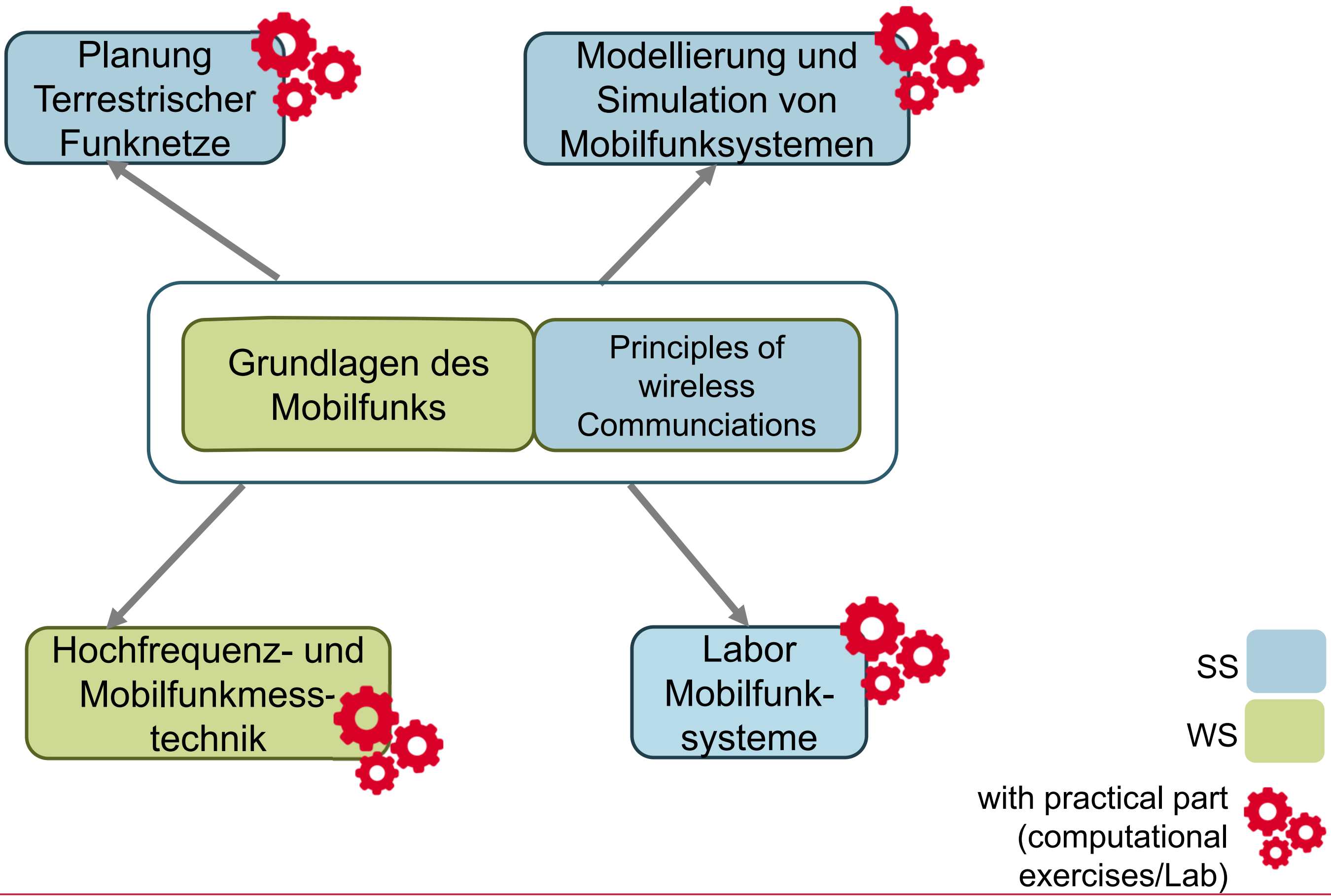
Organisation

Lecture and practical exercise in the winter semester (2 + 2 SWS, 5 CP):

- Lecture: on Friday; 9.45 h – 11.15 h; SN 22.1
- Practical exercise: on Friday; 8.00 h – 9.30 h; SN 22.1

- Slides and exercise sheets are available at StudIP
- Assistant: M. Sc. Maik Weber
- Examination: written; place and time are provided at a later time

Lectures on the Subject Mobile Communications



Objectives and Contents of the Lecture

- Objectives:

The lecture deals with **fundamentals** in the field of the **radio interface of mobile communications networks**. In doing so, knowledge about the structure and the mode of operation of **cellular mobile radio networks** as well as of **wireless local networks** is gained.

- Contents:

1. Introduction
2. Basic terms
3. Wave propagation
4. Radio transmission techniques
5. Media access methods
6. Mobile radio systems according to 3GPP
7. Mobile radio systems according to IEEE 802

Overview

Introduction
Chapter 1

Basic Terms
Chapter 2

Mobile Radio Systems according to 3GPP
Chapter 6

Media Access Methods
Chapter 5

Radio Transmission Techniques
Chapter 4

High Frequency Technology
Chapter 3

Mobile Radio Systems according to IEEE802
Chapter 7

Literature

- Literature recommend for the lecture

  - C. Lüders, Mobilfunksysteme, Vogel-Verlag 2001
  - J. Schiller, Mobilkommunikation, Addison-Wesley 2000
  - N. Geng, W. Wiesbeck, Planungsmethoden für die Mobilkommunikation, Springer-Verlag 1998
  - A. F. Molisch, Wireless Communications, Addison-Wesley 2005

Literature

- Further literature on mobile communications (general)

  - W. C. Y. Lee, Mobile Communications Design Fundamentals, Wiley 1993
  - L. M. Correia (Ed.), Wireless Flexible Personalised Communications – COST 259: European Co-Operation in Mobile Radio Research, Wiley 2001
  - B. Walke, Mobilfunknetze und ihre Protokolle (Bd. 1 u. Bd. 2), 3. Auflage, Teubner 2001
  - R. Rupp, G. Siegmund, Java in der Telekommunikation, dpunkt-Verlag 2004
  - J. G. Proakis, M. Saleh, Grundlagen der Kommunikationstechnik, Pearson Studium, 2. Auflage, 2004
  - S. Haykin, M. Moher, Modern Wireless Communications, Pearson Prentice Hall 2005

Literature

- Further literature on wave propagation

  - J. D. Parsons, Mobile Radio Propagation Channel, Wiley 2001
  - N. Blaunstein, Radio Propagation in Cellular Networks, Artech House 1999
  - N. Blaunstein, J. B. Andersen, Multipath Phenomena in Cellular Networks, Artech House 2002
  - H. L. Bertoni, Radio Propagation for Modern Wireless Systems, Prentice Hall 2000
  - S. R. Saunders, Antennas and Propagation for Wireless Communication Systems, Wiley 1999
  - R. Vaughan, J. B. Andersen, Channels, Propagation and Antennas for Mobile Communications, IEE Electromagnetic Waves Series 2003

Literature

- Further literature on the GSM system

  - M. Mouly, M.-B. Pautet, The GSM System for Mobile Communications, ISBN 2-9507190-0-7, 1992
  - J. Eberspächer, H.-J. Vögel, C. Bettstetter, GSM Global System for Mobile Communication, 3. Auflage, Teubner 2001
  - G. Heine, GSM-Signalisierung, Franzis-Verlag 2001
  - Z. Zvonar, P. Jung, K. Kammerlander, GSM – Evolution towards 3rd Generation Systems, Kluwer 1999

- Further literature on the UMTS/LTE system

  - H. Holma, A. Toskala (Ed.), WCDMA for UMTS – HSPA Evolution and LTE, Wiley 2007
  - J. Laiho, A. Wacker, T. Novosad, Radio Network Planning and Optimisation for UMTS, Wiley 2002
  - B. Walke, M. P. Althoff, P. Seidenberg, UMTS – Ein Kurs, 2. Auflage, J. Schlembach Fachverlag 2002

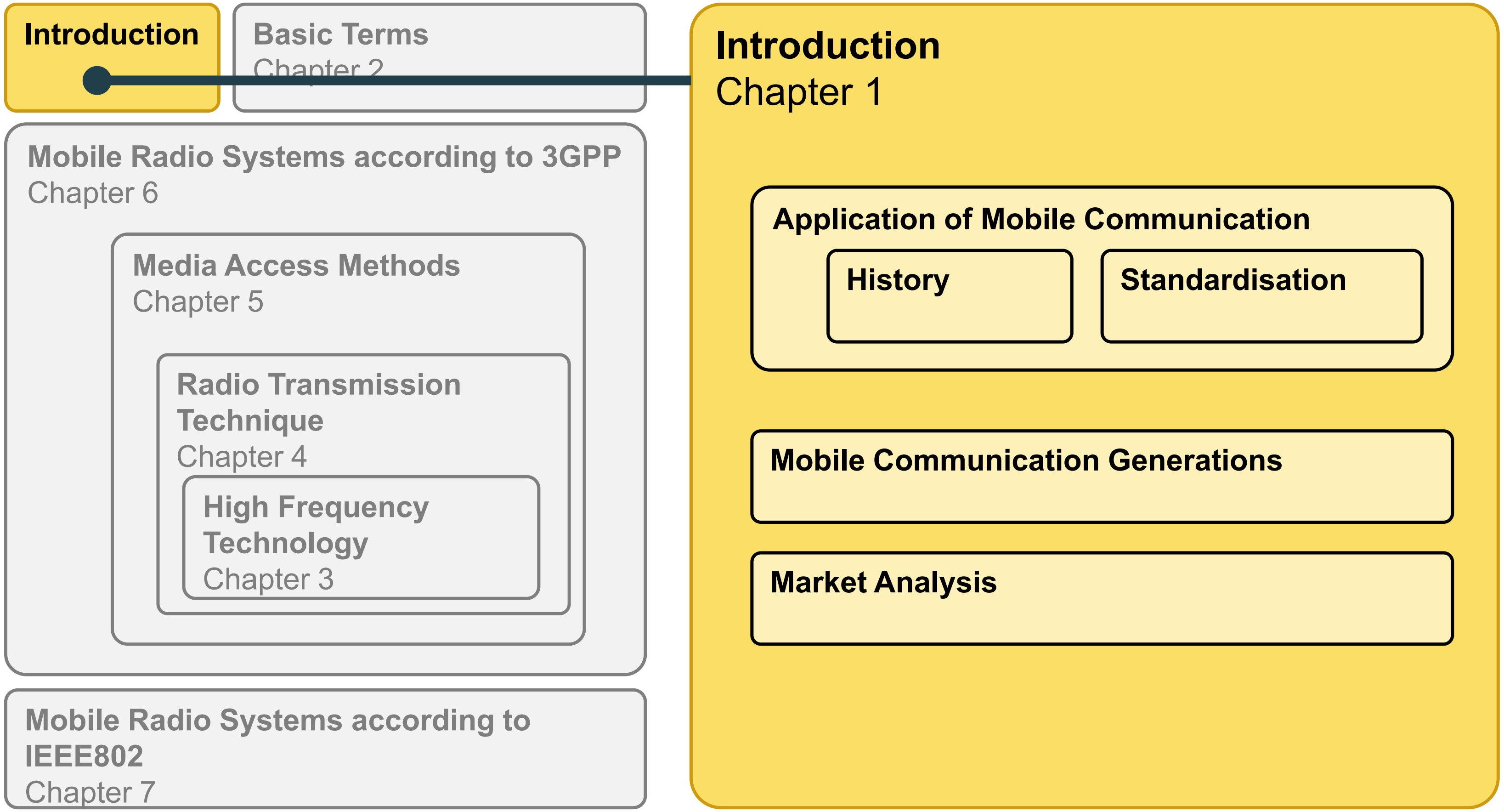
Literature

- M. Wuschke, UMTS-Paketvermittlung im Transportnetz, Protokollaspekte, Systemüberblick, Teubner 2004
- E. Dahlman, S. Parkwall, J. Sköld, P. Beming, 3G Evolution – HSPA and LTE for Mobile Broadband, Elsevier 2007
- H. Holma, A. Toskala (Ed.), LTE for UMTS – OFDMA and SC-FDMA Based Radio Access, Wiley 2009

Further literature on 5G systems

- W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020
- R. Tafazolli, P. Chatzimisios, C.-L. Wang, Wiley 5G Ref: The Essential 5G reference Online, Wiley 2019 (Online)

Chapter 1 - Introduction

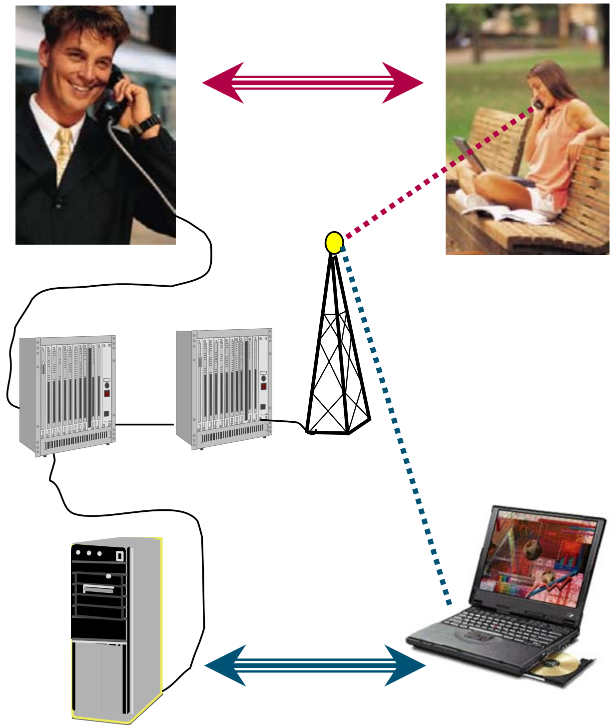


1 Introduction
1.1 Applications of Mobile Communications

- First half of the 20th century: wired communication is mainly used
  - telephone for the transmission of voice
  - telegraphy for the transmission of texts
- Technical progress (transmission and switching techniques, microelectronics) has enabled a rapid development of wireless communication
- Mobile radio networks allow the request for spatially unbound communication.

Examples (1)

- Voice communication in a public telephone network, at least one mobile user
  - examples: GSM, UMTS, LTE, 5G, TETRA
  - unresticted mobility in the coverage area of the network
- data communication between a laptop (mobile) or a smartphone and a stationary server
  - examples: GSM data transmission (HSCSD, GPRS), UMTS, LTE, 5G
  - unrestricted mobility in the coverage area of the network

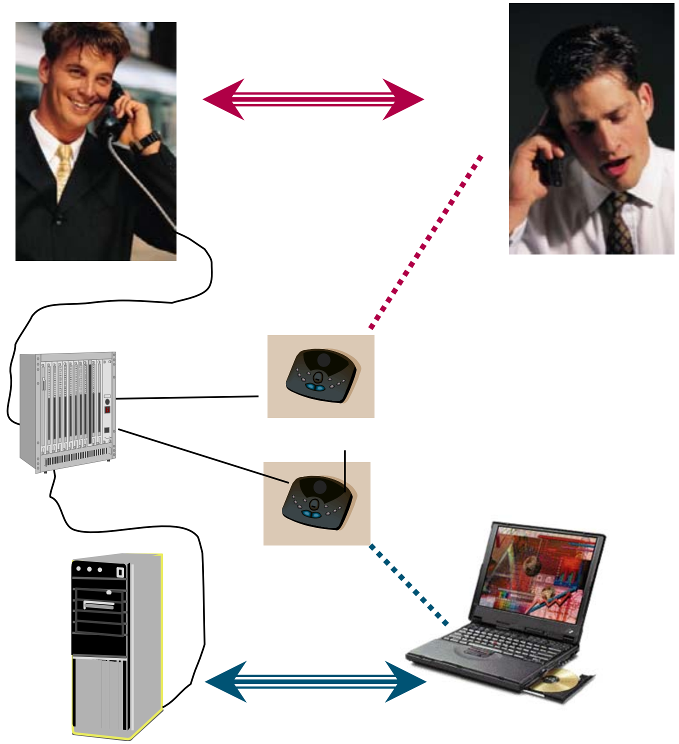


1.1 Applications of Mobile Communications

Examples (2)

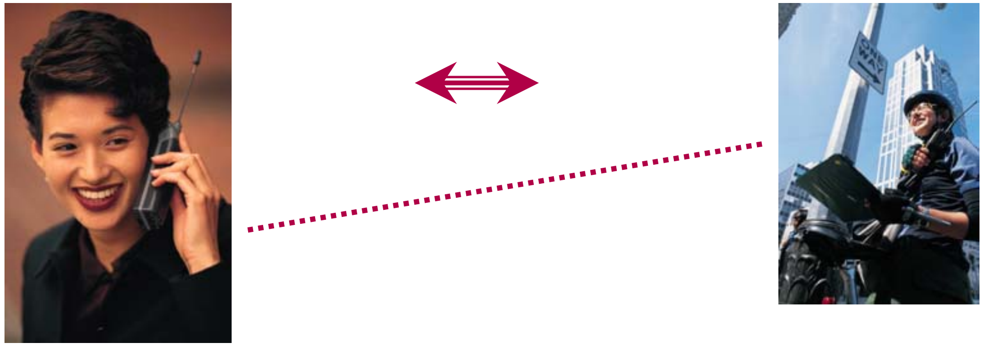
- voice communication in a public telephone network, with at least one subscriber using a cordless telephone
  - examples: cordless telephones (DECT)
  - restricted mobility within a small radius around the base station

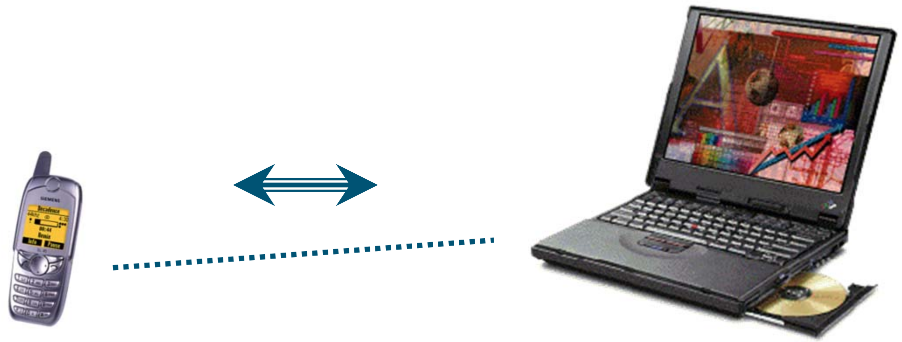
- data communication between a laptop (mobile) or a smartphone and a server (stationary) via a wireless network access
  - examples: WLAN
  - restricted mobility within a small radius around the access point



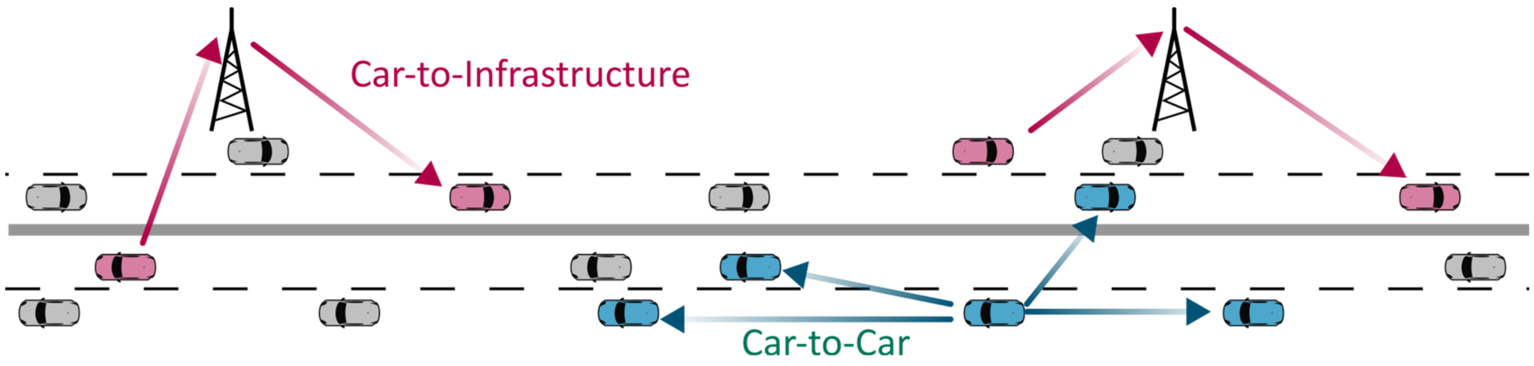
Examples (3)

- direct voice communication between two mobile users
    - example: hand-carried transceiver („walkie-talkie“)
    - mobility is heavily restricted due to the limited coverage between the users
- direct data communication between two mobile terminals
    - example: bluetooth, D2D, IEEE 802.11p
    - mobility is heavily restricted due to the limited coverage between the two terminals





Examples (4)



- Communication between mobile users in road traffic (C2C)
- Communication with an infrastructure, e. g. traffic lights (C2I)
- C2C communication makes basically new demands on a radio standard

1.2 Development of Mobile Communications

- 1864 Theory of the electromagnetic fields, wave equations by James Maxwell
- 1888 Experimental proof by Heinrich Hertz in Karlsruhe that electromagnetic waves exist
- 1897 Development of the first suitable system for telegraphic transmission by Guglielmo Marconi
- 1901 First transatlantic wireless data transmission
- 1906 First World Administrative Radio Conference (WARC), which regulates the use of frequency bands worldwide
- 1926 Telephone aboard the train on the route Hamburg-Berlin
- After 1945 first radio systems in taxis in Germany

From A-Network to GSM

- 1958 A-network in Germany
  - analogue, 160 MHz, call set-up only from the mobile station, no handover, 80 % coverage, 11.000 subscribers in 1971
- 1972 B-network in Germany
  - analogue, 160 MHz, call set-up also from the fixed network (location of the mobile station has to be known), 13.000 subscribers in 1979
- 1982 Start of the GSM specification (Groupe Spécial Mobile)
  - objective: pan-European mobile radio network with roaming
- 1987 Essential characteristics of radio transmission technique for GSM were defined
  - Formation of the GSM Memorandum of Understanding (MoU) Association

From C-Network to E-Network

- 1989 C-network in Germany
  - analogue, 450 MHz, handover possible, digital signalling, automatic localisation of the mobile station, 98 % coverage, data services (fax, Datex-P, modem, e-mail), 600.000 subscribers in 1996, in use until 2000
- 1990 Freezing of phase 1 of the GSM specification
- 1992 D-networks in Germany
  - D1, D2, completely digital, GSM, 900 MHz, automatic localisation, handover, cellular
  - roaming in Europe (meantime available worldwide)
- 1994 E-network in Germany
  - GSM, 1800 MHz (E-Plus), smaller cells, at the end of 1997 98% of the population reachable (licence condition)
- 1997 Allocation of a further E-network licence in Germany
  - coverage obligation of only 75 % in 1998

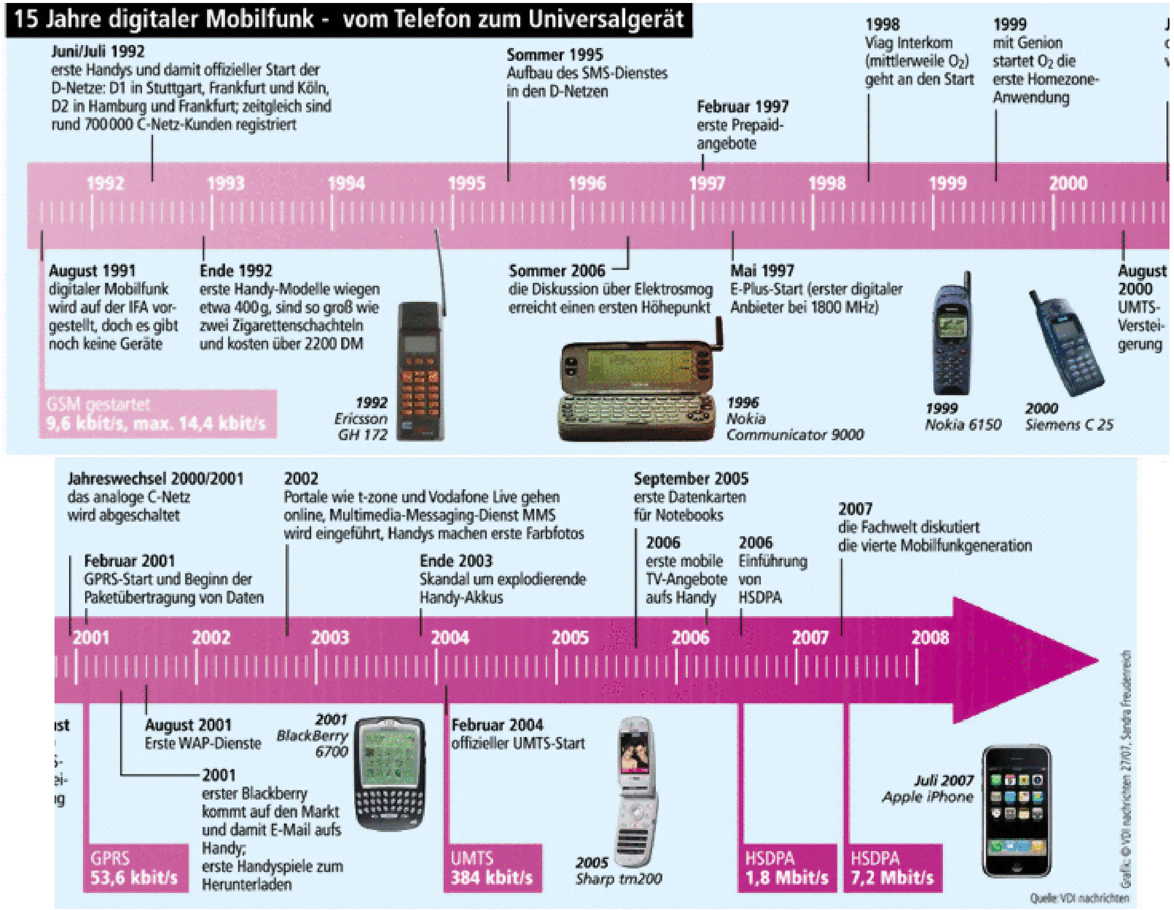
Development of UMTS

- Essential characteristics of the radio transmission technique for the European „candidate“ (UMTS) for IMT-2000 were defined
- 1999 Allocation of the first European UMTS licence (Finland)
- 2000 End of the UMTS auction in Germany
  - Allocation of 6 licences, auction proceeds 100 Mrd. DM
- 2001 Start of operation of the first 3rd generation network worldwide in Japan
  - NTT DoComo (start of operation of the network in October 2001, W-CDMA standard), 200,000 subscribers in February 2003, 3 million subscribers on 31st March 2004
  - KDDI (start of operation of the network in April 2002, cdma2000 standard) reached 13 million subscribers on 12th March 2004
- 2003 Hutchison UK launched the first UMTS network in Great Britain

From UMTS to LTE/5G

- 2004 Launch of the first UMTS networks in Germany
- 2006 Commercial launch of HSDPA in Germany
- 2007 IEEE 802.16 (WiMAX) adopted as additional IMT standard
- 2009 Essential characteristics for the new standard LTE (Longterm Evolution) defined
- 2010 Auction of mobile radio frequencies at a bandwidth of 360 MHz in Germany
- 2010 In Oslo and Sweden, TeliaSonera launches the first LTE networks
- 2011 Commercial launch of LTE in Germany
- 2015 and 2019 Auction of mobile radio frequencies in Germany
- 2019 First 5G networks in operation

Overview


15 Jahre digitaler Mobilfunk - vom Telefon zum Universalgerät
Juni/Juli 1992
erste Handys und damit offizieller Start der D-Netze: D1 in Stuttgart, Frankfurt und Köln, D2 in Hamburg und Frankfurt; zeitgleich sind rund 700 000 C-Netz-Kunden registriert
Sommer 1995
Aufbau des SMS-Dienstes in den D-Netzen
Februar 1997
erste Prepaid-angebote
1998
Viag Interkom (mittlerweile O2) geht an den Start
1999
mit Genion startet O2 die erste Homezone-Anwendung
1992 1993 1994 1995 1996 1997 1998 1999 2000
August 1991
digitaler Mobilfunk wird auf der IFA vorgestellt, doch es gibt noch keine Geräte
Ende 1992
erste Handy-Modelle wiegen etwa 400 g, sind so groß wie zwei Zigarettenschachteln und kosten über 2200 DM
Sommer 2006
die Diskussion über Elektrosmog erreicht einen ersten Höhepunkt
Mai 1997
E-Plus-Start (erster digitaler Anbieter bei 1800 MHz)
August 2000
UMTS-Versteigerung
GSM gestartet
9,6 kbit/s, max. 14,4 kbit/s
1992 Ericsson GH 172
1996 Nokia Communicator 9000
1999 Nokia 6150
2000 Siemens C 25
Jahreswechsel 2000/2001
das analoge C-Netz wird abgeschaltet
2002
Portale wie t-zone und Vodafone Live gehen online, Multimedia-Messaging-Dienst MMS wird eingeführt, Handys machen erste Farbfotos
September 2005
erste Datenkarten für Notebooks
2007
die Fachwelt diskutiert die vierte Mobilfunkgeneration
Februar 2001
GPRS-Start und Beginn der Paketübertragung von Daten
Ende 2003
Skandal um explodierende Handy-Akkus
2006
erste mobile TV-Angebote aufs Handy
2006
Einführung von HSDPA
2001 2002 2003 2004 2005 2006 2007 2008
August 2001
Erste WAP-Dienste
2001 BlackBerry 6700
2001
erster Blackberry kommt auf den Markt und damit E-Mail aufs Handy; erste Handyspiele zum Herunterladen
Februar 2004
offizieller UMTS-Start
2005 Sharp tm200
Juli 2007 Apple iPhone
GPRS
53,6 kbit/s
UMTS
384 kbit/s
HSDPA
1,8 Mbit/s
HSDPA
7,2 Mbit/s
Grafik: © VDI nachrichten 27/07, Sandra Freudenreich
Quelle: VDI nachrichten

1.3 Standardisation of Mobile Radio Systems

- At present, two large standards committees standardising mobile radio systems exist worldwide

http://www.3gpp.org/

http://www.ieee802.org/

3GPP

3rd Generation Partnership Project (3GPP)

- Founded in 1998, comprises six so-called *Organizational Partners*:
  - ARIB (Association of Radio Industries and Businesses, Japan)
  - ETSI (European Telecommunication Standards Institute)
  - ATIS (previously T1) (Alliance for Telecommunications Industry Solutions, USA)
  - TTA (Telecommunications Technology Association, Korea)
  - TTC (Telecommunications Technology Committee, Japan)
  - CCSA (China Communications Standards Association, China)
- Standards: GSM (GERAN), WCDMA (UMTS, UTRAN), LTE, LTE-Advanced (E-UTRAN)
- Furthermore, there is the project 3GPP2, which forms a cooperation of companies working on the CDMA2000 standard.

IEEE 802

IEEE 802 is a project of the IEEE

- Founded in 1980 (therefore denoted as 802)
- develops standards in the range of local networks (LAN)
- Meantime, the project deals primarily with radio systems.
- Forming of different working groups also dealing with new aspects and systems according to requirements.

- Standards: e. g. IEEE 802.11 (WLAN), IEEE 802.15 (Wireless Speciality Networks WSN), IEEE 802.16* (WiMAX)

* is no longer continued

1.4 Classification of Mobile Radio Systems into Generations

1st Generation (analogue networks, e. g. C-network, NMS):

- Different systems for different applications
- Nationally/regionally limited
- Analogue transmission
- Expensive bulky terminals
- Low security level
- Low network capacity

2nd Generation (e. g. GSM, DECT):

- Small number of systems for numerous applications
- International roaming
- Digital transmission
- ISDN services < 9.6 kbit/s, SMS
- Favourable handheld terminals
- Encryption, authentication
- Significantly higher network capacity

UMTS, WIMAX, LTE

3rd Generation (e. g. UMTS):

- Worldwide harmonisation
- Universal systems, convergence
- Optimised transmission technique
- Increase of the radio network capacity
- Increase of the data rates
- Multimedia, mobile internet

Transition from 3rd to 4th Generation

- HSPA (3.5G)
- LTE, WIMAX (3.9G)

4th Generation (LTE-Advanced, WiMAX-Advanced 802.16m)

- Data rates of 100 MBit/s at high mobility and 1GBit/s at low mobility
- Bandwidths of up to 100 MHz
- Very low latencies

5th Generation

5th Generation: currently in its introductory phase

- Essential requirements are e. g.:
  - Higher data rates
  - Significantly lower latencies (e. g. for tactile internet)
  - Ultra-high availability
  - Very high density of connections (Internet of Things, sensor networks)
  - High mobility

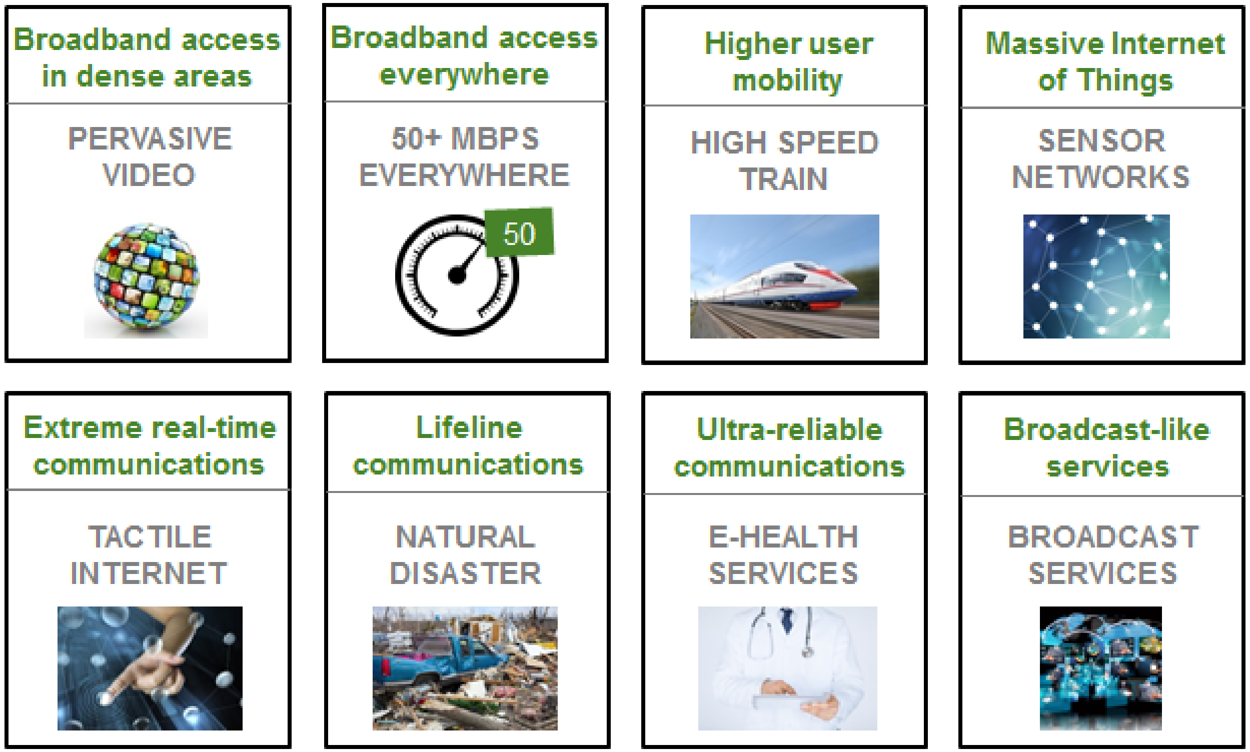
- 5G contains, e. g.
  - New radio interfaces, e. g. with carrier frequencies > 6 GHz
  - Smart opportunities for the management of heterogeneous networks

6th Generation: currently in research, beginning of standardisation

- Standardisation will start in 2025/2026
  - Amongst others Augmented/Virtual Reality, Integrated Communication and Sensing, x100 Gbps, carrier frequencies > 100 GHz

5th Generation – New Applications

5G Use cases

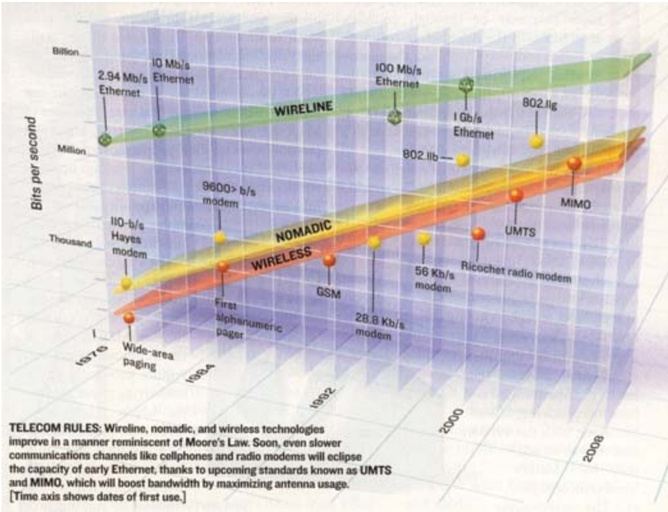


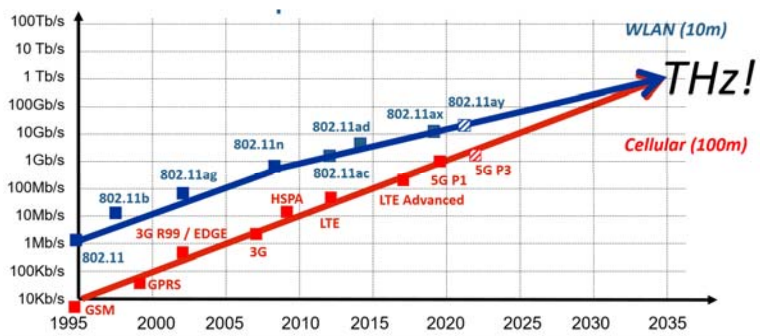
Source: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

1.5 WLAN and WSN Standard for Local Radio Networks

- **IEEE 802.11 (Institute for Electrical and Electronics Engineers):** American system; data rates up to 54 Mbit/s; use of the ISM band (ISM: Industrial, Scientific and Medical) at 2.4 GHz, 5 GHz and 60 GHz with data throughput > 1Gbit/s
- **Bluetooth (IEEE 802.15.1, meanwhile not an IEEE 802 standard anymore):** development by the Bluetooth Interest Group (founded in 1998); substitution of cable connections via short distances between devices by simple, favourable and flexible radio links; maximum data rate 720 kbit/s; operation in the public domain ISM band
- **Ultrawideband systems (IEEE 802.15.3a):** data rates up to 500 Mbit/s; standard has never been adopted. Thus, only a standard from ECMA (ECMA-368) exists.
- **Millimeter wave communication / THz communication:** data rates of several Gbit/s at 60 GHz (IEEE802.15.3c, IEEE 802.15.3e) and 300 GHz (IEEE 802.15.3d), respectively
- **Sensor networks (IEEE 802.15.4 family):** Zigbee standard

1.6 Data Rates of Telecommunication Systems



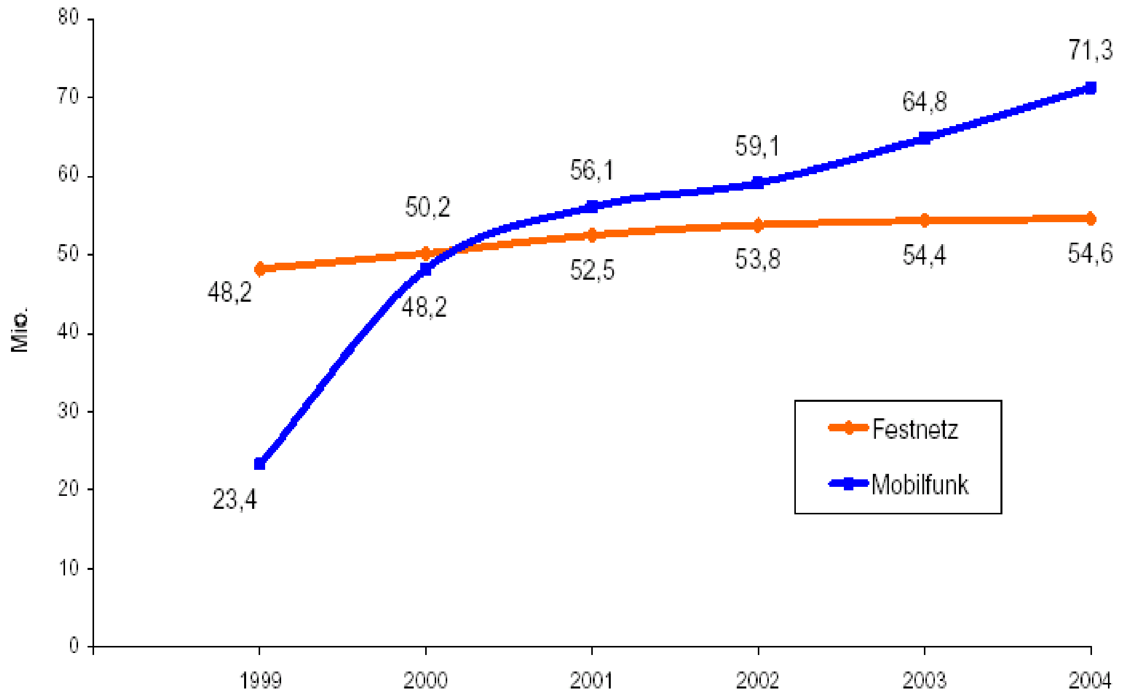


Source: IEEE Spectrum, Juli 2004

Source: G. Fettweis, 1St TERAFLAG Workshop Cassis 2018

Fixed Network and Mobile Radio Communication

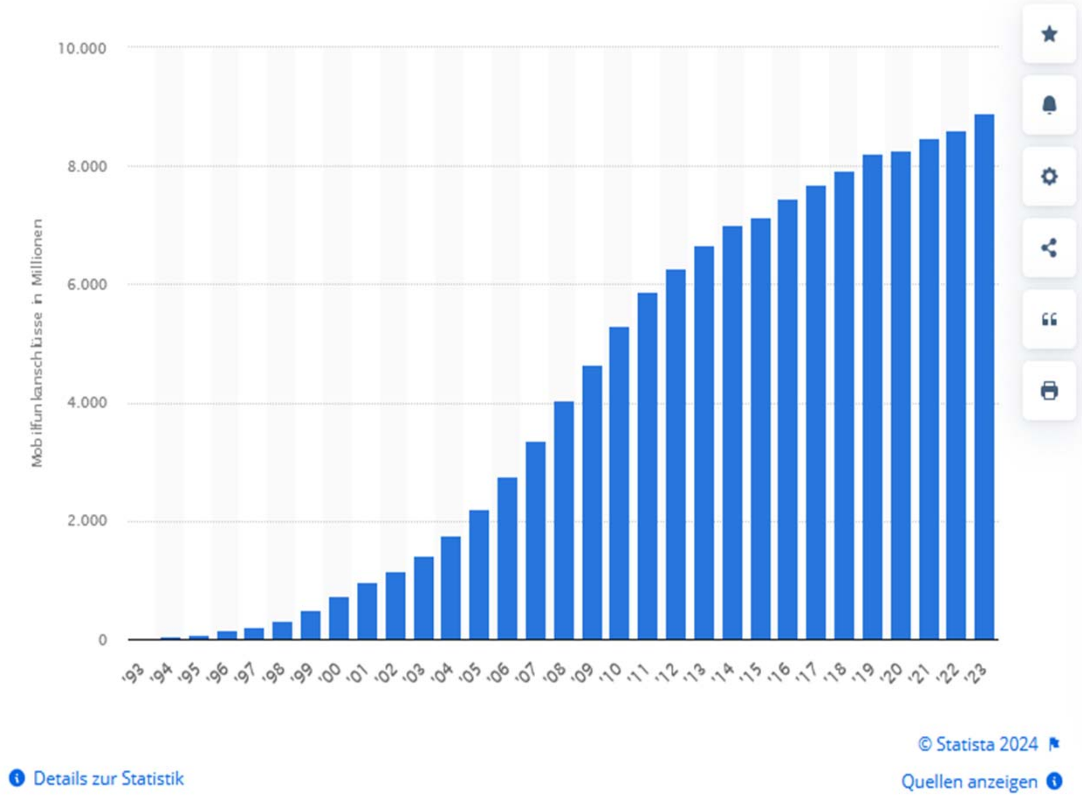
Comparison mobile users / fixed network connections in Germany



Source: Marktbeobachtungsdaten der Regulierungsbehörde für Post und Telekommunikation, Jahresbericht 2004

1.7 Markets for Mobile Communications

- Development of the number of mobile users worldwide

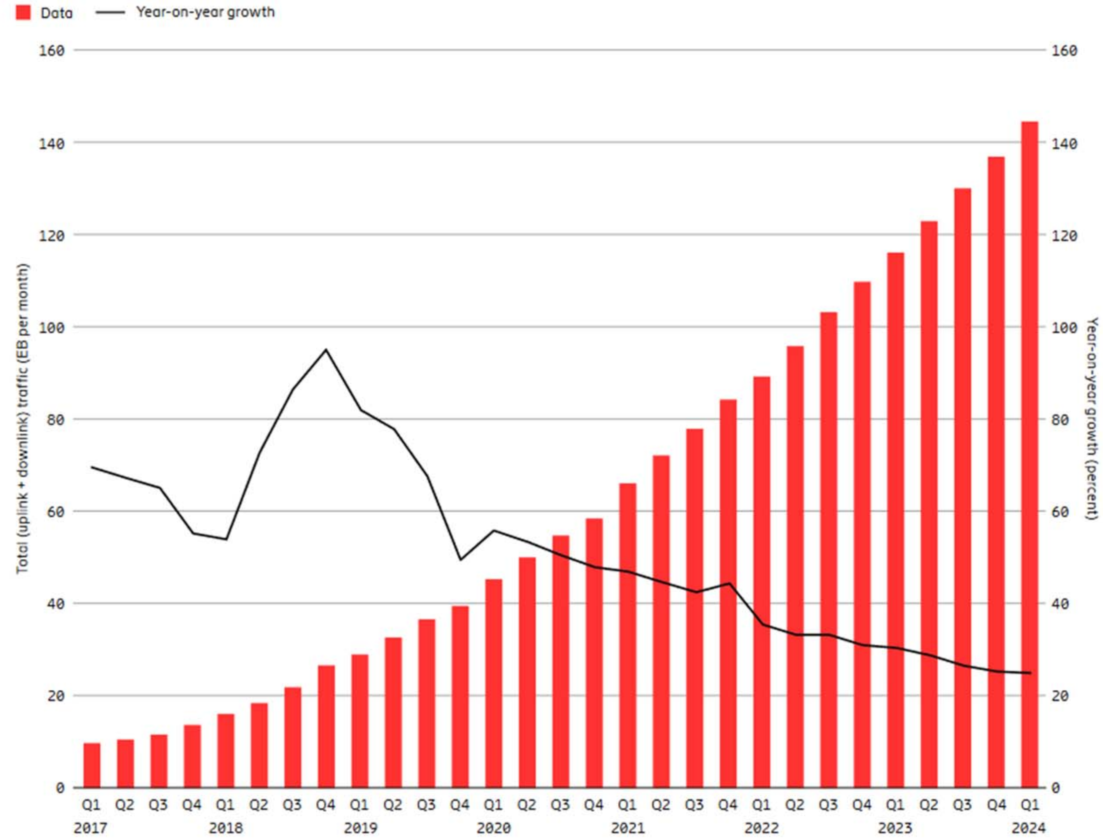


Source: https://de.statista.com/statistik/daten/studie/2995/umfrage/entwicklung-der-weltweiten-mobilfunkteilnehmer-seit-1993/

Data Traffic

Development of Mobile Data Traffic

Figure 5: Global mobile network data traffic and year-on-year growth (EB per month)

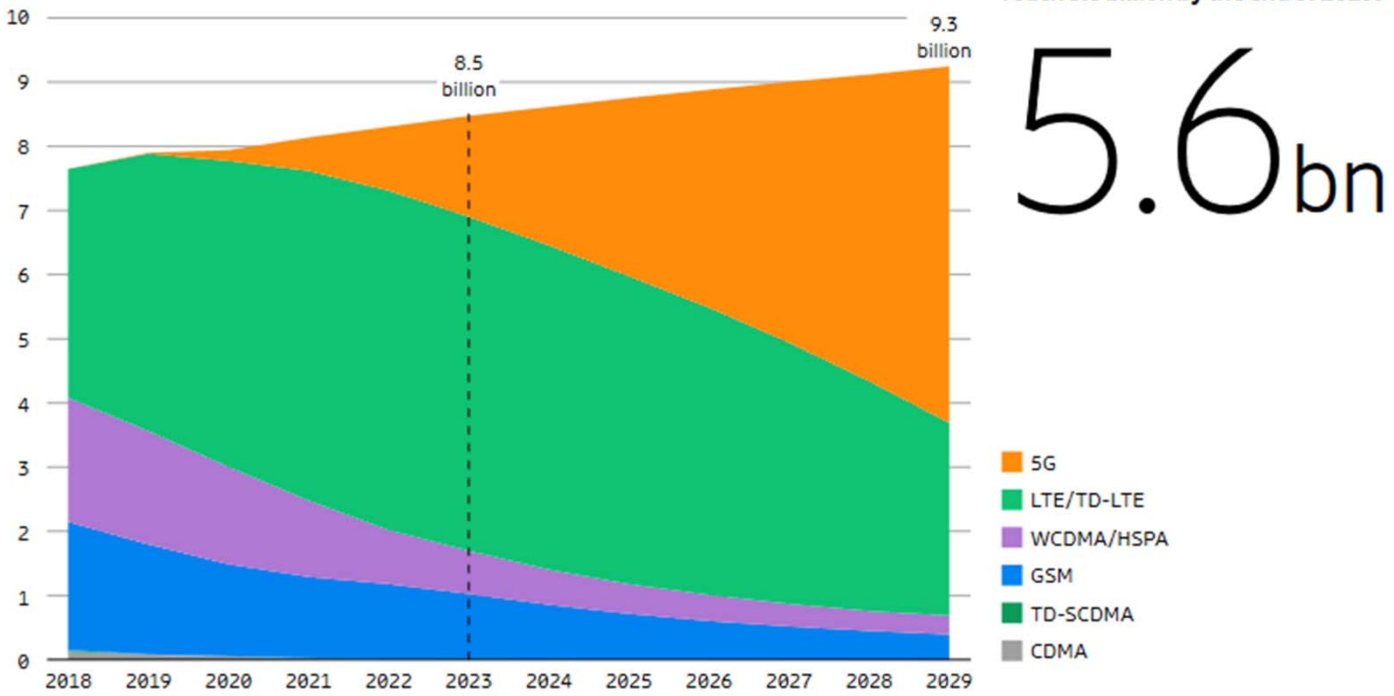


Note: Mobile network data traffic also includes traffic generated by Fixed Wireless Access services.

Quelle: Ericsson Mobility Report, https://www.ericsson.com/49ed78/assets/local/reports-papers/mobility-report/documents/2024/ericsson-mobility-report-june-2024.pdf

Worldwide Subscriptions

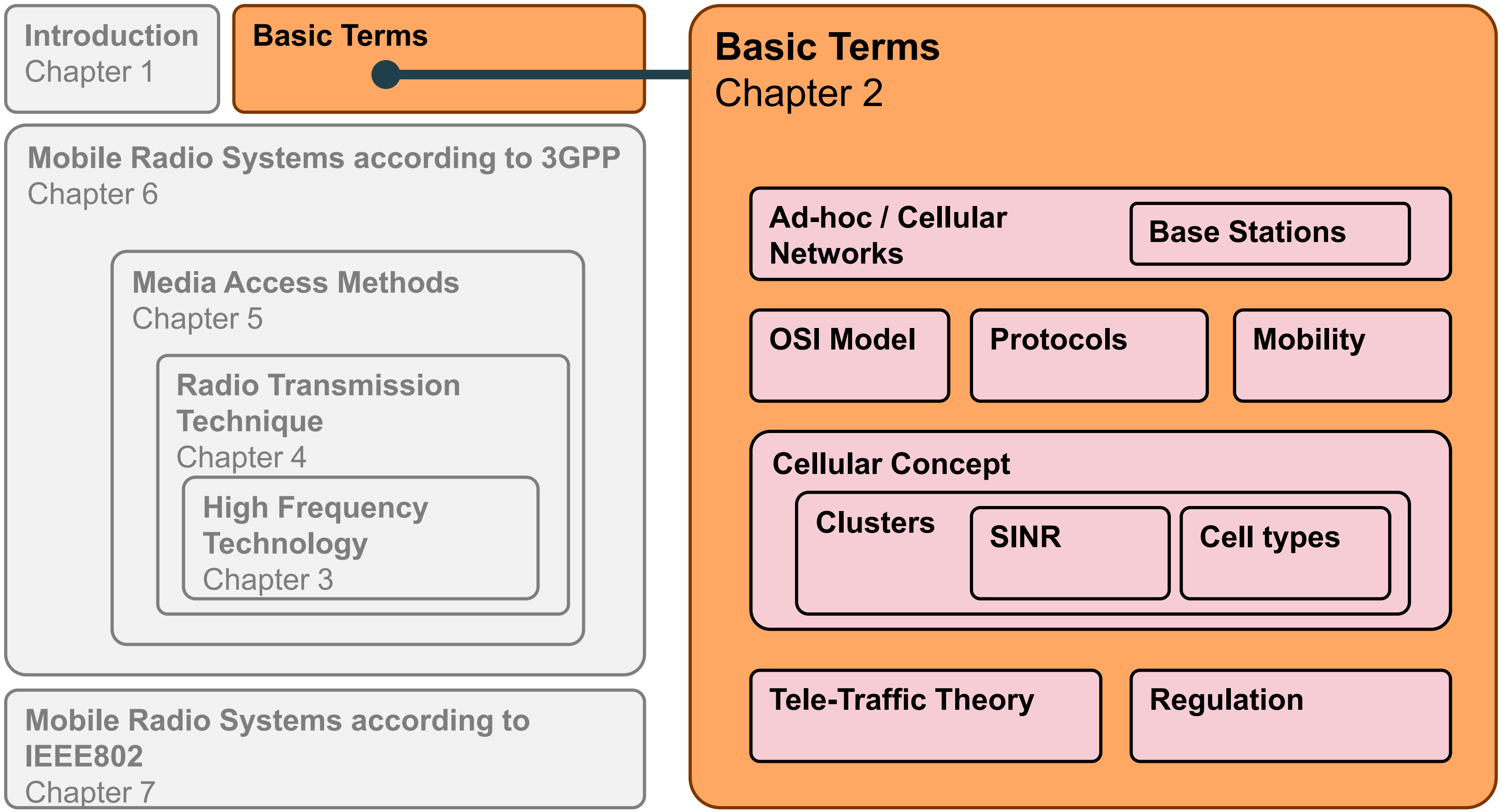
Figure 1: Mobile subscriptions by technology (billion)



[1] A 5G subscription is counted as such when associated with a device that supports New Radio (NR), as specified in 3GPP Release 15, and is connected to a 5G-enabled network.
[2] GSA and Ericsson (May 2024).

Quelle: https://www.ericsson.com/49ed78/assets/local/reports-papers/mobility-report/documents/2024/ericsson-mobility-report-june-2024.pdf

Chapter 2 – Basic Terms



2 Basic Terms

The three components of the term „mobile radio systems“:

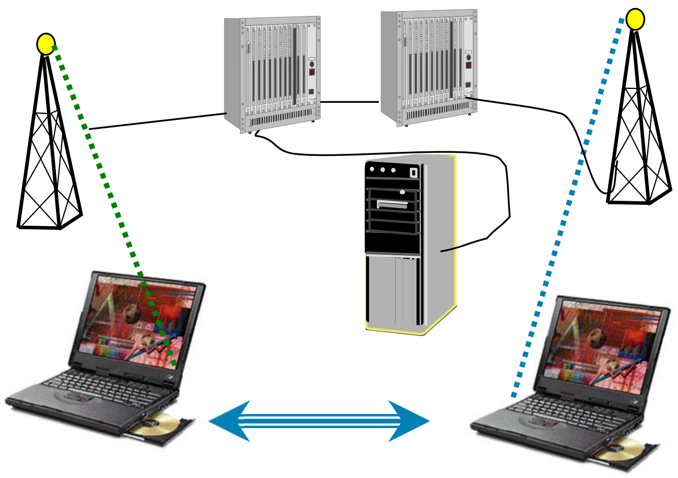
- Telecommunication system consisting of the components
  - terminals (interfaces between user and system)
  - transmission equipments
  - Switching equipments

- Mobility: users move in the mobile radio network
  - Extension of the telecommunication system by further components for the mobility management

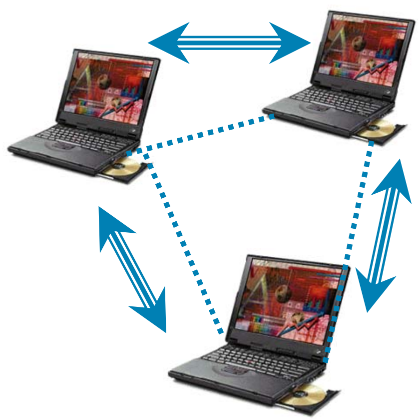
- Radio channel as transmission medium
  - strong variations of the received power level
  - Normally mutual interferences between radio links

2.1 Description of Mobile Radio Systems

- Mobile radio networks are divided into infrastructure networks and ad-hoc networks



„infrastructure network“



„ad-hoc network“

Infrastructure-based Networks

- Infrastructure-based networks
  - No direct communication between the terminals
  - In general, communication takes place between two wirelessly interworking terminals and an access point (access point, base station)
  - Existence of an infrastructure is absolutely necessary
  - Low flexibility
  - Control of the medium access by the infrastructure
  - Access to other networks
  - Forwarding of data between different networks possible
  - Complexity of the terminal is relatively low
  - Examples: Typical mobile radio networks such as GSM, UMTS, LTE, 5G etc.

Ad-hoc Networks

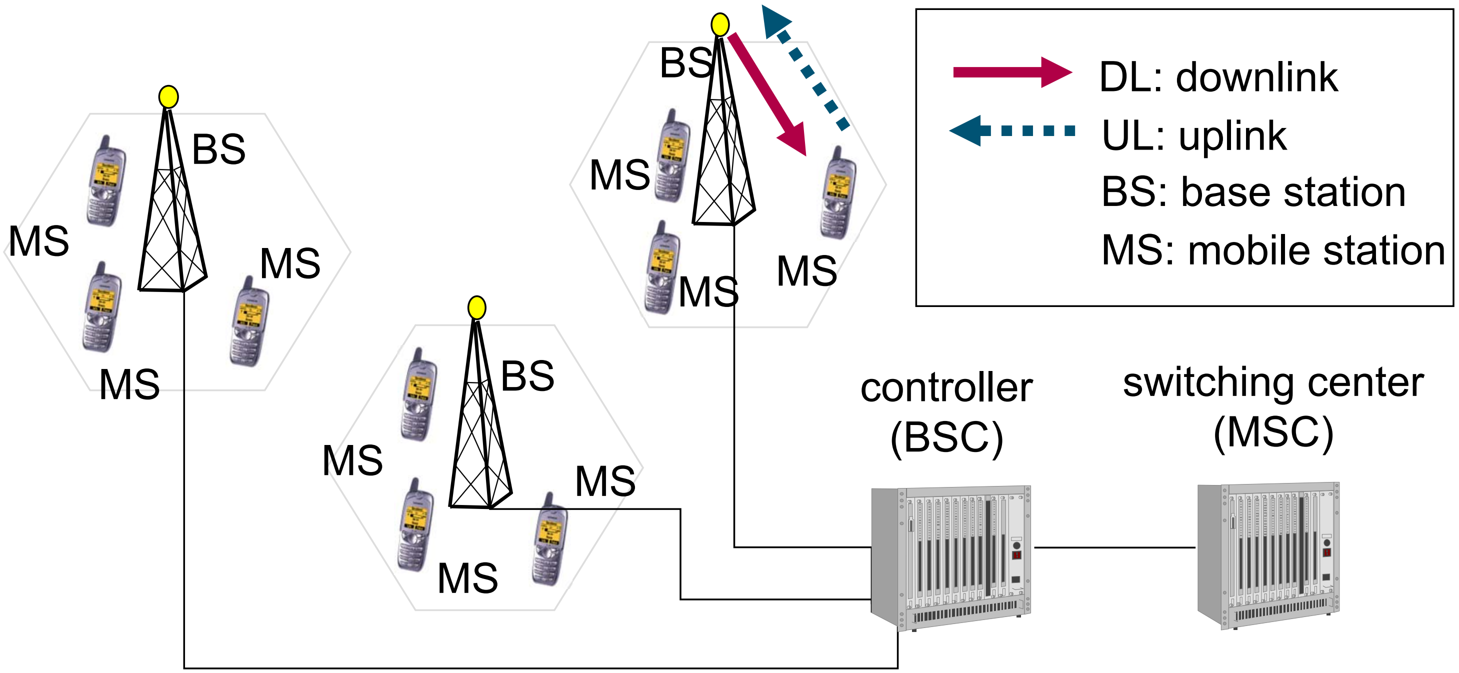
- Ad-hoc networks

  - No infrastructure required
  - Every terminal can communicate with the other one directly
  - In order to control the medium access, no access point is required
  - Complexity of the terminal is higher, since all mechanisms for medium access have to be included
  - Largest possible flexibility (e. g. destroyed infrastructure, catastrophe)
  - Typical example: Bluetooth

- IEEE 802.11 can be operated in infrastructure as well as in ad-hoc networks.

2.2 Set-Up of a Cellular Mobile Radio System

- Set-up of a cellular mobile radio system in principle (infrastructure-based)

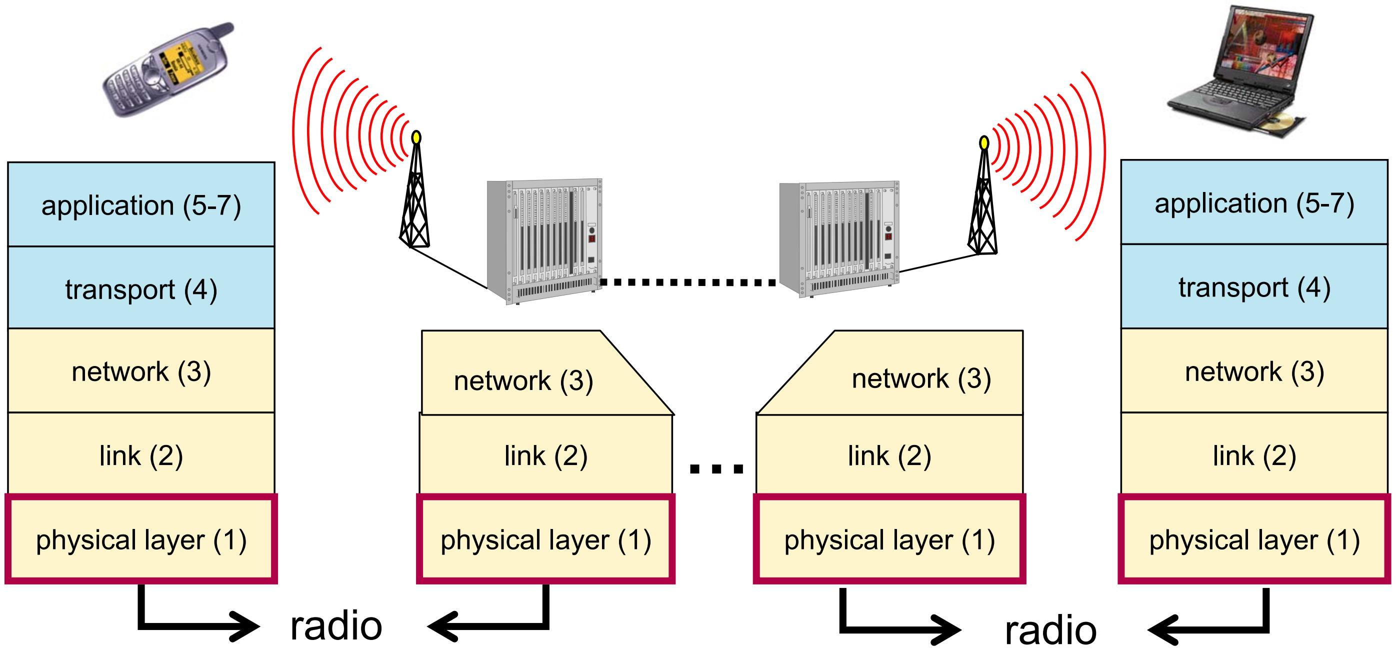


Base Station

- A cellular mobile radio system consists of one or several fixed radio stations (base stations), which are connected with each other via switching centers.
- In terms of radiocommunication, each base station covers a certain area, the so-called radio cell.
- The radio link direction from the BS to the MS is called Downlink (DL).
- The radio link direction from the MS to the BS is called Uplink (UL).

2.3 OSI Reference Model

- For the concise and systematic description of the system components, the tasks are divided into seven layers
  => OSI reference model (open system interconnection)



Tasks of the Layers

- Tasks of the single layers of the ISO-OSI reference model

  - Layers 5-7: application layers
    - description of the real telecommunication service (example: telephony, telefax, e-Mail etc.)
    - definition of the format for the data exchange (example: HTML)

  - Layer 4: umongst others provisioning of methods to guarantee the correct end-to-end order
  - Layer 3: call set-up, thus guidance, routing and forwarding of the data; mobility management in mobile communications
  - Layer 2: error detection and error correction (Logical Link Control) as well as control of the access to the transmission medium (Medium Access Control)
  - Layer 1: physical transport of the data, no classification according to reference and control data; data packet consists of a stream of bits

Rules

- Rules for the OSI reference model:

  - Two layers lying one upon the other are independent from each other. One layer obtains a service from the respective lower layer. In return, it provides a service to the upper layer. The lower layer is not „interested“ in the content of the information.

  - Each layer only communicates with the layer located directly above or below it and with its „partner“ layer on the other side.

  - In case more than two nodes are involved in a communication process, in the nodes between transmitter and receiver only the layers 1-3 exist.

  - The layers 4-7 only exist in the terminal stations of a communication process.

2.4 Protocol

- A protocol is a set of rules according to which communication within a layer is effected.

- The protocol defines:
  - which messages exist within a layer
  - what the messages consist of
  - how the receiver has to react to a certain incoming message

- Examples of protocols on the Internet:
  - loading of websites – (Hypertext Transfer Protocol - HTTP)
  - data transfer – (Transfer Control Protocol - TCP)

2.5 Services

Teleservices

- transmission of form and content
- primary services (example: telephony, telefax, SMS, e-mail)
- additional services (example: call waiting, broker‘s call, call forwarding)
- value-added network services (example: mailbox, directory inquiring and reservation services)

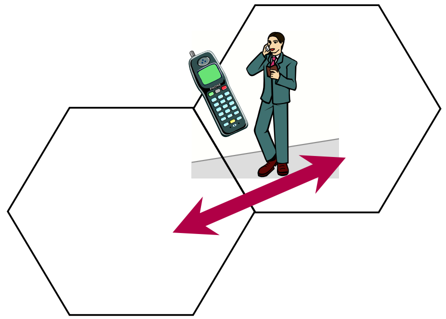
Bearer service

- transmission of bits
- characterisation by call set-up delays, data rates, maximum expected bit rate, maximum expected delay time
- examples: 57.6 kbit/s HSCSD, 26.8 kbit/s GPRS

2.6 Mobility

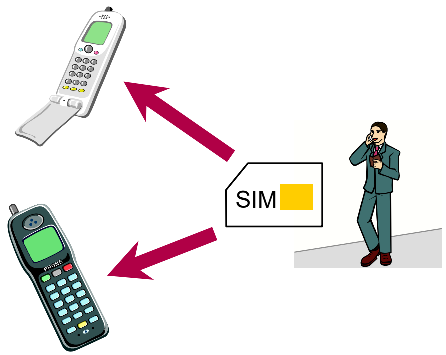
Terminal Mobility

- subscriber can move with his/her terminal in the coverage area without restrictions
- roaming at every place



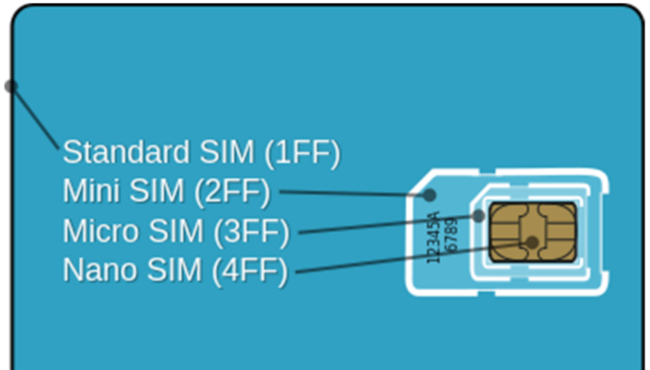
Personal Mobility

- use of the subscribed telecommunication services from every standard-compliant terminal by change of the SIM card (Subscriber Identity Module)
- availability at the same number independent from the terminal



SIM Cards

- SIM card contains
  - subscriber data identifying the user (IMSI)
  - sequence of numbers and algorithms for ciphering and authentication
  - temporarily saved network information, e. g. about frequencies of the latest cells, in which the mobile telephone was checked in or about preferred networks abroad



Source: Justin Ormont; CC BY-SA 3.0

- SIM Application Toolkit / USAT (UMTS Aim Application Toolkit): enables the storage of smaller executable programs on the SIM card

- SIM Access Profile: reading out the content of the SIM card by the use of a firmly installed device via bluetooth

Embedded SIM Card (e-SIM)

- Specification by the GSM Association from the year 2014
  - adresses particularly the Machine-to-Machine (M2M) communication, i. a. also the automotive sector

- Permanently installed in the terminal
  - 8 pins replace the 8 gold contacts of the conventional SIM card

- Includes all functionalities of a plug-in SIM
  - additionally enables the safe download of a new SIM profile „over-the-air“ and with this a change of the network operator without physical replacement of the SIM card

- Retrofit of plug-in SIM cards also permits the usage of the SIM specification with plug-in M2M SIM cards

- Further detailed information:

http://www.gsma.com/connectedliving/wp-content/uploads/2014/10/Embedded-SIM-Toolkit-Oct-14-updated1.pdf

Grades of Mobility

Grades of mobility

- For individual reception: coverage area is a cell with a radius of 50 … 200 m around the base station (example: cordless telephone)
- regional/local: radio networks of a small number of cells, limited to e. g. premises, city centers, regions (example: commercial radiotelephony)
- national: radio network consisting of lots of cells, which almost cover a country completely (example: C network)
- international: availability in several countries - international roaming (example: GSM; at the end of 2002: 467 networks in 169 countries)
- global: availability at almost every place of the earth (example: satellite assisted mobile communications)

Technical Requirements

- Technical requirements of mobility

  - Guarantee of radio coverage in the favoured area
    - main task of radio network planning

  - In case of movement and change of the radio cell, the connection has to be kept alive by suitable mechanisms
    - Mobile radio system has to provide a cell change procedure
    - This mechanism is called handover

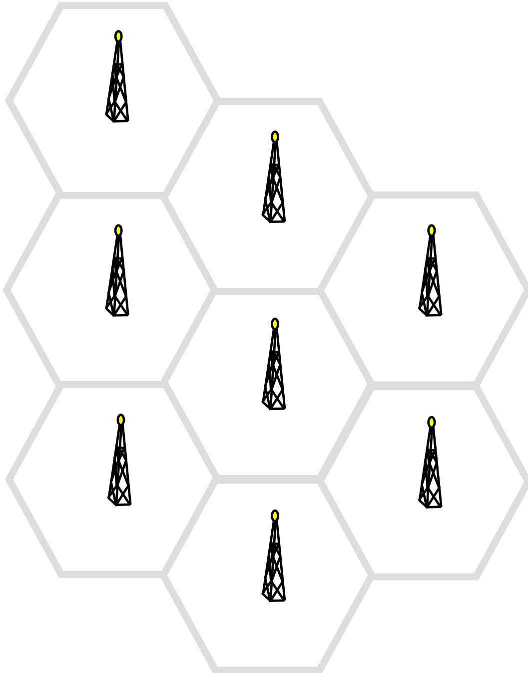
  - Subscriber is allowed to move arbitrarily in the network and is found automatically in case of incoming calls
    - Mobile radio system requires a mobility management
    - The respective mechanism is called roaming (general case: international roaming).

2.7 Cellular Concept

- Starting point: consideration of an area as large as possible by a base station at a site as high as possible

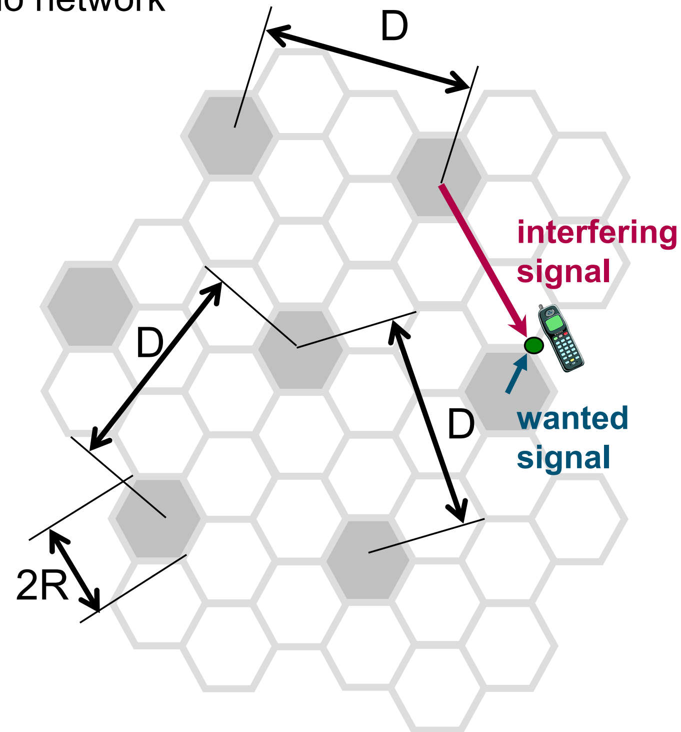
- Problem: limited frequency bands => relatively small number of speech channels

- Idea: splitting of the coverage area in smaller areas, the so-called cells (Bell Labs Patent von 1972)
  - application of antenna positions with lower heights
  - spatial frequency re-use



Frequency Re-Use

- Simplified modelling of the cells as hexagons
- Every cell i contains a subset of frequencies
  $f_i = \{f_{i,1}, f_{i,2}, \dots, f_{i,N}\}$ from the total f_{ges} allocated to the mobile radio network
- Re-use of a frequency $f_{i,n}$ with the frequency
  re-use distance D
- For adjacent cells, it is not allowed to use the
  same frequency
- D has to be adequately large to keep
  co-channel interferences low
- Automatic frequency change at transition
  between two cells (handover)



Signal-to-Noise Ratio

- The interference generated by the adjacent cells and the noise is stated as the signal-to-interference-plus-noise ratio (*SINR)*

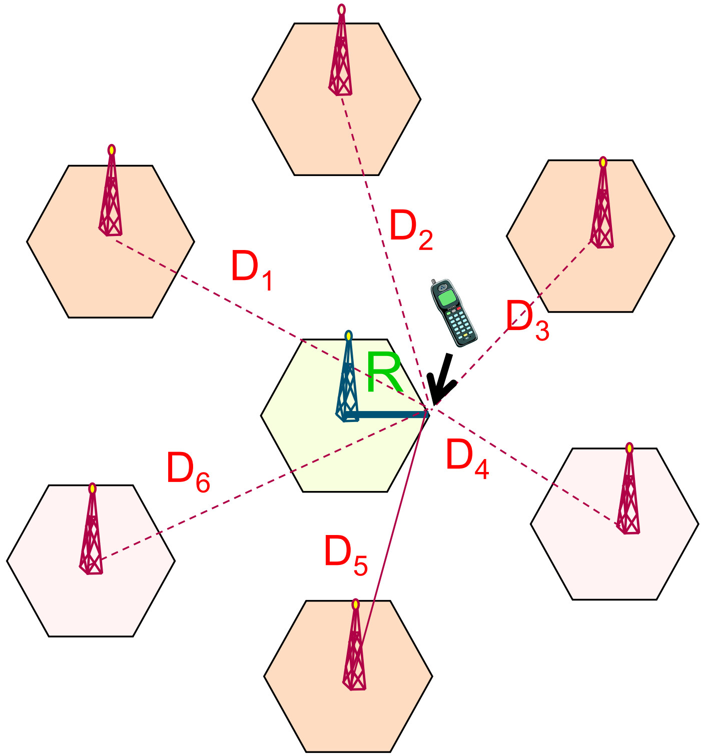
$$SINR = \frac{\text{wanted signal}}{\text{adjacent cell interference +noise}} = \frac{P}{I+N} \quad (1.1)$$

- Essentially, intensity of the interference by cochannel interferences depends on the frequency re-use separation D
- Worst-case estimation for the case that the mobile station is located on the cell boundary under the assumption of $D >> R$ (D and R: normalised values) and the same transmitting power $P_i = P_0$ for all base stations:

$$SINR = \frac{P_0 G_0 R^{-\gamma}}{\sum_{i=1}^{m} P_i G_i D_i^{-\gamma} + N} \approx \frac{P_0 G_0 R^{-\gamma}}{\sum_{i=1}^{m} P_0 G_i D^{-\gamma} + N} = \frac{P_0 G_0 R^{-\gamma}}{6 P_0 G_i D^{-\gamma} + N} \quad (1.2)$$

P_0: *transmitting power of the wanted signal,* ***G_0***: *path gain of the user at the distance of the reference value of R,*
P_i: *transmitting power of the interferer i,* ***G_i***: *path gain of the interferer i at the distance of the reference value of R,*
R: *normalised distance mobile device to the transmitter of the wanted signal,*
D_i: *normalised distance between mobile device and interferer i,*
N: *noise power,* ***γ***: *propagation coefficient*

Cell Geometry for Worst-Case Estimation



Signal-to-Interference Ratio

- Neglecting the noise, the *signal-to-interference ratio* (SIR) or the *carrier-to-interference ratio* (C/I) are indicated approximately:

$$SIR = \frac{1}{6}\left(\frac{R}{D}\right)^{-\gamma} = \frac{1}{6}\left(\frac{D}{R}\right)^{\gamma} \qquad (1.3)$$

- Signal-to-interference ratio essentially depends on the ratio R/D
- At a given cell radius R and a demanded threshold for W, a minimum separation $D_{\min}$ for the frequency re-use is required.
- In order to guarantee a regular re-use of frequencies, cells are grouped in a cluster.

Formation of Clusters

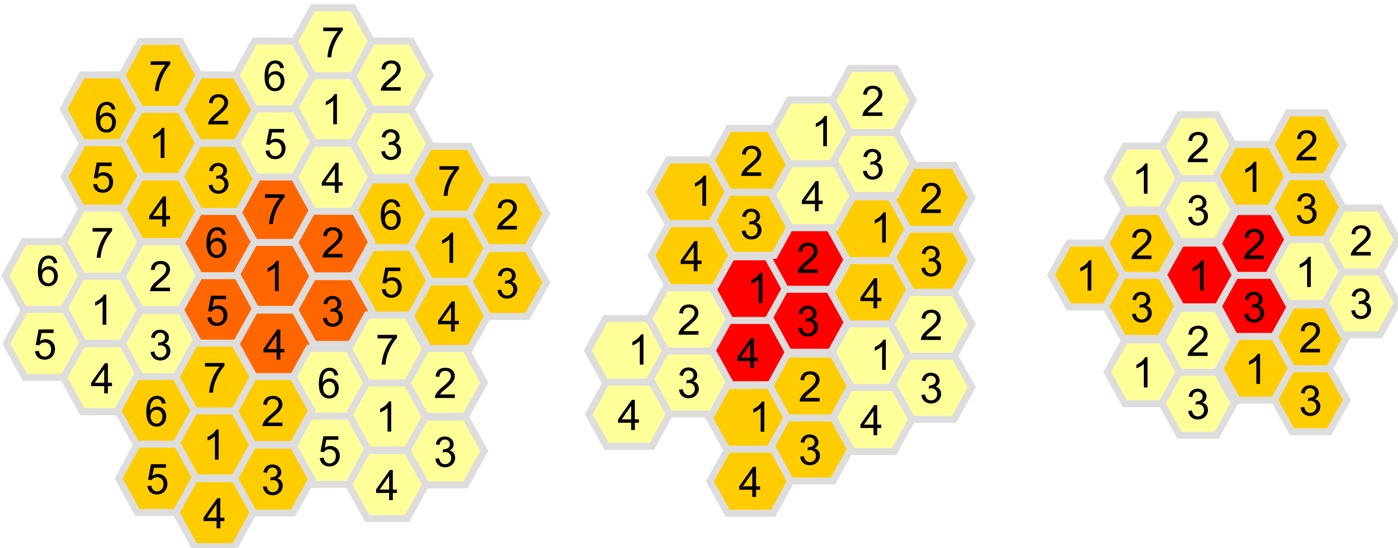
- Size of the cluster k indicates the number of cells per cluster
- A cluster can have all frequencies of the mobile radio system
- Inside a cluster no re-use of frequencies; re-use of frequencies f_i in the adjacent cluster at the earliest
- k defines the frequency re-use separation D
- Dependency between D and k from geometrical considerations in the hexagonal model

$$D = R\sqrt{3k} \qquad (1.4)$$

- Dependency between SIR and k from equations (1.3) and (1.4):

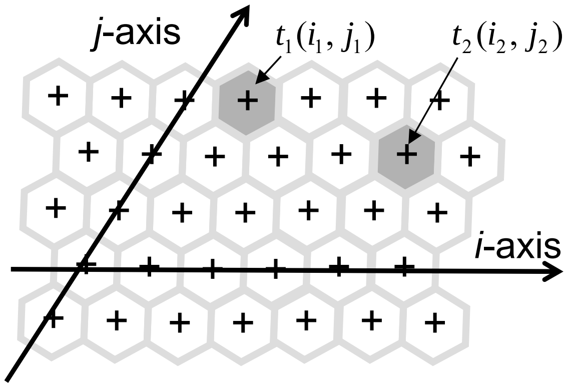
$$SIR = \frac{1}{6}(3k)^{\frac{\gamma}{2}} \qquad (1.5)$$

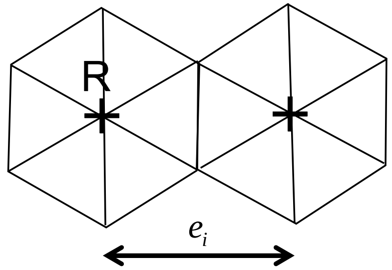
Examples of Clusters (Omni-Cells)



k=7 *k*=4 *k*=3

Geometry in the Triangular Network





$$e_i = e_j = \sqrt{3}R \quad (1.6)$$

distance between arbitrary hexagons

$$d(t_1, t_2) = \sqrt{(i_2 - i_1)^2 + (i_2 - i_1)(j_2 - j_1) + (j_2 - j_1)^2}\; e_i \quad (1.7)$$

cochannel distance

$$d(0, t_2) = \sqrt{i_2^2 + i_2 j_2 + j_2^2}\; e_i \quad (1.8)$$

cluster size

$$k = i_2^2 + i_2 j_2 + j_2^2 \quad , i,j \text{ integer} \quad (1.9)$$

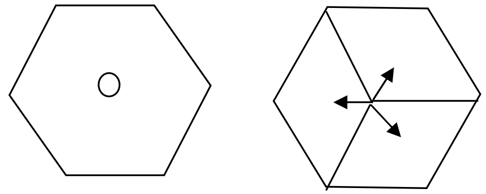
possible cluster sizes k = 1,3,4,7,9,12,13,16,19,21 etc.

Sectorisation

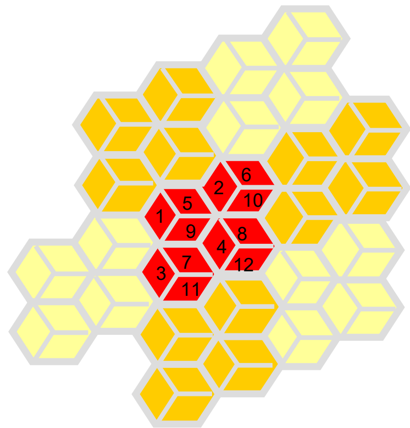
- Common measure to reduce the interferences in the network
- At every position, coverage of n = 2, n = 3 or n = 6 sectors with an angle of 180°, 120° or 60° by several antennas with distinctive directivity
- Re-use pattern is called (k, n) cluster
- For SIR applies: $SIR \approx \frac{n}{6}(3k)^{\frac{\gamma}{2}}$ (1.10)

  for $i \neq j$ in eq. (1-9)

Despite that, cluster with $i = j$ possible for most of the antennas, however, in this case (1.10) only applies with restrictions



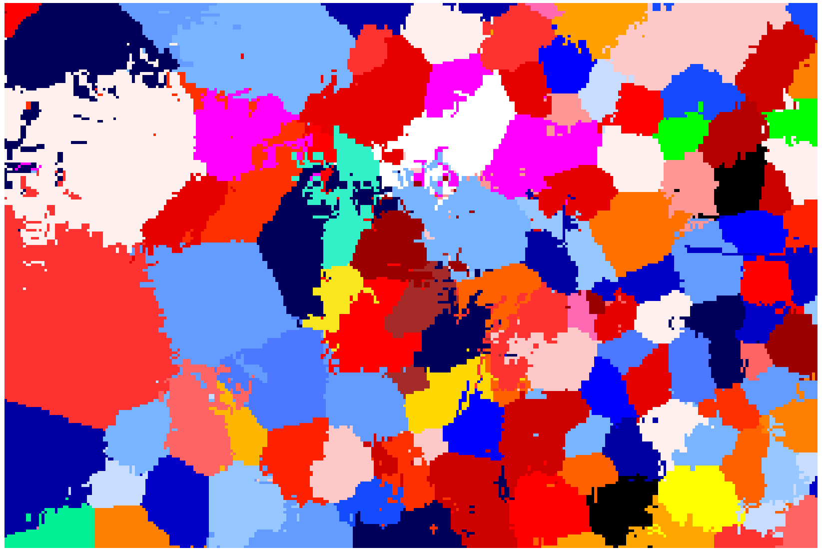
„Omni“ position 3-sector position



(4,3)-frequency re-use pattern

Cell Representation for a Real Network

- It is very idealised to describe a mobile radio network by hexagonal cells.
- In reality, cells have very irregular shapes and different sizes due to varying propagation conditions.
- Cell boundaries are not sharp; allocation of a mobile station to a cell can only be indicated with a certain probability.



Cell representation for a real network; definition of a cell by the strongest received signal at a location

Cell Types and Cell Radii

Cell type	Typical cell radius	Typical position of the base station antenna
macro cell	1 … 30 km	„outdoor“; high site; in urban areas, antenna mounting clearly above the mean height of all surrounding buildings
small macro cell	500 m … 1 km	„outdoor“; in urban areas, antenna position just above the building height; at least some of the surrounding buildings have approximately the same height
micro cell	< 1 km	„outdoor“; antenna height clearly below the height of the surrounding buildings
pico cell	< 500 m	„indoor“; normally antenna mounting inside buildings
femto cell	< 100m	Connection of the cell via DSL; installation by the user (comparable to a WLAN router)

2.8 Tele-Traffic Theory

- Traffic capacity and traffic dimensioning
  - Number of frequencies per cell:

$$n_F = \frac{B_t}{B_c k} \qquad (1.11)$$

  k: cluster size

  B_t: total bandwidth of the system

  B_c: bandwidth of the channel†

  - Number of channels* per cell (FDMA/TDMA system):

$$n_T = m n_F \qquad (1.12)$$

  m: number of time slots per frequency

  - The number of channels* represents the respective maximum traffic load.

Please note: The term channel is not clearly defined in literature and is used as a synonym for a frequency† (mostly in the context of the frequency assignment) as well as for a time slot*!
In this lecture, the term channel normally refers to a time slot.

Offered Traffic

- The load of a channel which corresponds to an observation period *t* is called traffic intensity (offered traffic) *A*.

$$A = \frac{Y}{t} \qquad (1.13)$$

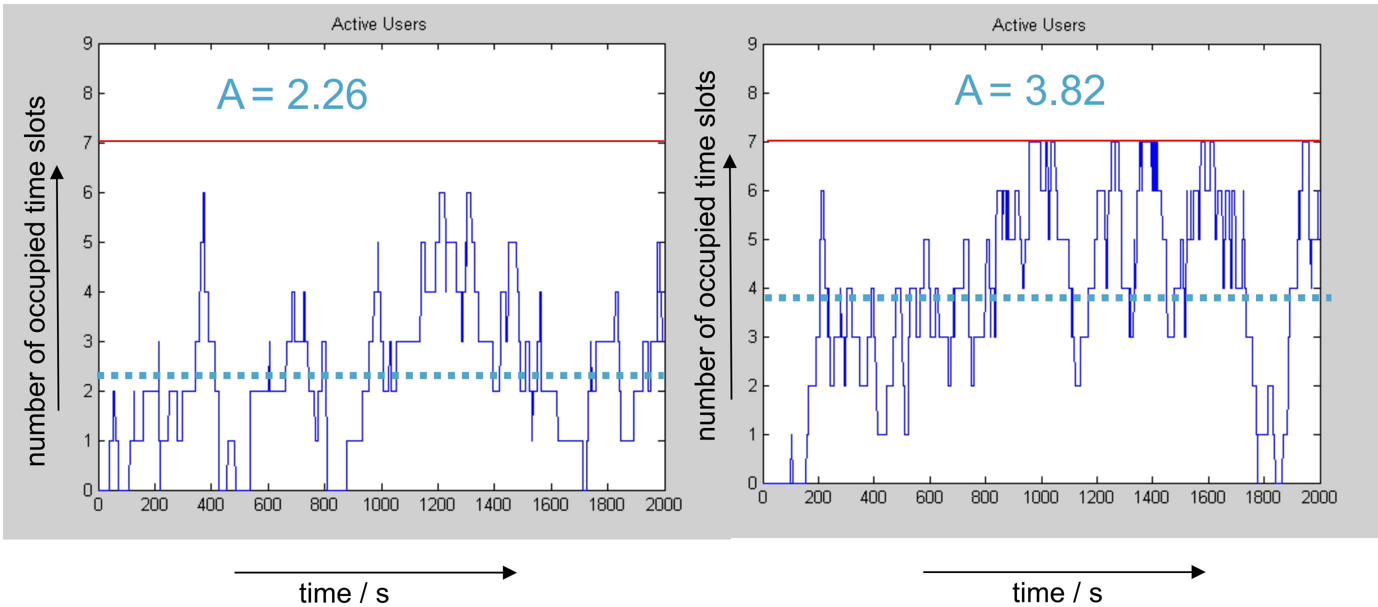
Y: mean number of busy channels
t: observation period in hours

- The unit of the traffic intensity is Erlang (Erl), called after the Danish mathematician A. K. Erlang.

- Example:
  If a channel is observed for one hour and thereby occupied for 30 minutes all in all, it has a traffic intensity of 0.5 Erlang.
  The traffic intensity is the basis for the dimensioning of telecommunication networks.

Example of a Time Slot Occupancy

- In tele-traffic theory, a cell is a lost call system with n service units (channels)
- Negative exponentially distributed intervals between incoming calls (Poisson process) regarding incoming calls and service
- Example: simulation of the time slot occupancy in GSM (7 traffic channels)



Erlang-B Formula

- Description of the dependency between offer A and blocking probability B by the blocking equation according to Erlang:

$$B = \frac{\frac{A^n}{n!}}{\sum_{i=0}^{n} \frac{A^i}{i!}} \quad (1.14)$$

n : number of available channels

- maximum offer A_{BHCA} in the busy hour at a given blocking probability *B:*

$$A_{\mathrm{BHCA}} = \lambda_{\mathrm{BHCA}} T_{\mathrm{m}} \quad (1.15)$$

λ_{BHCA}: mean number of „Busy Hour Call Attempts“ (BHCA)

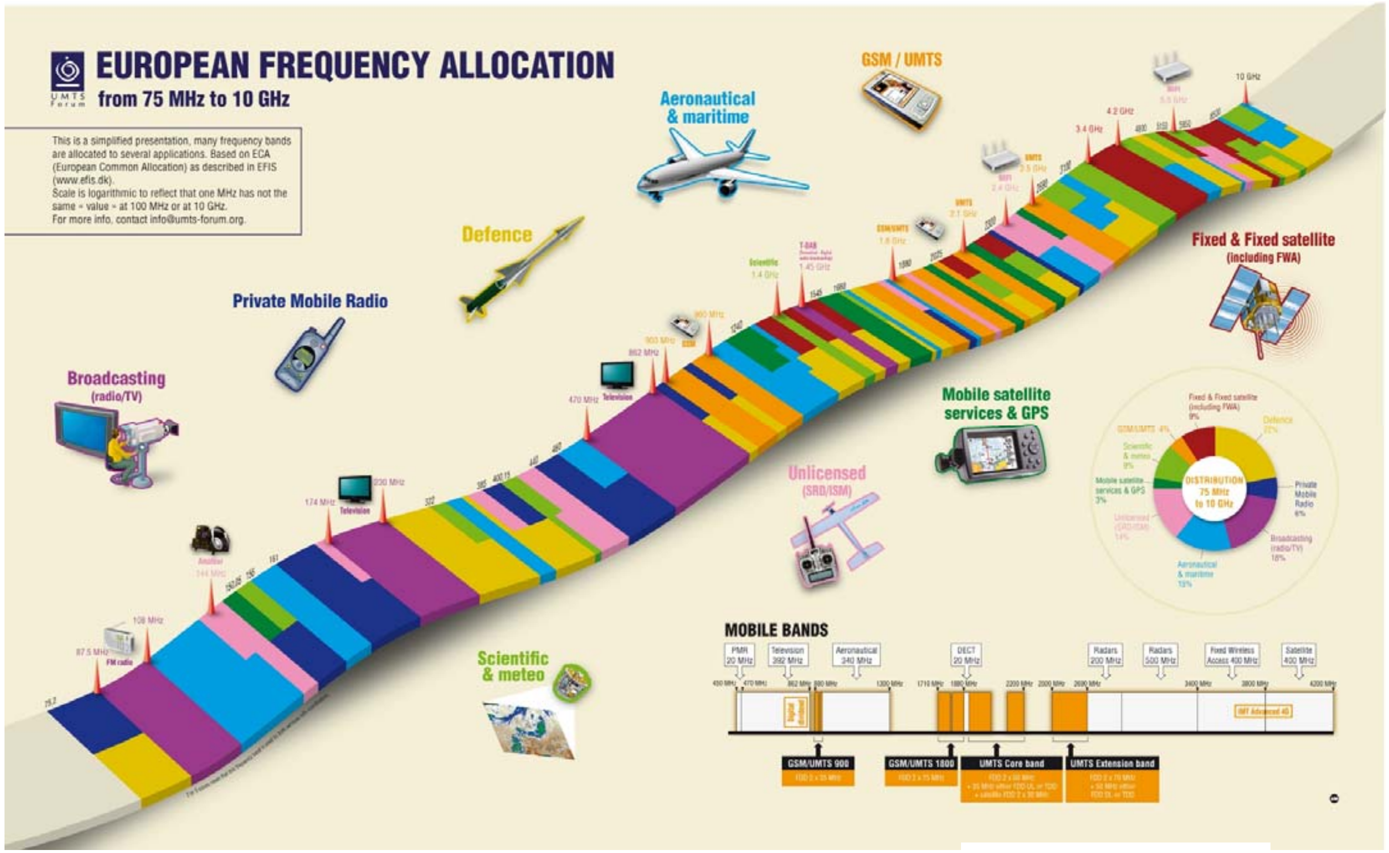
T_{m}: mean call duration (in hours)

Erlang-B Table

- The values for equation 1.15 are available in the form of a table.
- Extract from the Erlang-B table:

n	A_{max} /Erl for B=1%	A_{max} /Erl for B=2%	A_{max} /Erl for B=5%	A_{max} /Erl for B=10%
2	0.15	0.22	0.38	0.6
4	0.87	1.09	1.52	2.05
6	1.91	2.28	2.96	3.76
8	3.13	3.63	4.54	5.60
10	4.46	5.08	6.22	7.51
14	7.35	8.20	9.73	11.5
22	13.7	14.9	17.1	19.7
30	20.3	21.9	24.8	28.1
36	25.5	27.3	30.7	34.5

2.9 Frequency Ranges and Regulation



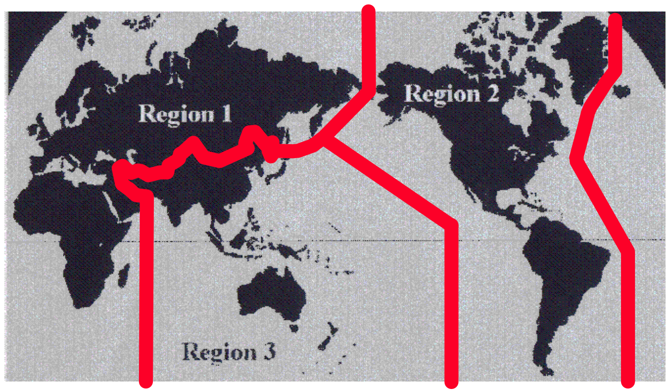
Source: UMTS Forum

Worldwide Coordination of the Usage of Frequencies

- ITU (International Telecommunications Union) controls the usage of the spectrum worldwide.
- The worldwide valid usage of frequencies is documented in the „Radio Regulations“.
- Approx. every three years, the World Radio Conference (WRC) takes place, in the course of which the usage of frequencies is adapted to the latest technical developments.

Worldwide Harmonisation

- Frequency ranges exist which are harmonised worldwide and only regional, respectively
- 3 regions have been defined worldwide
- Example: excerpt from Radio Regulations for the IMT2000/UMTS coreband



<table>
<tr><th>region 1</th><th>region 2</th><th>region 3</th></tr>
<tr><td>1930-1970
FIXED
MOBILE

S5.388</td><td>1930-1970
FIXED
MOBILE
Mobile-satellite
(Earth-to-space)
S5.388</td><td>1930-1970
FIXED
MOBILE

S5.388</td></tr>
<tr><td colspan="3">1970-1980 FIXED
MOBILE S5.388</td></tr>
<tr><td colspan="3">1980-2010 FIXED
MOBILE
MOBILE-SATELLITE (Earth-to-space)
S5.388 S5.389A S5.389B S5.389F</td></tr>
</table>

S5.388 The bands 1885-2025 MHz and 2110-2200 MHz are intended for use, on a worldwide basis, by administrations wishing to implement International Mobile Telecommunications-2000 (IMT2000). Such use does not preclude the use of these bands by other services to which they are allocated. The bands should be made available for IMT2000 in accordance with Resolution 212 (Rev. WRC-97).

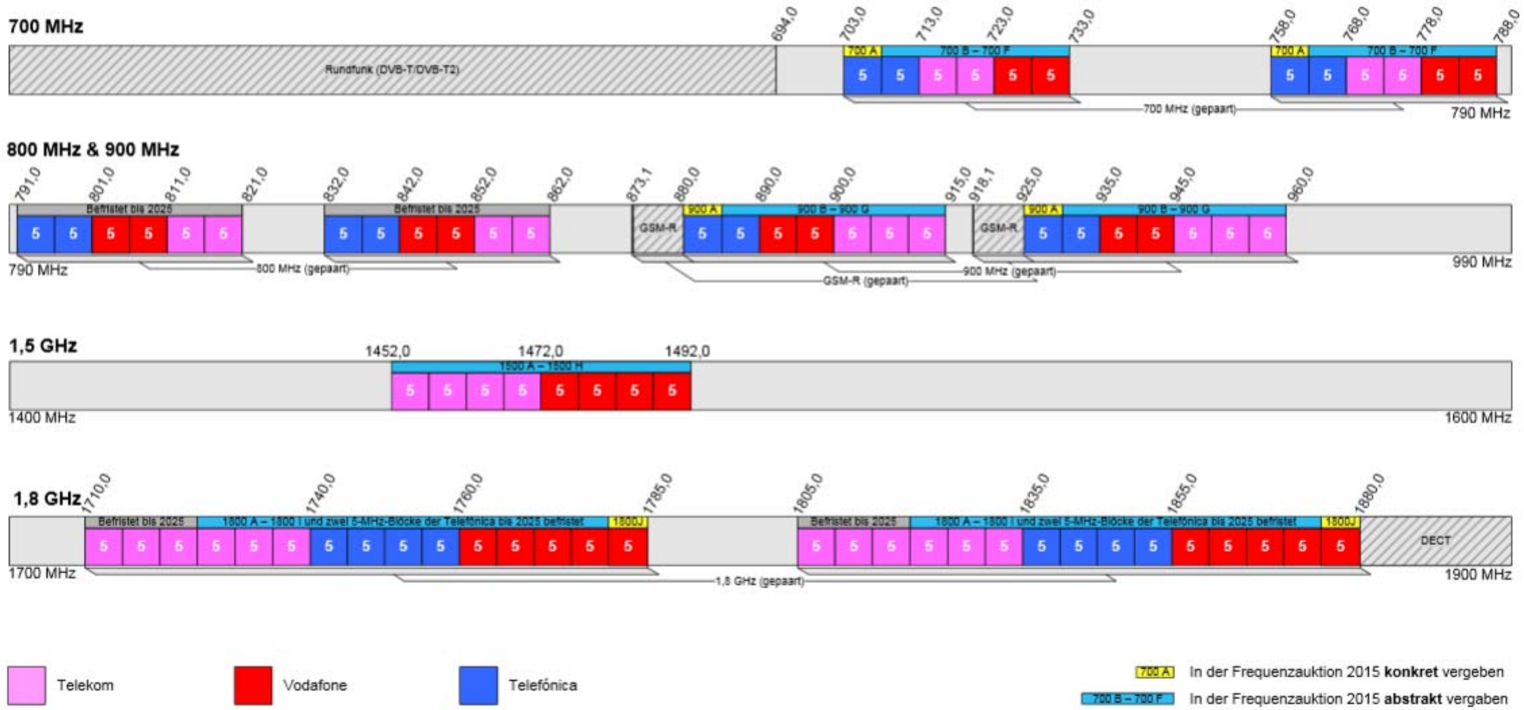
Quelle: ITU-R Radio Regulations

Result from the Frequency Auction in May/June 2015

Unternehmen	Frequenzmenge		Zuschlagspreis
Telefónica Deutschland GmbH & Co. OHG	700 MHz: 900 MHz: 1800 MHz:	2 x 10 MHz 2 x 10 MHz 2 x 10 MHz	1.198.238.000 €
Telekom Deutschland GmbH	700 MHz: 900 MHz: 1800 MHz: 1500 MHz:	2 x 10 MHz 2 x 15 MHz 2 x 15 MHz 20 MHz	1.792.156.000 €
Vodafone GmbH	700 MHz: 900 MHz: 1800 MHz: 1500 MHz:	2 x 10 MHz 2 x 10 MHz 2 x 25 MHz 20 MHz	2.090.842.000 €
Gesamt	**270 MHz**		**5.081.236.000 €**

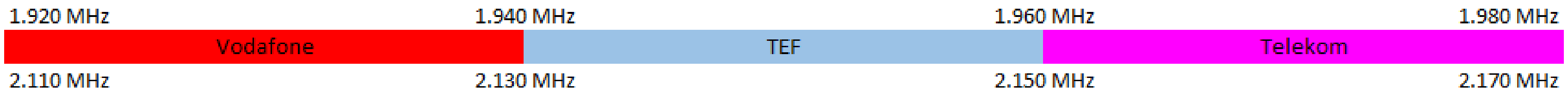
Source: www.bundesnetzagentur.de

Frequency Allocation in Germany (as of 2015)

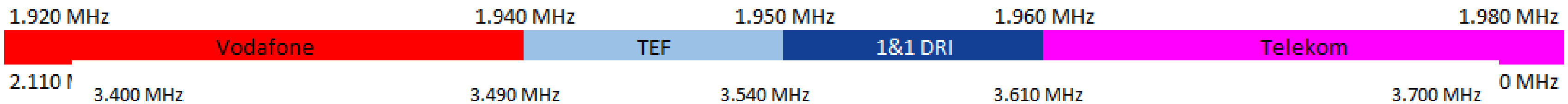


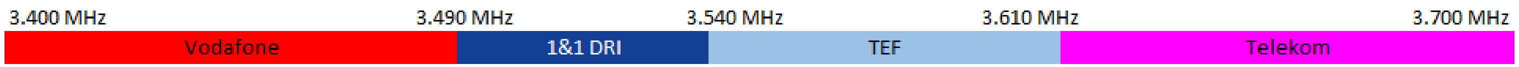
Source: www.bundesnetzagentur.de

Result from the Auction 2019 in Germany



Bandlage 01.01.2021 bis 31.12.2025

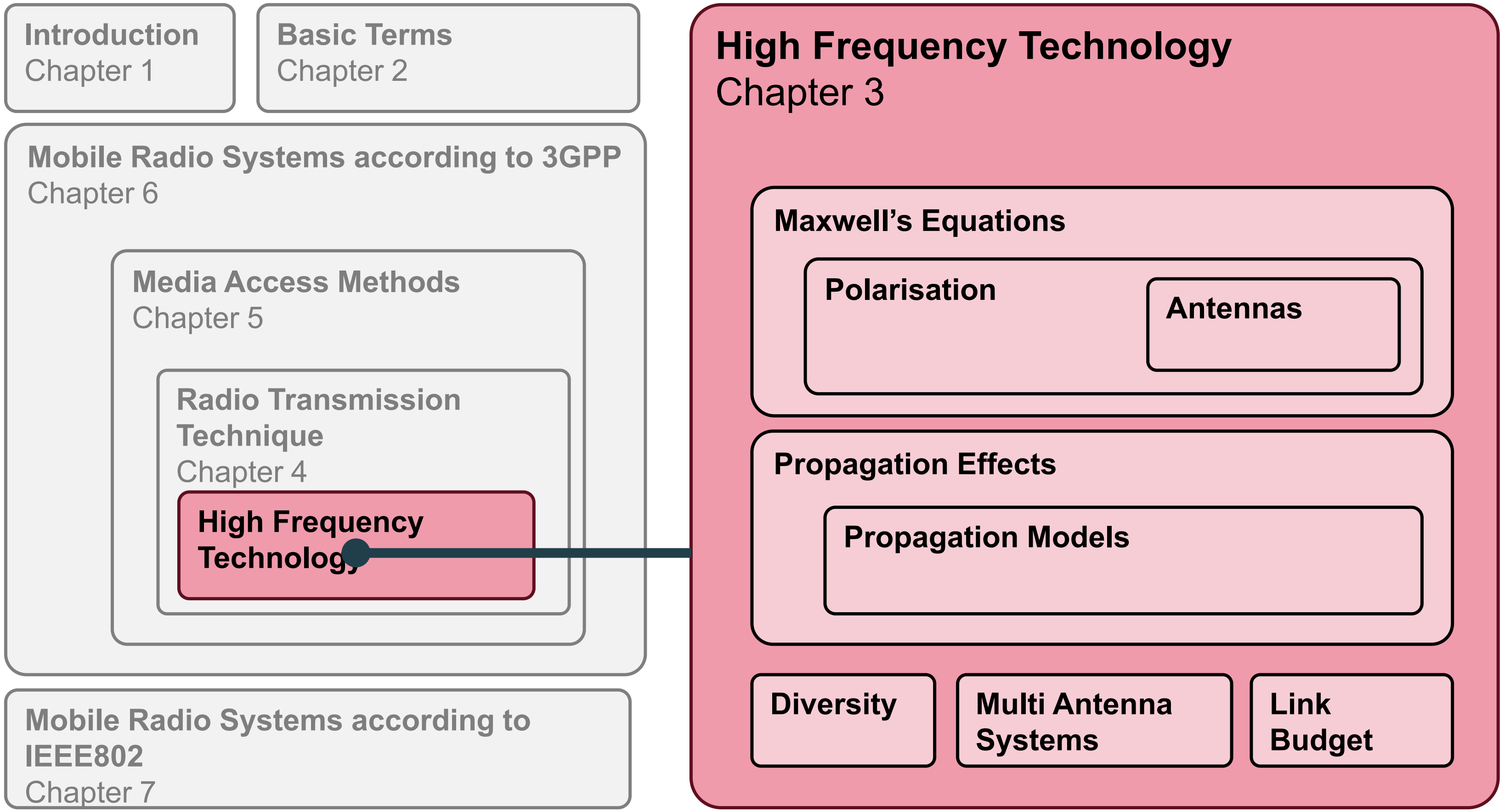




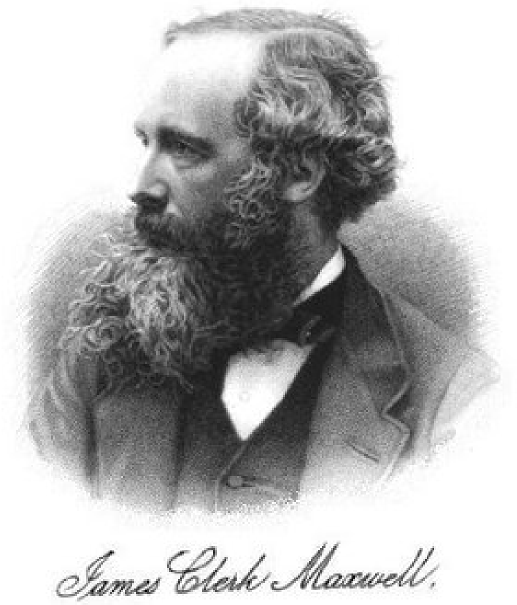
Bandlage im Bereich 3,6 GHz

Source: www.bundesnetzagentur.de

Chapter 3 – High Frequency Technology



3 High Frequency Technology
3.1 Maxwell‘s Equation




Heinrich Hertz

- Complete description of the electromagnetic fields and their time dependency by Maxwell‘s Equations

The Field Equations in Integral Form

$$\oint_C \vec{H}\mathrm{d}\vec{r} = \iint_A \vec{J}\mathrm{d}\vec{A}$$

(law of magnetic flux)
(3.1)

A magnetic field is induced by a time-variant electrical field or a current.

$$\oint_C \vec{E}\mathrm{d}\vec{r} = -\frac{\partial}{\partial t}\iint_A \vec{B}\mathrm{d}\vec{A}$$

(law of induction)
(3.2)

An electrical field is induced by a time-variant magnetic field.

$$\oiint_A \vec{B}\mathrm{d}\vec{A} = 0$$

(source-freedom)
(3.3)

Magnetic flux lines are closed.

$$\oiint_A \vec{D}\mathrm{d}\vec{A} = \iiint_V p\mathrm{d}V$$

(continuity equations)
(3.4)

Electrical flux lines either begin and end at charges or they are closed.

Material Equations

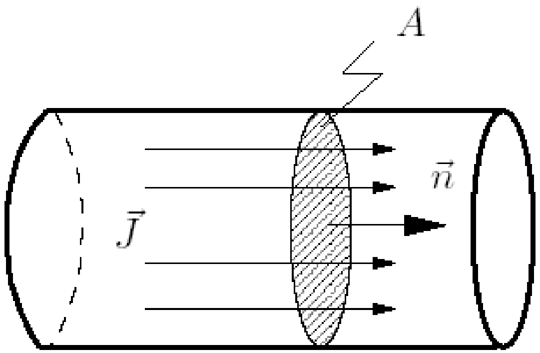
$$\vec{D} = \epsilon\vec{E} \qquad \vec{H} = \frac{1}{\mu}\vec{B}$$

(Material equations)
3.5

Essential facts:

- For processes in the current-free and charge-free space, the following restrictions apply: $\vec{J} = 0$ und $\rho = 0$
- Electrical fields lines have a source and a sink.
- Magnetic fields lines are divergence free.
- Alternating electrical and magnetic fields induce each other (electro-magnetic wave).

Field Equation of the Stationary Electrical Field



$$= \vec{J}\vec{n} \cdot A \qquad (2.6)$$

$$= \kappa\vec{E} \qquad (2.7)$$

κ: electrical conductivity

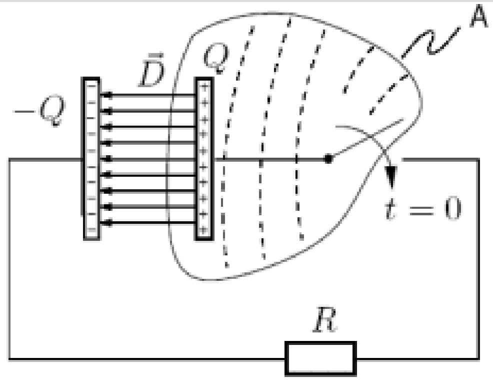
general form:

$$I = \iint_A \vec{J}\mathrm{d}\vec{A} \qquad (2.8)$$

and for a closed contour:

$$\oiint_A \vec{J}\mathrm{d}\vec{A} = 0 \qquad (2.9)$$

Displacement Current Density



- Plate capacitor with electrical charge Q

$$t < 0\colon\ Q = \oint\!\!\!\oint_A \vec{D}\mathrm{d}\vec{A} \qquad (2.10)$$

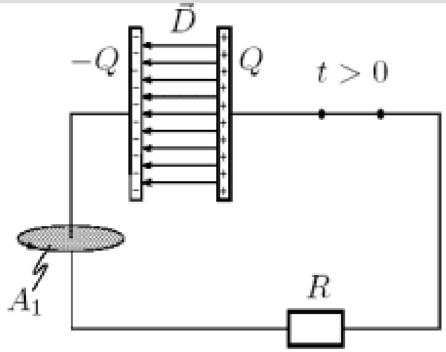
- At the time $t = 0$ the switch is closed.
- $t > 0$: The capacitor is discharged. Current flows through the hull

$$-\frac{\partial Q}{\partial t} = \oint\!\!\!\oint_A \vec{J}\mathrm{d}\vec{A} = -\frac{\partial}{\partial t}\oint\!\!\!\oint_A \vec{D}\mathrm{d}\vec{A} \rightarrow \dim\left[\frac{\partial}{\partial t}\vec{D}\right] = \dim[\vec{J}] \qquad (2.11)$$

$\frac{\partial}{\partial t}\vec{D}$ is called displacement current density.

- Overall current density $(\frac{\partial}{\partial t}\vec{D} + \vec{J})$ is source-free: $\oint\!\!\!\oint \left(\frac{\partial}{\partial t}\vec{D} + \vec{J}\right) d\vec{A} = 0$ (2.12)

Electromagnetic Fields (1)



- At the time $t = 0$ the switch is closed.
- The capacitor is discharged.

$$\iint_{A_1} \vec{J} \mathrm{d}\vec{A} \neq 0 \quad \text{, but} \quad \iint_{A_2} \vec{J} \mathrm{d}\vec{A} = 0 \qquad (2.13)$$

- According to the law of magnetic flux, the current density is connected with a magnetic field. This is clearly defined only if

$$\oint_C \vec{H} \mathrm{d}\vec{r} = \iint_A \left(\frac{\partial}{\partial t} \vec{D} + \vec{J} \right) \mathrm{d}\vec{A} \qquad \text{(1}^{\text{st}} \text{ Maxwell's equation)} \qquad (2.14)$$

- In terms of generation of magnetic fields, conduction current density and displacement current density are equivalent. A time-variant displacement field generates a magnetic field without current flow, i.e. also in a vacuum. In terms of its magnetic effect, a time-variant conduction current interrupted by an insulator can be theoretically continued through a displacement current of the same amperage.

Electromagnetic Fields (2)

- Assumption:
  - The law of induction also applies if the path of integration C is not along with a conductor.
  - Thus, for any closed circulation *C* the following applies:

$$\oint_C \vec{E}\mathrm{d}\vec{r} = -\frac{\partial}{\partial t}\iint_A \vec{B}\mathrm{d}\vec{A} \qquad \text{(2nd Maxwell‘s equation)} \qquad (2.15)$$

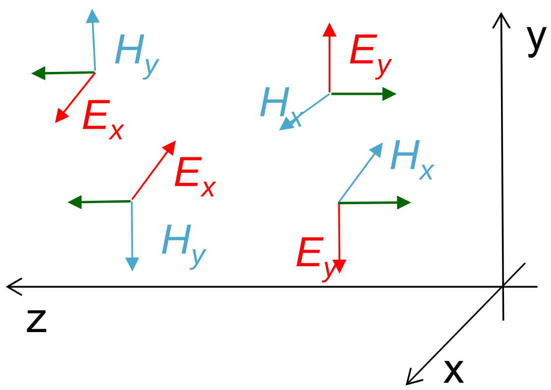
- From this follows:
  - The flux lines of a time-variant magnetic field are circularly surrounded by electrical flux lines.
  - The flux lines of a time-variant electrical field are surrounded by magnetic flux lines.

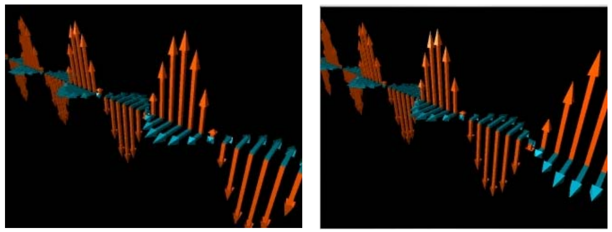
3.2 Several Electrodynamic Principles

- For Maxwell's equations, several solutions also exist following the a.m. restrictions. The simplest solution is the plane wave.
- We refer to a wave as a plane wave, if the instantaneous values of the **field values $\underline{\vec{E}}$ und $\underline{\vec{H}}$** do not depend on the coordinates vertically located to the direction of propagation.
- Since $\vec{E}$ and $\vec{H}$ are orthogonal in the free space and are in phase, they are proportional to each other.

$$\underline{E}_y = Z_{F0}\underline{H}_x \qquad (2.16) \qquad\qquad \underline{E}_x = -Z_{F0}\underline{H}_y \qquad (2.17)$$

Z_{F0}: wave impedance of the free space





$H_x(z,t_1), E_y(z,t_1)$ $H_x(z,t_2), E_y(z,t_2)$

Snap-shots of E_y and H_x

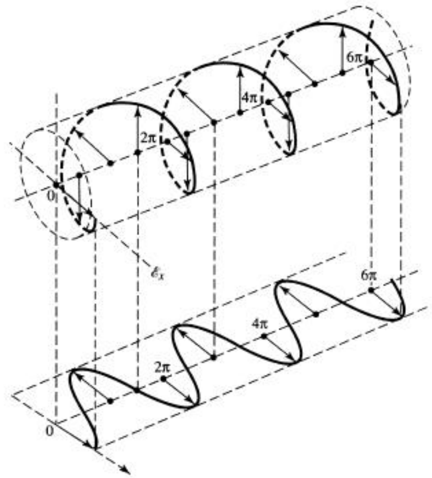
Polarisation

- Polarisation is the characteristic of a single-frequent electromagnetic wave that describes the amount and the direction of oscillation of the field vector as a function of place and time.
- In the far field of an antenna, for a plane wave the electric field vector is located in a plane vertical to the direction of propagation of the wave.
- Components of the electric field in x and y direction:

$$E_x = E_{x0}\cos(2\pi f t - \frac{2\pi}{\lambda}z + \phi_x) \qquad (2.18)$$

$$E_y = E_{y0}\cos(2\pi f t - \frac{2\pi}{\lambda}z + \phi_y) \qquad (2.19)$$

f: frequency λ: wavelength



General case of the elliptical polarisation

- The special case for linear polarisation is obtained for $\phi = \phi_x = \phi_y$.
- Surface of the earth as the reference for the direction of polarisation of a linearly polarised wave: vertical polarisation for E_x=0 and horizontal polarisation for E_y=0

Circular Polarisation

- For the unique characterisation of an elliptically and circularly polarised wave, the direction of rotation of the spiral has to be considered.
  - For this, a stationary plane vertical to the direction of propagation is considered and defined:
    - For an observer looking into the direction of propagation, the vector of the E-field in this plane for right-handed polarisation rotates clockwise

$$\Phi_x - \Phi_x = -\frac{\pi}{2} \qquad (2.20)$$

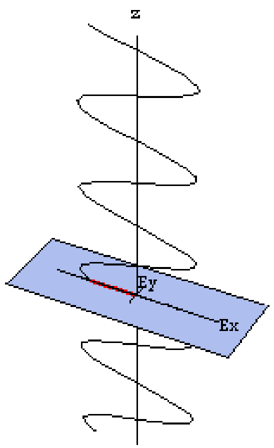
    - The common term in case of counter-clockwise rotation is left-hand polarisation

$$\Phi_x - \Phi_x = +\frac{\pi}{2} \qquad (2.21)$$

Examples of Polarisation

linear polarisation

$E_{y0} = 0.$



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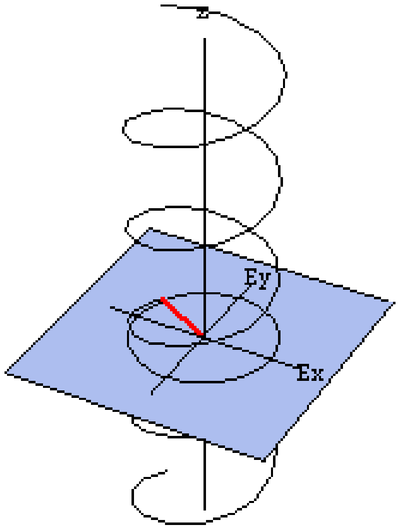
left-handed circular polarisation

$E_{x0} = E_{y0}$

$\phi_x - \phi_y = \frac{\pi}{2}$

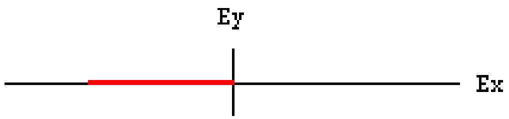


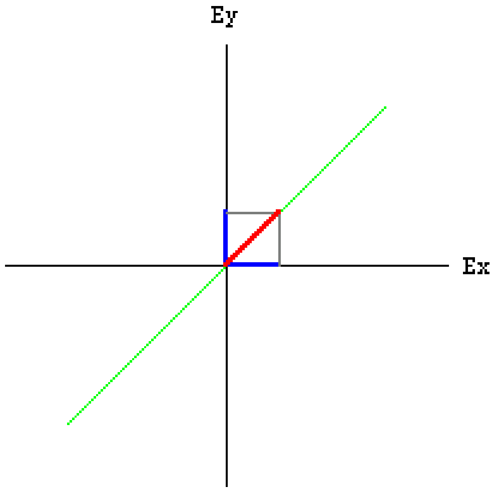
Created by Hsiu C. Han, 1996.

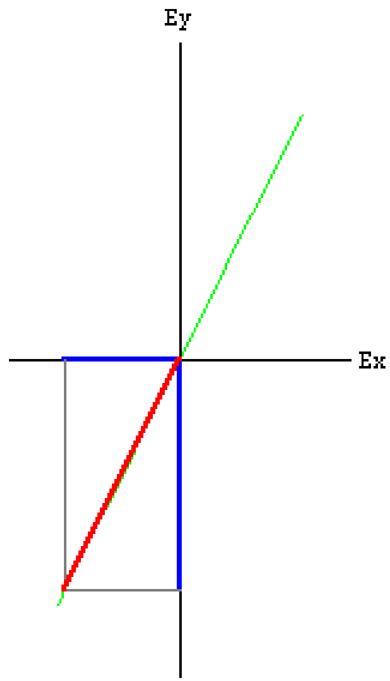
Source: http://vulcan.ece.iastate.edu/~hsiu/em_movies.html

Examples of Linear Polarisation

- Projection onto the x-y plane
  - Linear polarisation







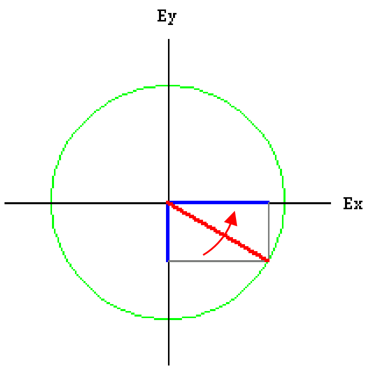
$E_{y0} = 0$

$E_{x0} = E_{y0}$
$\phi_x = \phi_y$

$E_{y0} = 2E_{x0}$
$\phi_x = \phi_y$

Examples of Circular Polarisation

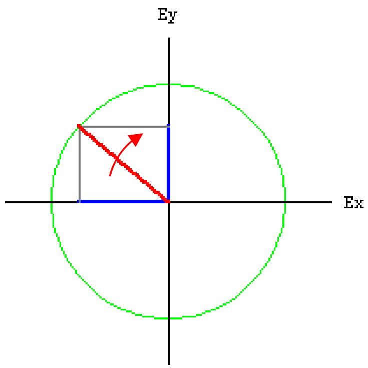
- Circular Polarisation



$$E_{x0} = E_{y0}$$

$$\phi_x - \phi_y = -\frac{\pi}{2}$$

right-handed circular polarisation



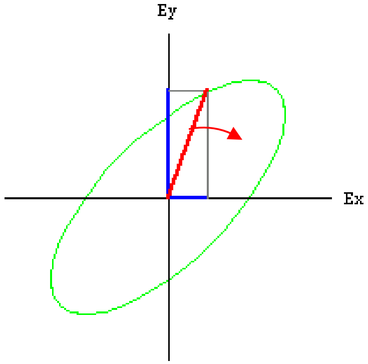
$$E_{x0} = E_{y0}$$

$$\phi_x - \phi_y = \frac{\pi}{2}$$

left-handed circular polarisation

Examples of Elliptic Polarisation

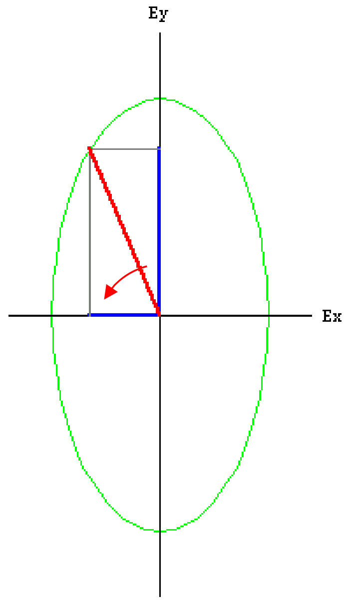
- General elliptic polarisation



$E_{x0} = E_{y0}$

$\phi_x - \phi_y = \frac{\pi}{4}$

left-handed elliptic polarisation



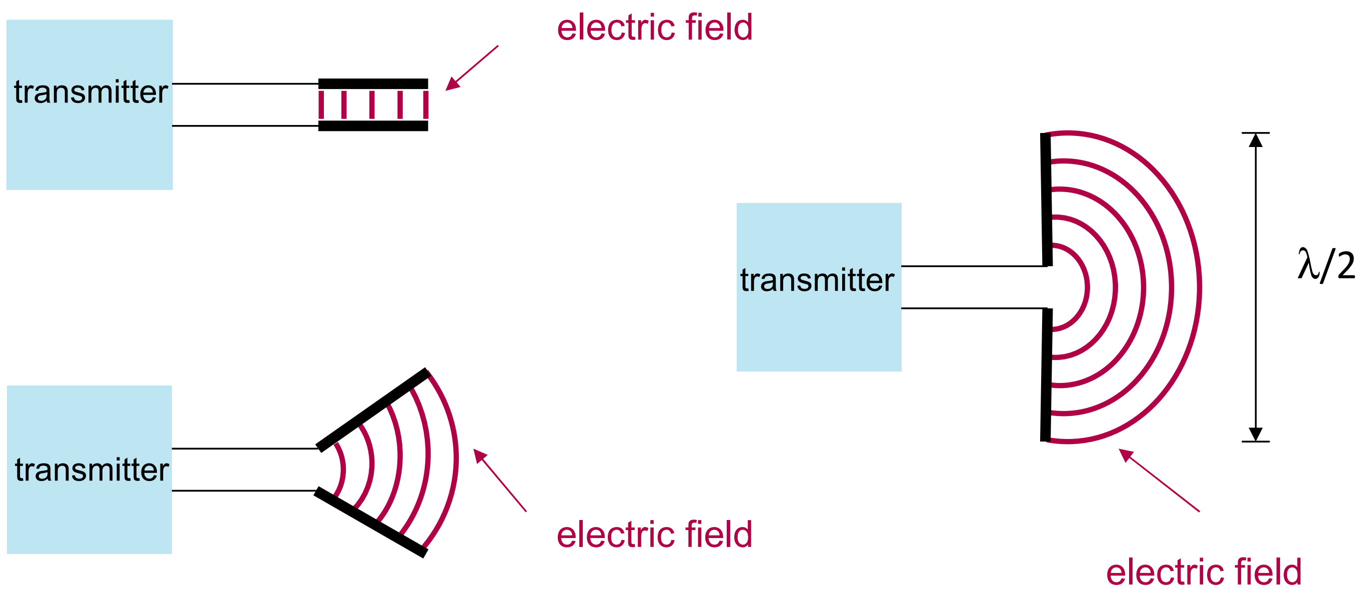
$E_{y0} = 2E_{x0}$

$\phi_x - \phi_y = -\frac{\pi}{2}$

right-handed elliptic polarisation

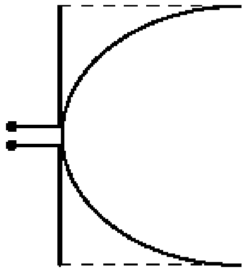
3.3 Generation of Electromagnetic Waves

- Theoretical experiment:
  - Forming an antenna using a plate capacitor

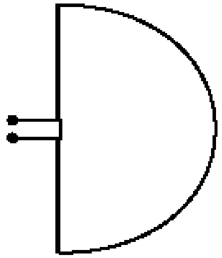


3.3 Generation of Electromagnetic Waves

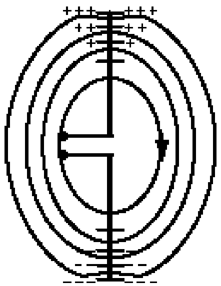
Field Distribution at a λ/2 Dipole



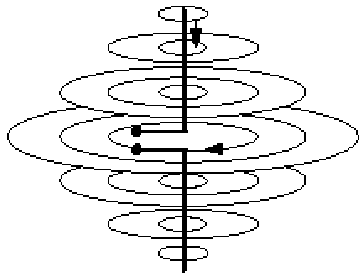
Spannungsverteilung (U)



Stromverteilung (I)



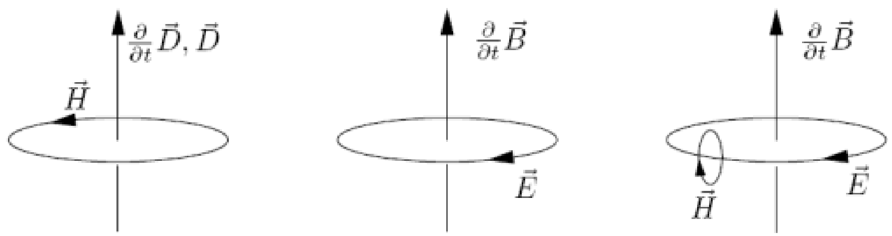
Elektrisches Feld (E)



Magnetisches Feld (H)

Radiation of Electromagnetic Waves from the Antenna

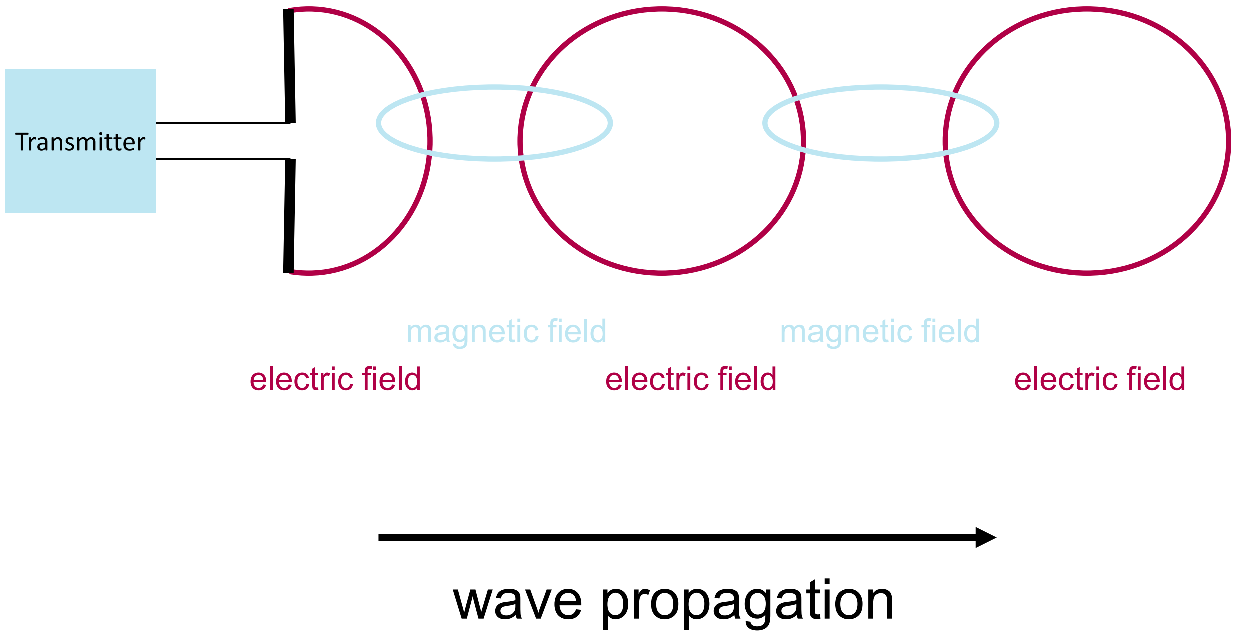
- Why do electromagnetic waves radiate from the antenna?
  - A time-variant electric field generates a magnetic rotational field.
  - A time-variant magnetic field generates an electric rotational field. In case that $\frac{\partial}{\partial t}\vec{B}$ is time-variant, the induced voltage generates another $\vec{H}$ field.
  - Electric and magnetic fields induce each other.



  - Electromagnetic waves are transverse waves propagating with the (phase) velocity

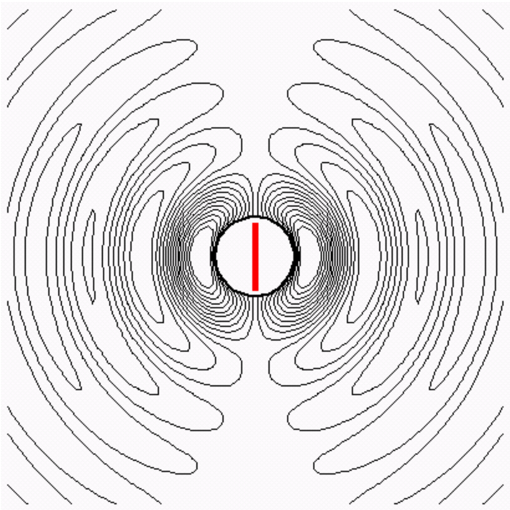
$$v = \frac{1}{\sqrt{\epsilon\mu}}\,.$$

Interaction between E- and H-Field

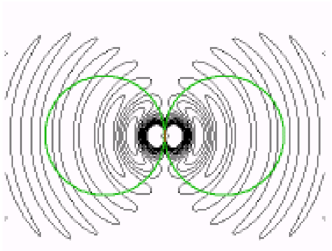


3.4 Antennas

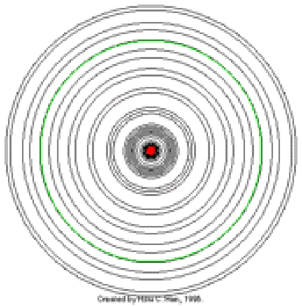
- Hertzian dipole
  - infinitesimal radiation source, e. g.
    - a short piece of wire of the length Δz, which is flown through by a current I_0
    - two spheres with the charge $+Q_0$ at intervals of Δz



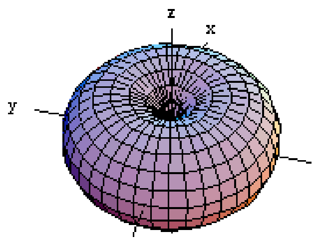
flux lines of the hertzian dipole



radiation pattern E plane



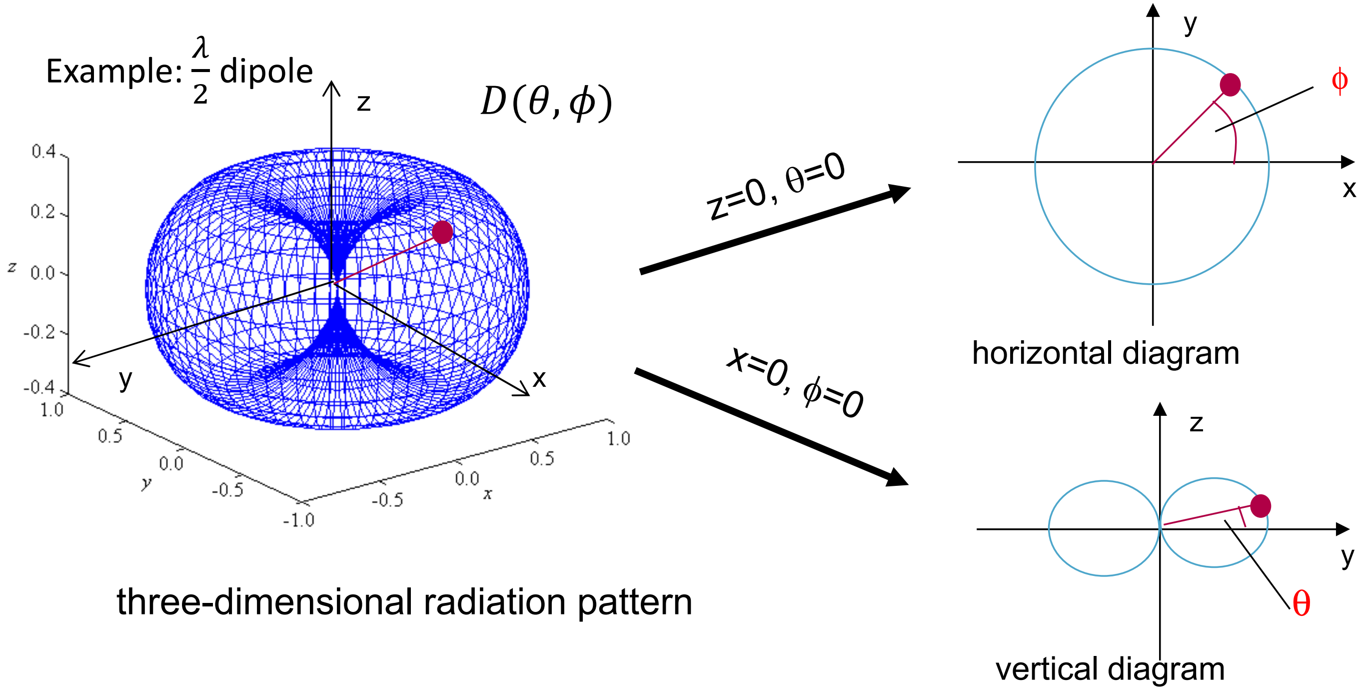
radiation pattern H plane



3D radiation pattern

Radiation Pattern of the λ/2 Dipole

- Directivity of antennas is described by a radiation pattern
  - radiation pattern $D(\theta,\phi)$: dimensionless quantity, absolute value between 0 and 1 (in linear presentation; in practice, often logarithmic values D_{dB})

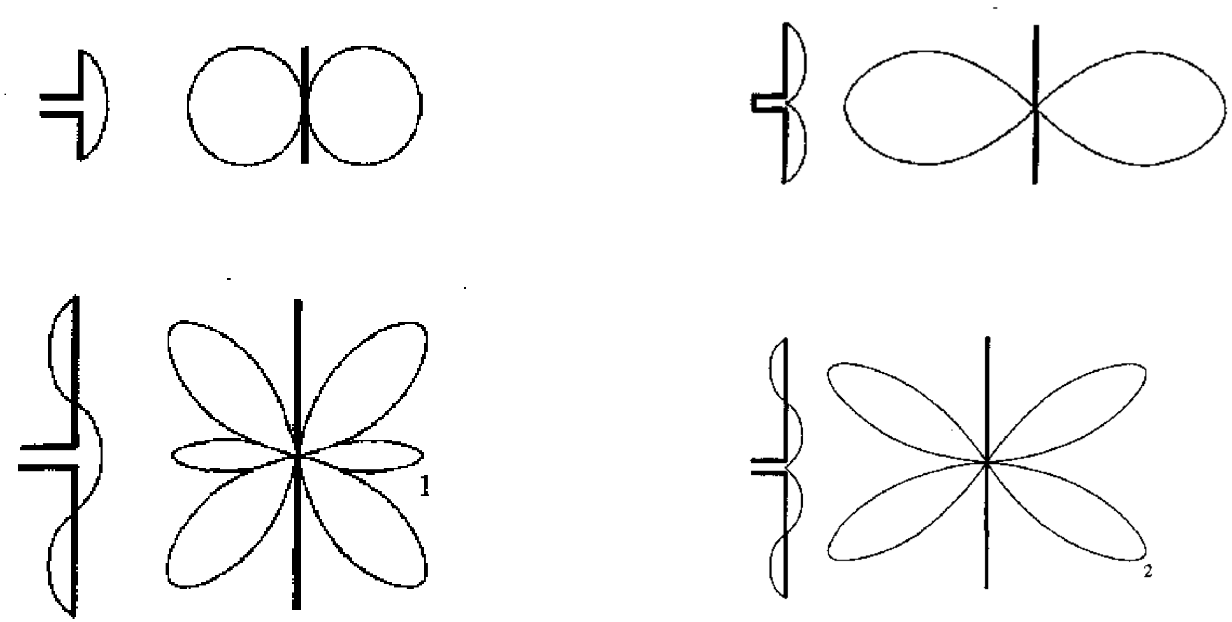


Important Antenna Characteristics

- Half power beam width (3-dB width, HPBW):
  - characterises the angle around the radiation peak at the boundaries of which the radiation density is half as large as in the maximum (i.e. 3 dB less)
- Gain: $G = \dfrac{4\pi}{\int_0^{2\pi} \int_0^{\pi} D^2(\theta, \phi) \sin\phi \, \mathrm{d}\phi \, \mathrm{d}\theta}$ (2.22)
  - The gain is completely characterised by the radiation pattern. It is a measure for the characteristic of an antenna to preferably radiate energy to only one direction and to receive energy from only one direction, respectively.
  - The larger the dimension of an antenna (aperture) relating to the wavelength, the larger the gain and with it the directivity of this antenna.

3.4 Antennas

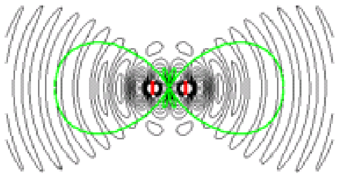
Current Distribution and Vertical Radiation Pattern of Simple Antennas

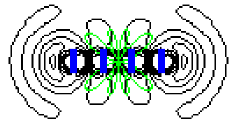


Groups of Antennas

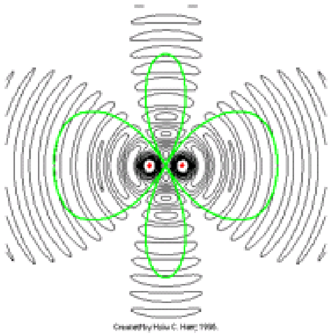
- Superposition of the fields of the single antennas

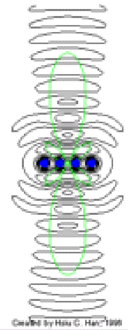
Radiation pattern E plane



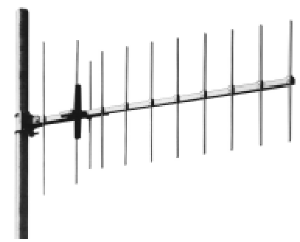


Radiation pattern H plane

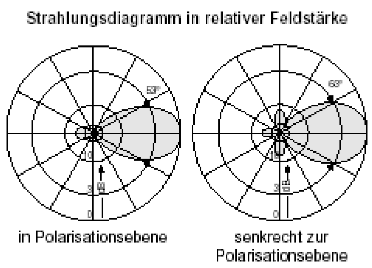




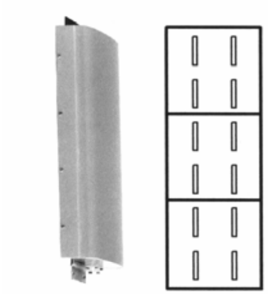
Antenna Designs (1)



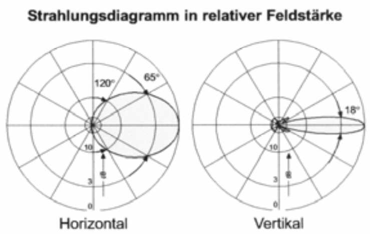
Yagi-Antenne K 52 07 21
146 – 174 MHz



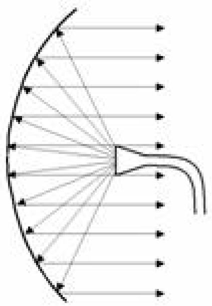
Yagi antenna



Zwölfer-Feld 730 684
890 – 960 MHz



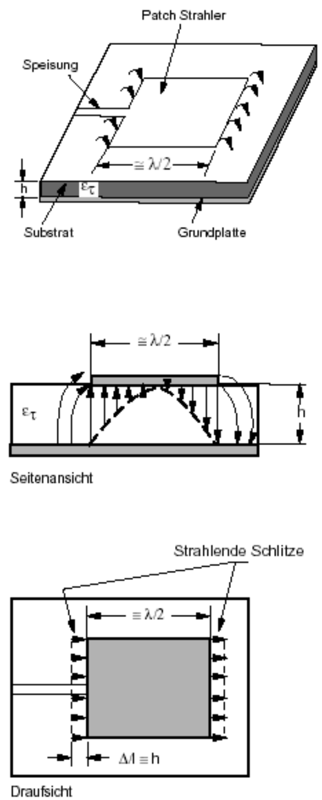
array of $\lambda/2$ dipoles



dish antenna

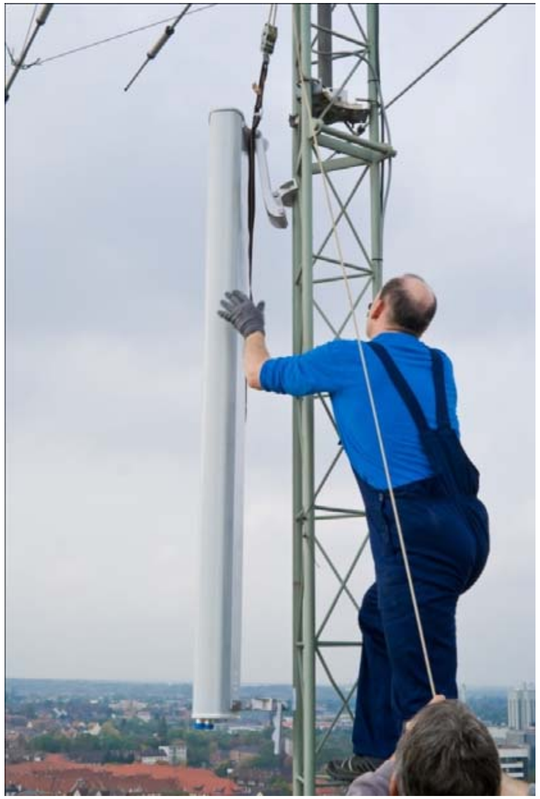
Antenna Designs (2)

patch antenna



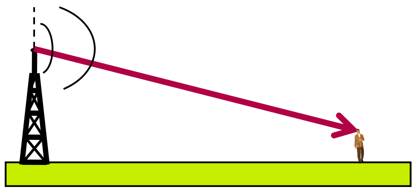
This is how an Antenna Installation for LTE800 looks like …

LTE800 test site at TU Braunschweig

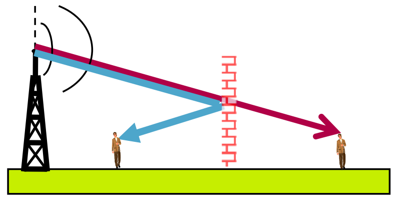


3.5 Propagation Mechanisms

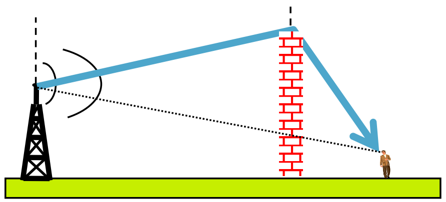
- Radio propagation is influenced by many factors and phenomena.
- In the frequency range interesting for mobile communications, the propagation characteristics can be considered as „quasi-optical“ in a first approximation.



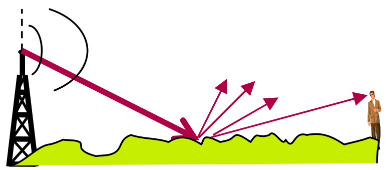
free-space propagation



reflection and transmission

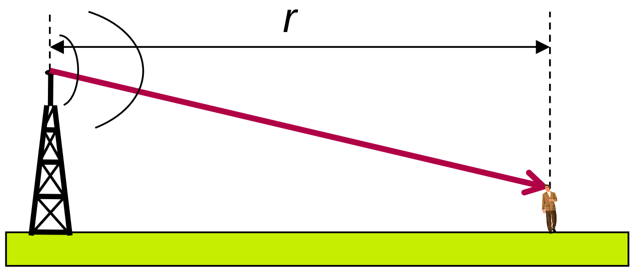


diffraction



scattering

Free-Space Propagation



$$P_{\mathrm{R}} = P_{\mathrm{T}} \frac{1}{r^2} \left(\frac{\lambda}{4\pi}\right)^2 G_{\mathrm{T}}(\theta_{\mathrm{T}}, \phi_{\mathrm{T}}) G_{\mathrm{R}}(\theta_{\mathrm{R}}, \phi_{\mathrm{R}}) \qquad (2.23)$$

green underline: influence of the free-space propagation
red underline: influence of the antenna

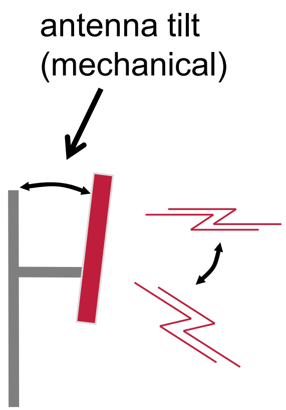
P_{T}: transmitting power of the transmitter (*Tx*)
P_{R}: received power at the receiver (*Rx*)
$G_{\mathrm{T}}(\theta_{\mathrm{T}}, \phi_{\mathrm{T}})$: antenna diagram of the transmitter
$G_{\mathrm{R}}(\theta_{\mathrm{R}}, \phi_{\mathrm{R}})$: antenna diagram of the receiver

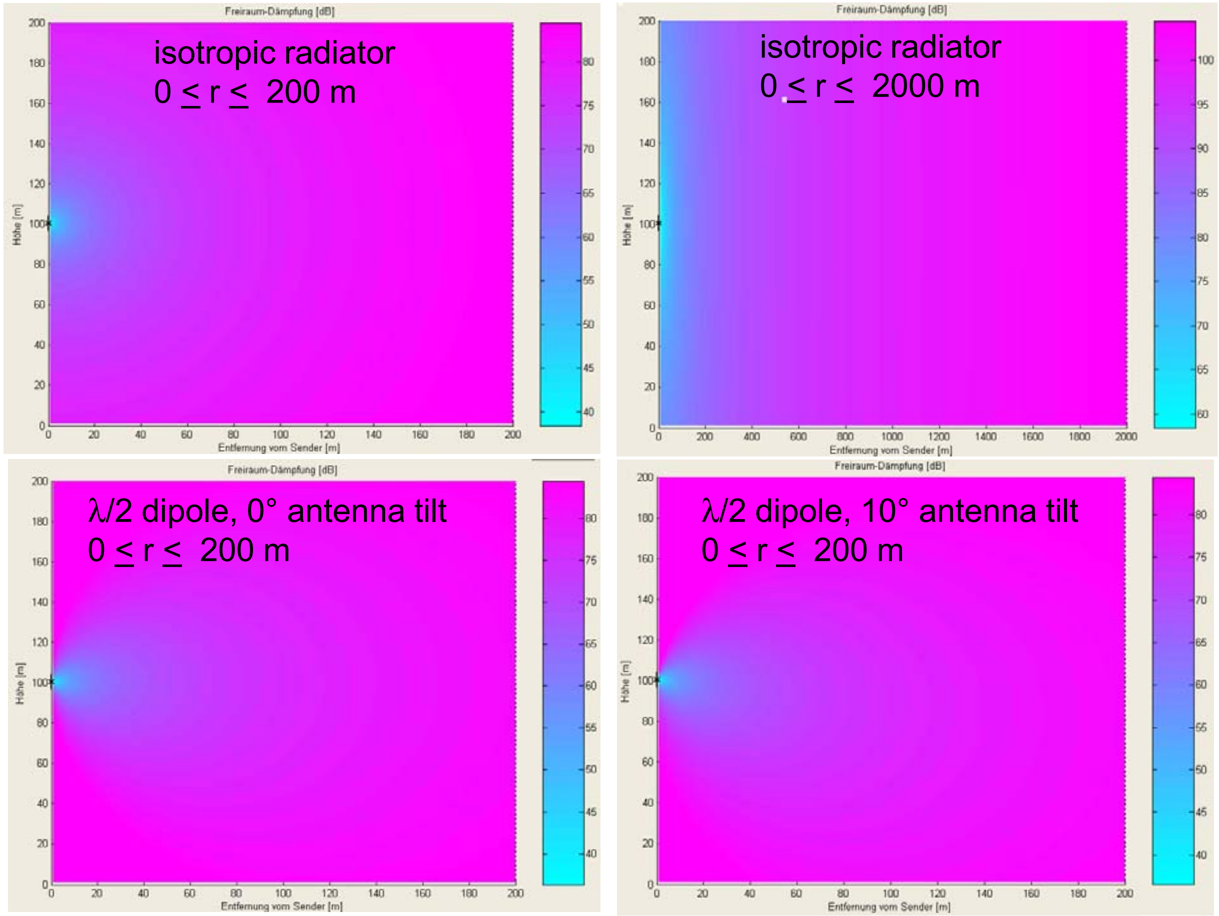
Note: Here and in the following, the downlink case is considered only. Since propagation is reciprocal, however, the same attenuations apply to the uplink.

- free-space attenuation in dB: $L_{\mathrm{dB,F}} = 32{,}4 + 20\log\frac{r}{\mathrm{km}} + 20\log\frac{f}{\mathrm{MHz}}$ (2.24)

Examples of Free-Space Loss at 2 GHz

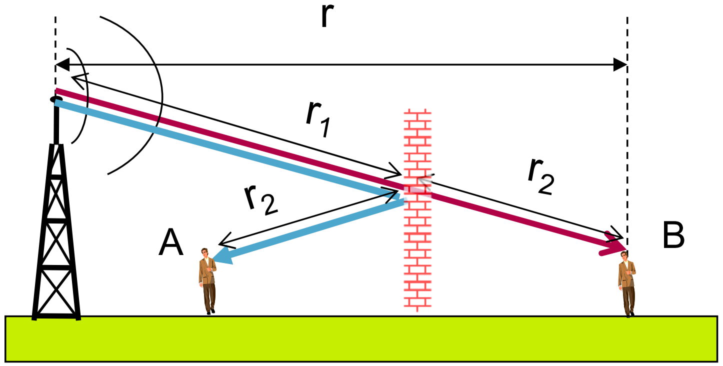
antenna height 100 m





3.6 Reflection and Transmission

- Splitting of the field into incident, reflected and transmitted contributions
- Additional reflection loss (polarisation-dependent reflection factor $r_{\mathrm{TE/TM}}$) for the reflected contribution
- Additional transmission loss (polarisation-dependent transmission factor $t_{\mathrm{TE/TM}}$) for the transmitted contribution

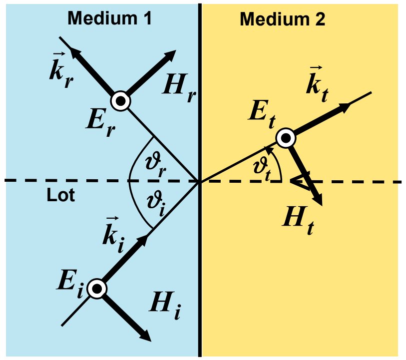


$$P_{\mathrm{R,A}} = P_{\mathrm{T}} \frac{1}{(r_1+r_2)^2} \left(\frac{\lambda}{4\pi}\right)^2 G_{\mathrm{T}}(\theta_{\mathrm{T}}, \phi_{\mathrm{T}}) G_{\mathrm{R}}(\theta_{\mathrm{R}}, \phi_{\mathrm{R}}) \underline{r}_{\mathrm{TE/TM}}\, \underline{r}^*_{\mathrm{TE/TM}} \quad (2.25)$$

$$R_{\mathrm{R,B}} = P_{\mathrm{T}} \frac{1}{(r_1+r_2)^2} \left(\frac{\lambda}{4\pi}\right)^2 G_{\mathrm{T}}(\theta_{\mathrm{T}}, \phi_{\mathrm{T}}) G_{\mathrm{R}}(\theta_{\mathrm{R}}, \phi_{\mathrm{R}}) \underline{t}_{\mathrm{TE/TM}} \underline{t}^*_{\mathrm{TE/TM}} \quad (2.26)$$

Fresnel's Reflection and Transmission Factors

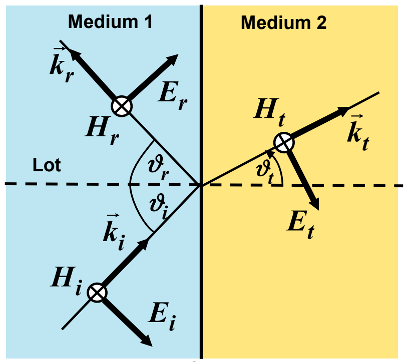
general case | special case for $\underline{\epsilon}_1 = 1; \underline{\epsilon}_2 = \underline{\epsilon}_r$



a) TE polarisation, E field⊥ incidence plane

$$\underline{r}_{\mathrm{TE}} = \frac{\cos(\vartheta_i) - \sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_t)}{\cos(\vartheta_i) + \sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_t)} \qquad \underline{r}_{\mathrm{TE}} = \frac{\cos(\vartheta_i) - \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}}{\cos(\vartheta_i) + \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}} \qquad (2.27)$$

$$\underline{t}_{\mathrm{TE}} = \frac{2\cos(\vartheta_i)}{\cos(\vartheta_i) + \sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_t)} \qquad \underline{t}_{\mathrm{TE}} = \frac{2\cos(\vartheta_i)}{\cos(\vartheta_i) + \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}} \qquad (2.28)$$



b) TM polarisation, H field ⊥ incidence plane

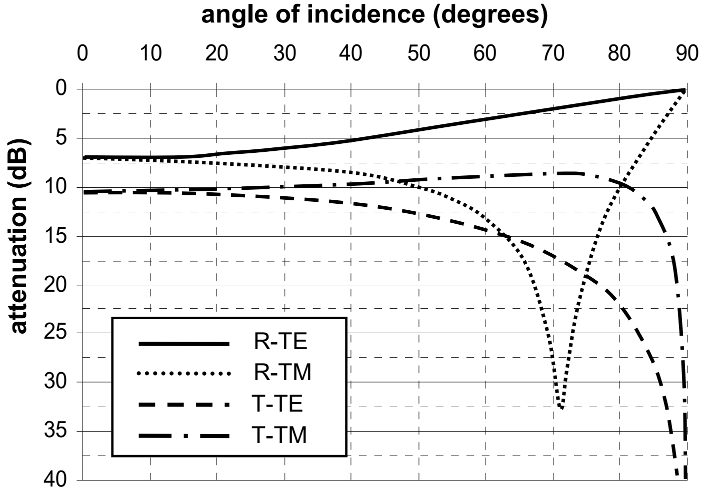
$$\underline{r}_{\mathrm{TM}} = \frac{\sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_i) - \cos(\vartheta_t)}{\sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_i) + \cos(\vartheta_t)} \qquad \underline{r}_{\mathrm{TM}} = \frac{\underline{\epsilon}_r\cos(\vartheta_i) - \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}}{\underline{\epsilon}_r\cos(\vartheta_i) + \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}} \qquad (2.29)$$

$$\underline{t}_{\mathrm{TM}} = \frac{2\cos(\vartheta_i)}{\sqrt{\frac{\underline{\epsilon}_2}{\underline{\epsilon}_1}}\cos(\vartheta_i) + \cos(\vartheta_t)} \qquad \underline{t}_{\mathrm{TM}} = \frac{2\sqrt{\underline{\epsilon}_r}\cos(\vartheta_i)}{\underline{\epsilon}_r\cos(\vartheta_i) + \sqrt{\underline{\epsilon}_r - \sin^2(\vartheta_i)}} \qquad (2.30)$$

For all cases applies: $\underline{\mu}_1 = \underline{\mu}_2 = 1$, incidence is stretched by the wave vector and the normal vector of the reflection plane.

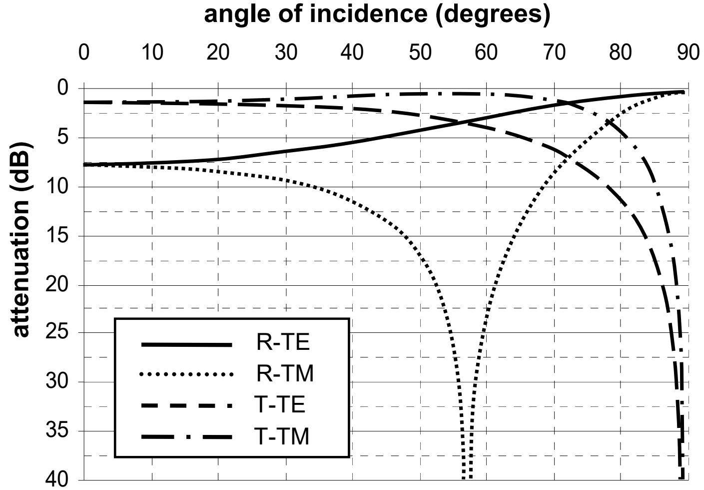
Examples of Reflection and Transmission Loss

- In the lossy medium, the transmission loss also depends on the thickness of the layer.
- Example: characteristics of concrete and wood at 1 GHz



Schichtdicke in cm	ε′	tanδ
30	9	0.1

concrete



Schichtdicke in cm	ε′	tanδ
5	2.5	0.01

wood

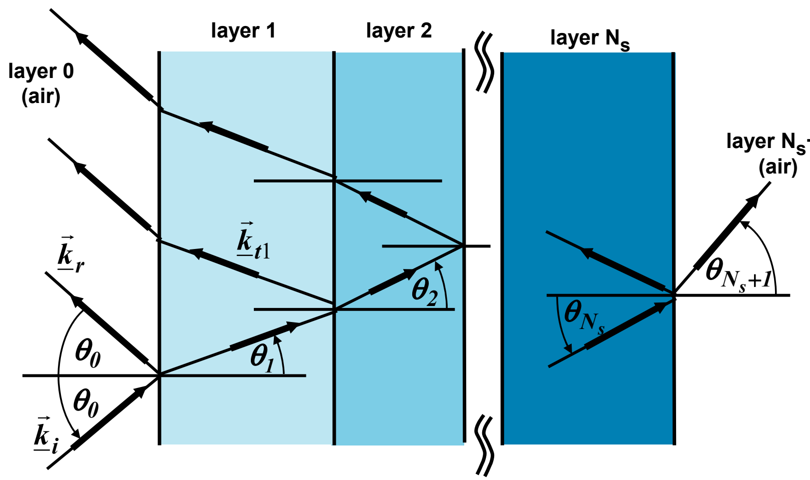
Source: D. Cichon

Modelling of Layers of Building Walls, Windows etc.

- A building wall or a window is described by a multi-layered arrangement of homogeneous layers of materials of a finite thickness

- Assumption that interfaces are plane and smooth

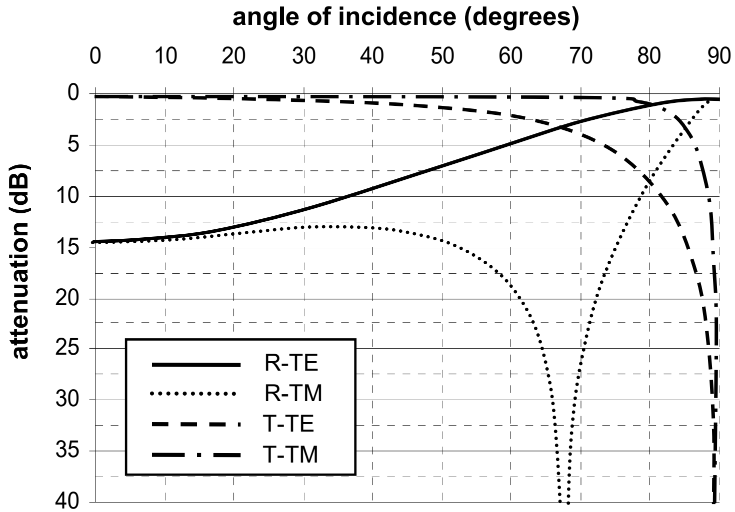
- Each layer is described by the real component of the relative permittivity, loss factor (tan δ), conductivity, thickness of layer



- Calculation by application of the so-called wave matrix method

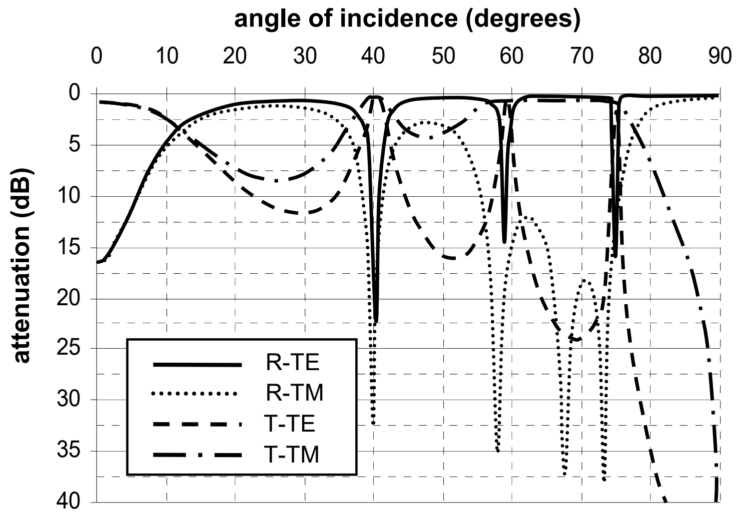
- Special feature: explicit frequency dependence, even in case all layers consist of non-dispersive materials

Example: 3-Layer Window



Schichtdicke in cm	ε′	tanδ
0.3 / 2 / 0.3	6 / 1 / 6	0.008 / 0 / 0.008

2 GHz

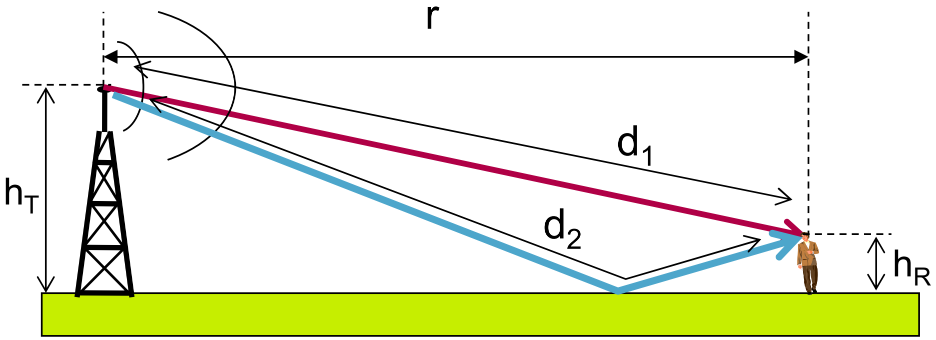


Schichtdicke in cm	ε′	tanδ
0.3 / 2 / 0.3	6 / 1 / 6	0.008 / 0 / 0.008

30 GHz

Source: D. Cichon

3.7 Ground Reflection and Two-Ray Theory



- At the receiver, superposition between the direct ray and a ray reflected on the surface of the earth can arise.
- For the received power, the following applies:

$$P_\mathrm{R} = P_\mathrm{T} \frac{1}{r^2} \left(\frac{\lambda}{4\pi}\right)^2 G_\mathrm{ZS}(r, h_\mathrm{T}, h_\mathrm{R}) G_\mathrm{T}(\theta_\mathrm{T}, \phi_\mathrm{T}) G_\mathrm{R}(\theta_\mathrm{R}, \phi_\mathrm{R}) \qquad (2.31)$$

  - with the term $\frac{1}{r^2} G_\mathrm{ZS}$ describing the attenuation resulting from the two rays

Standard Form of the Two-Ray Theory

- Neglecting the directional pattern of the antenna at first (valid for large distances r), G_{ZS} results from the complex superposition of both signal parts:

$$\tilde{G}_{\mathrm{ZS},v,h} = \left| \frac{\mathrm{e}^{-\mathrm{j}\frac{2\pi}{\lambda}d_1}}{\frac{d_1}{\mathrm{m}}} + \underline{r}_{\mathrm{TE,TM}}(\vartheta_i, \epsilon_r)\ \frac{\mathrm{e}^{-\mathrm{j}\frac{2\pi}{\lambda}d_2}}{\frac{d_2}{\mathrm{m}}} \right|^2 \qquad (2.32a)$$

with $$\tilde{G}_{\mathrm{ZS},v,h} = \frac{1}{r^2} G_{\mathrm{ZS},v,h} \qquad (2.32b)$$

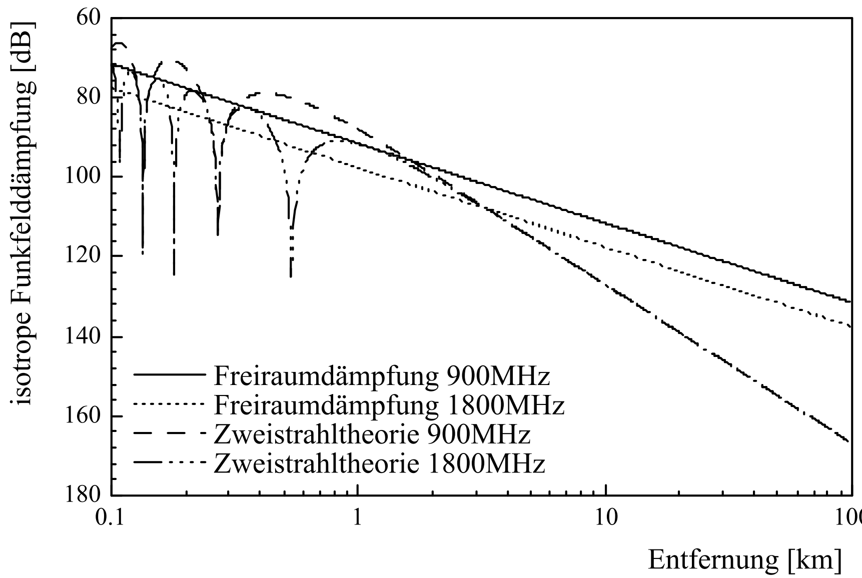
Approximation for large distances (r >> h_T and h_R):

- In the terms for the amplitude applies: $d_1 \approx d_2 \approx r$ (2.33)
- In the terms for the phase applies: $d_2 - d_1 \approx \frac{2h_\mathrm{R}h_\mathrm{T}}{d}$ (2.34)
- A metallic interface is assumed: $\underline{r}_{\mathrm{TE,TM}} = \pm 1$

Two-Ray Model

- Transmission loss of the two-ray model

$$G_{ZS,v,h} = \begin{cases} 4\cos^2 \dfrac{2\pi h_T h_R}{\lambda r}, \text{vertical polarisation} \\ 4\sin^2 \dfrac{2\pi h_T h_R}{\lambda r}, \text{horizontal polarisation} \end{cases} \quad (2.35)$$

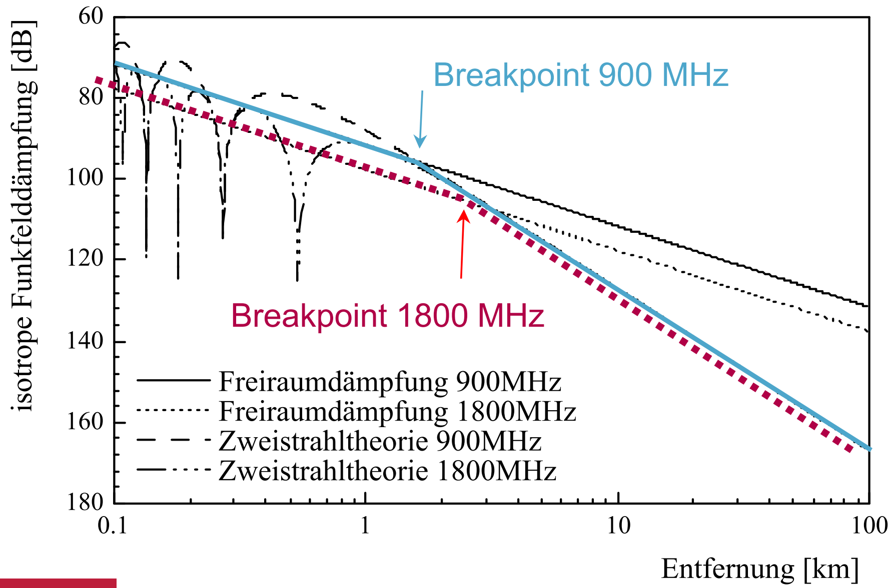


Source: N. Geng

- Example: isotropic transmission loss according to the two-ray theory for horizontal polarisation (h_T = 30 m, h_R = 1.5 m)

Break Point and Dual-Slope Approach

- Consideration of the envelope at horizontal polarisation
  - for small distances $G_{ZS}/r^2 \sim 1/r^2$ (complies with 20 dBd/decade)
  - for large distances $G_{ZS}/r^2 \sim 1/r^4$ (complies with 40 dB/decade)



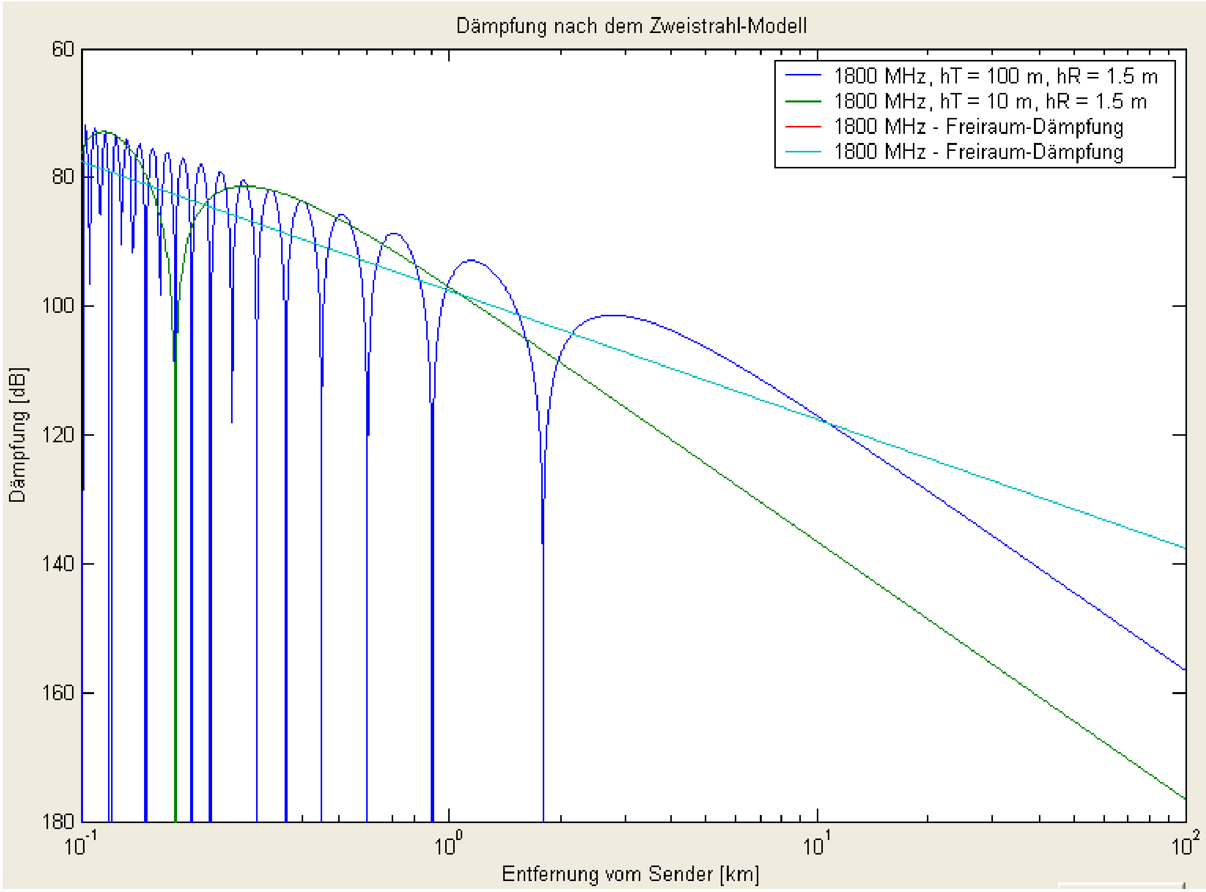
- break point distance:

$$r_{\text{break point}} = \frac{4\pi h_R h_T}{\lambda} \qquad (2.36)$$

- vitally practical importance; for real ground characteristics r, approximately valid for horizontal and vertical polarisation!

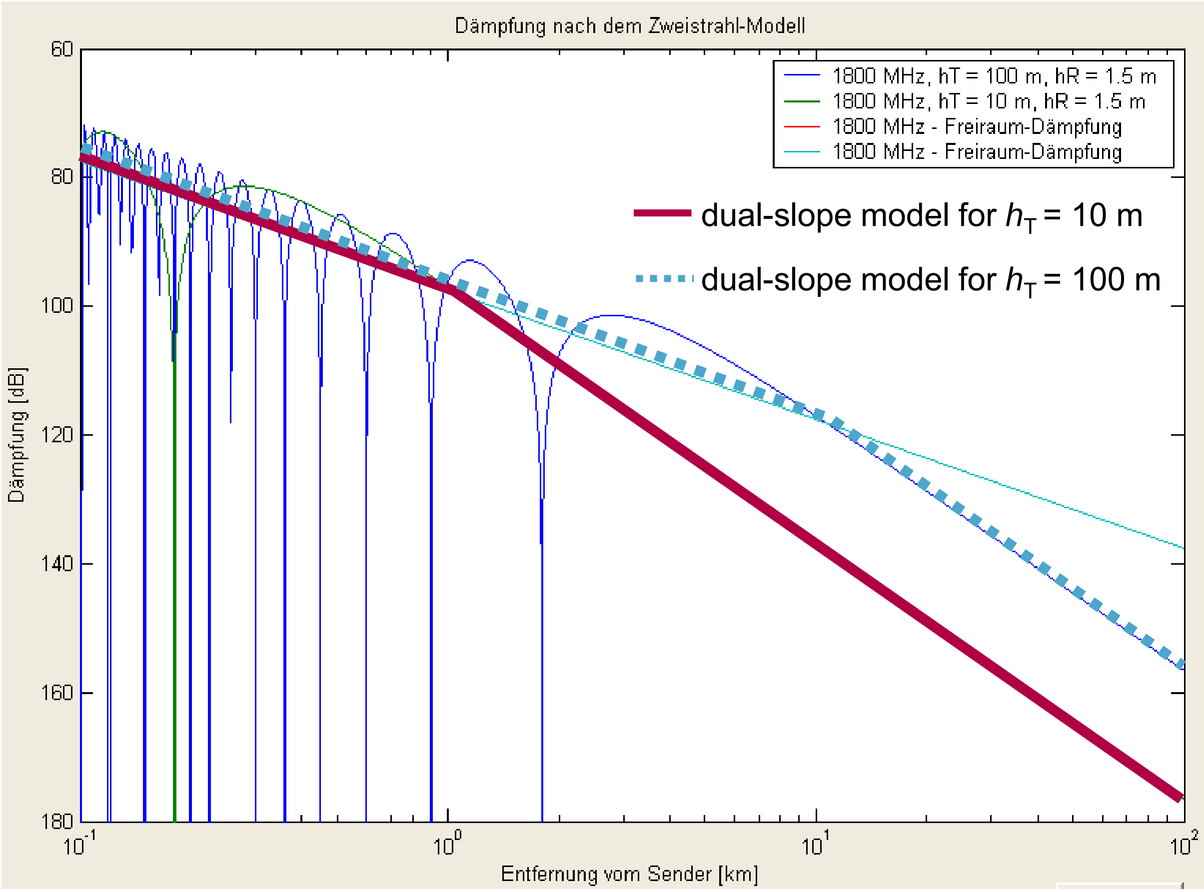
Example of Attenuation with the Two-Ray Model

dependency of the attenuation characteristic on h_T



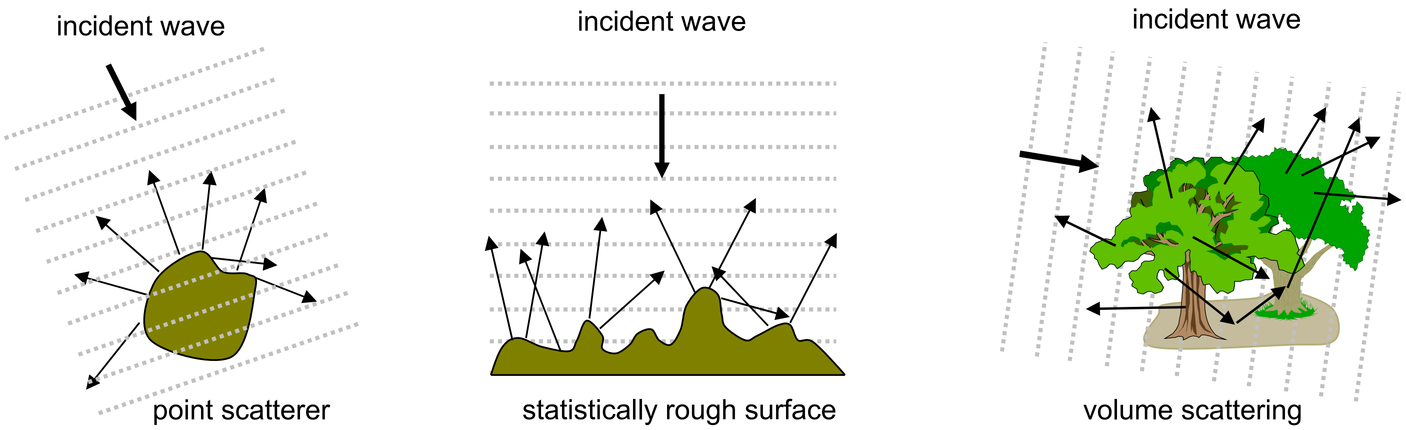
Example of Attenuation at the Two-Ray Model

dependence of the attenuation characteristic on h_T



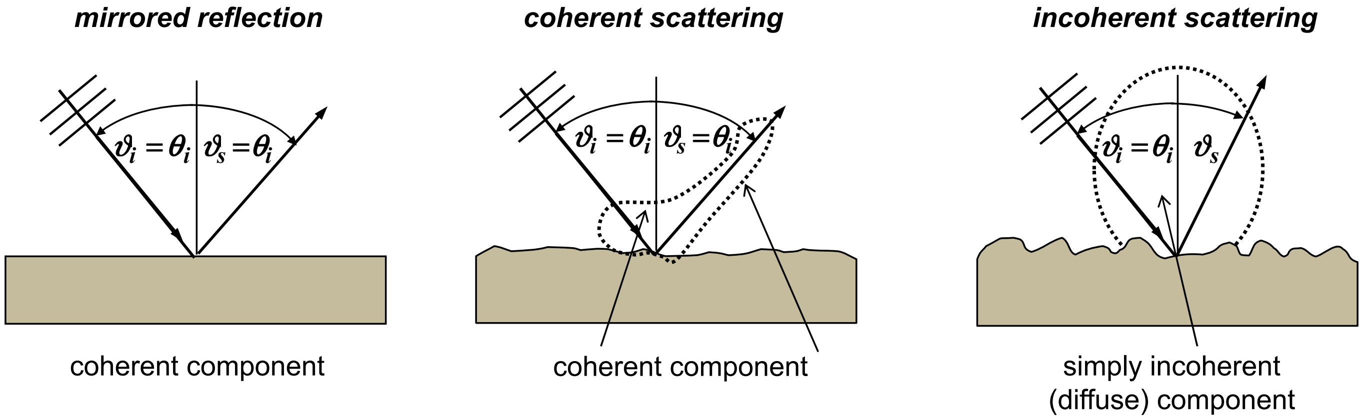
3.8 Scattering

- Scattering denotes the deviation of radiant energy from the original propagation direction occurring in an inhomogeneous medium, i.e. the complete power not reflected to mirror direction is scattered to other directions.
- The smaller the ratio object size to wavelength, the larger the deviation of the interaction of a wave with a single object from the behaviour considering
- Also for rough surfaces and groups of scatterers, treatment only be reflection and transmission is not sufficient.



Scattering at Rough Surfaces

- An ideally smooth, plane interface reflects an incident, locally plane wave in a single direction given by the reflection law.
- With increasing roughness, scattering in other directions (purely coherent scattering for slightly rough surfaces)
- For very high roughness or varying heights and slopes, the preferred direction of the mirrored reflection is no longer observable.



Criteria for Roughness

- Standard deviation σ of the surface roughness as a measure for the mean variation in height compared with the mean value as well as the correlation length I_{corr} as a measure for the statistical relation of two points on the rough surface at intervals of Δr
- The ratio σ to wavelength λ is decisive for the differentiation scattering/reflection.
- A surface can be considered smooth in case the Fraunhofer criterion is fulfilled:

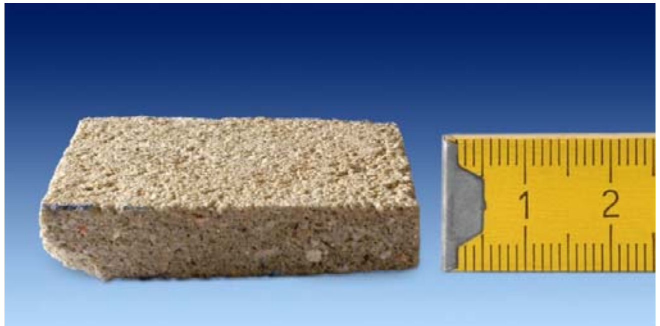
$$\sigma < \frac{\lambda}{32 \cos \theta_i} \tag{2.37}$$

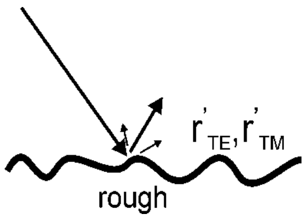
- For very large areas (measurements >> λ) and low roughness σ << λ, an approximation for the reduction of the field strength amplitude in the reflected direction (modified Fresnel reflection factors) exists:

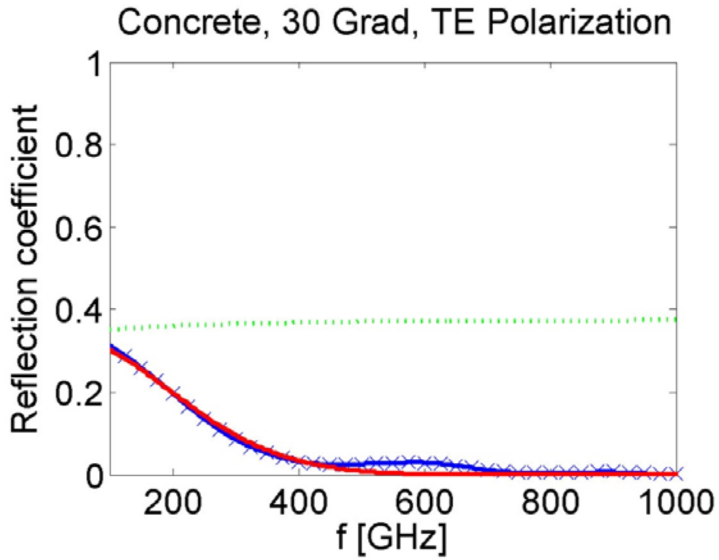
$$\underline{r}_{\mathrm{TE/TM}}^{\mathrm{mod}} = \underline{r}_{\mathrm{TE/TM}} \mathrm{e}^{-8\pi^2 \left(\frac{\sigma}{\lambda}\right)^2 \cos^2 \theta_i} \tag{2.38}$$

- For definite validity ranges of σ/λ and $I_{\mathrm{corr}}/\lambda$, analytical methods of calculation (Kirchhoff theory, small perturbation method) for calculation of the scattered parts exist.

Example: Reflection on Rough Plaster (σ=0.15mm) Beyond 100 GHz





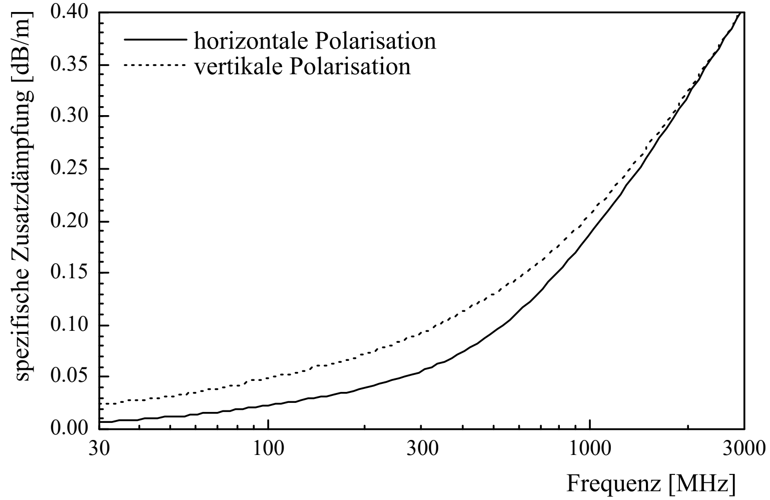


Volume Scattering and Attenuation due to Vegetation

- Estimation of the volume scattering
  - Modelling of the interaction of an electromagnetic wave with a volume, in which scattering objects of different shapes, sizes, orientation and material parameters are statistically distributed, is very complex (e. g. by Radiative Transfer Theory) and, mostly, only possible by approximation.
- Estimation of the attenuation without vegetation
  - simple empirical approximation procedure for the loss on passing through a vegetation layer (CCIR-Rep. 236-5):

$$L_{\mathrm{dB,veg}} = \eta \left(\frac{f}{\mathrm{MHz}}\right)^{\nu} \left(\frac{d}{\mathrm{m}}\right)^{\gamma} \qquad (2.39)$$

  - $L_{\mathrm{dB,veg}}$ denotes an excess loss that has to be added to the transmission loss arising without vegetation.
  - typical values: $\eta = 0.187; \nu = 0.284; \gamma = 0.588$

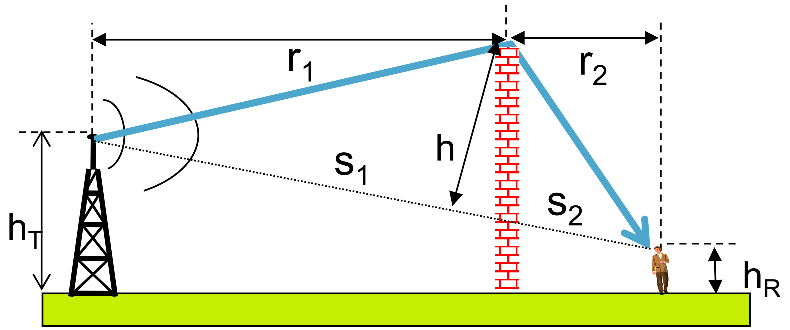


specific excess loss according to ITU-R Rec. 833

3.9 Diffraction

- Electromagnetic waves can move round obstacles and thus can reach the geometrical coverage gap. It depends on the wavelength as well as on the shape of the obstacle how much the field is diffracted, i.e. how much it penetrates the shadow region.

As a first approximation,
diffraction effects at sharp-edged obstacles can be described with the help of absorbing half-planes (knife edges) that are introduced vertically to the connecting line transmitter-receiver.



- For the received power, the following applies:

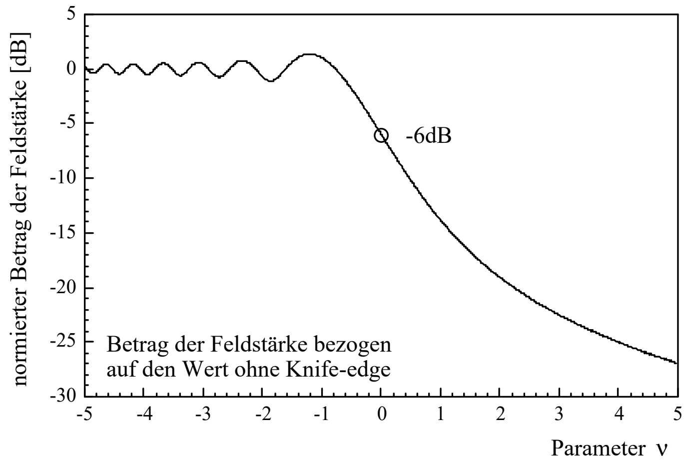
$$P_{\mathrm{R}} = P_{\mathrm{T}} \frac{1}{(r_1+r_2)^2} \left(\frac{\lambda}{4\pi}\right)^2 G_{\mathrm{T}}(\theta_{\mathrm{T}}, \phi_{\mathrm{T}}) G_{\mathrm{R}}(\theta_{\mathrm{R}}, \phi_{\mathrm{R}}) L_{\mathrm{B}} \qquad (2.40)$$

Attenuation for Knife-Edge Diffraction

$$L_{\mathrm{B}} = 10^{-\frac{\tilde{L}_{\mathrm{B}}}{10}} \qquad (2.41)$$

$$\tilde{L}_{\mathrm{dB,B}} = 6.9 + 20\log(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1) \qquad (2.42)$$

$$\nu = h^* \sqrt{\frac{2}{\lambda}\left(\frac{s_1 + s_2}{r_1 r_2}\right)} \qquad (2.43)$$

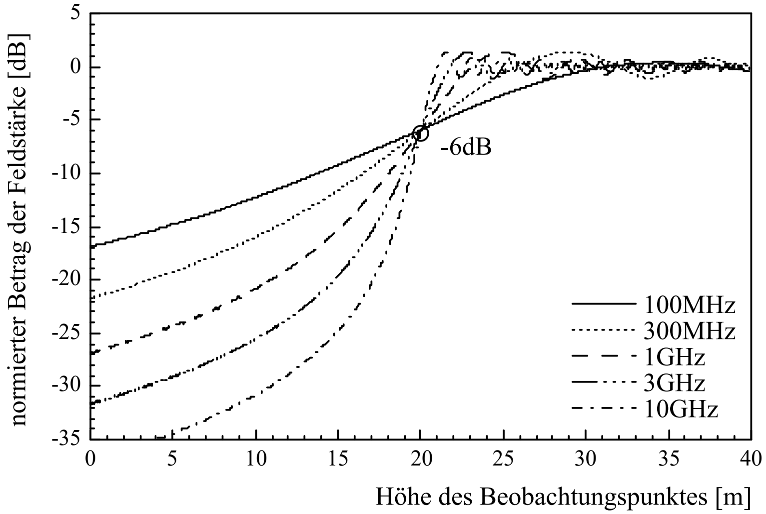


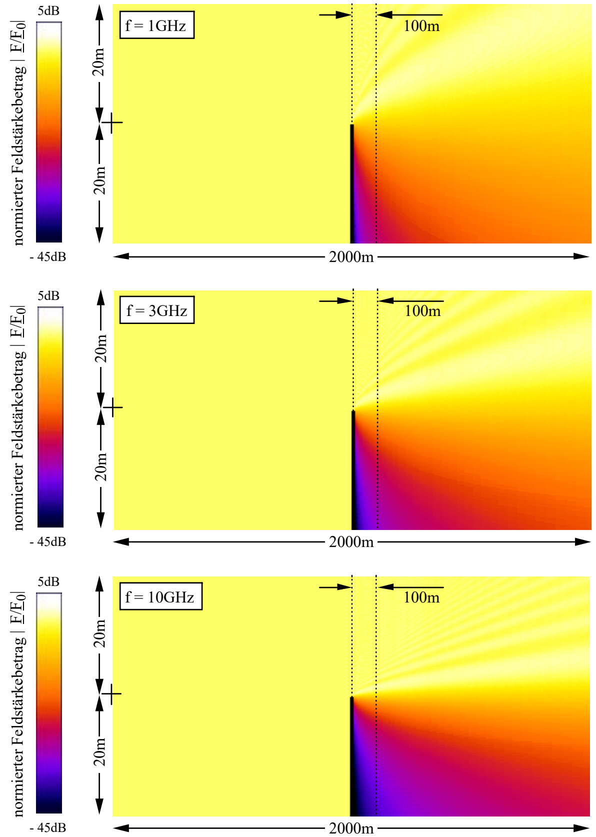
Source: N. Geng

- Although sharp-edged obstacles rarely occur in reality, the attenuation behaviour at realistic obstacles can be well approached by Knife-Edge diffraction.

Variation with Frequency

Normalised amplitude of the field strength as a function of the height of the observation point at a distance of 100m behind the half-plane (calculation with the Parabolic Equation Method):

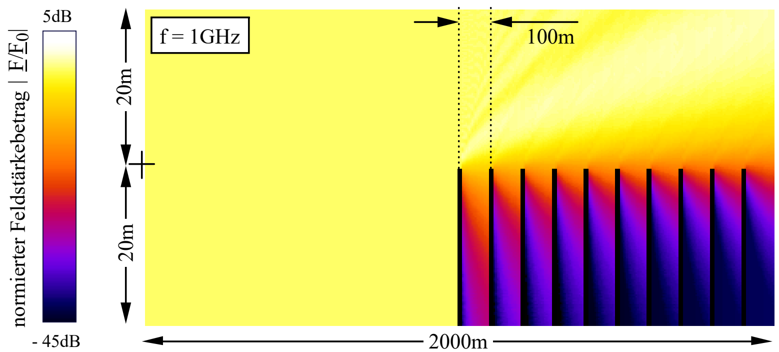




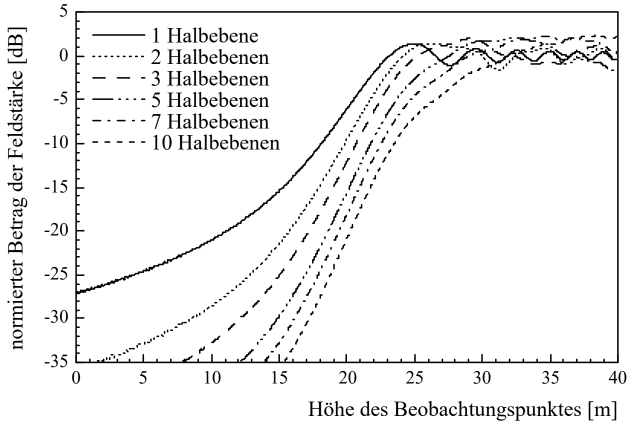
Source: N. Geng

Multiple Diffraction

- In practise, for lots of problems a half-plane is not sufficient.
- Substitution of obstacles by a set-up of several half-planes



Relative field strength in a vertical cutting plane at 1 GHz



Height dependency of the relative field strength at intervals of 100 m from one half-plane to the next

Source: N. Geng

Refraction and Effective Radius of the Earth

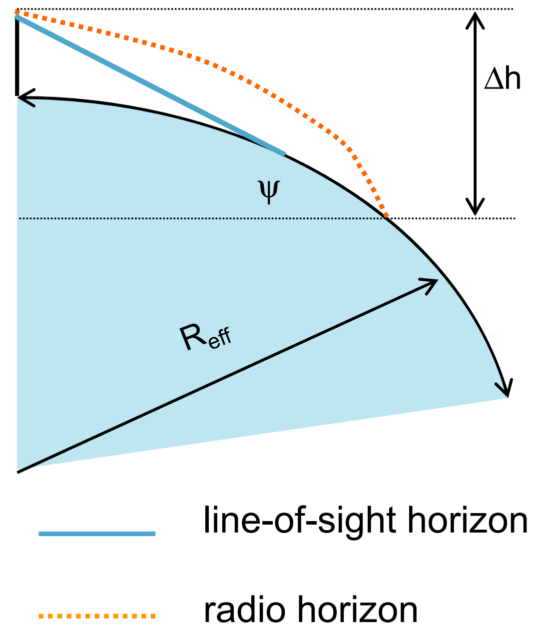
- Defining differences in height along a terrain profile, the curvature of the earth has to be considered.
  - projection of the height onto a sphere with the radius
    $R = R_{earth} = 6370 \text{ km}$

- Tropospheric refraction effects enlarge the coverage of electromagnetic waves in the VHF/UHF range.

  - Extension of the radio horizon compared to the sight horizon can be considered by the effective radius of the earth

$$R_{\text{Eff}} = k \cdot R_{\text{earth}} \qquad (2.44)$$

  - For Europe $k = 4/3$ applies.



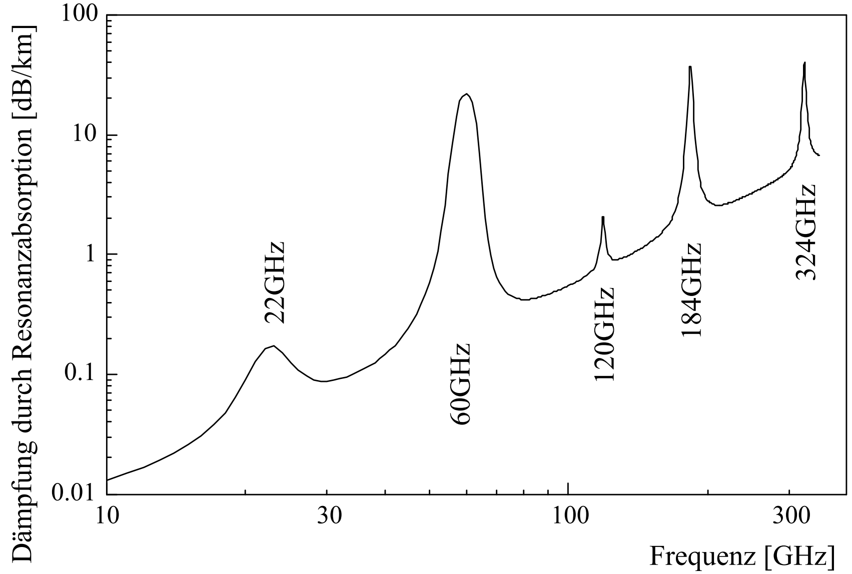
3.10 Resonant Absorption

- Resonant absorption occurs in case of discrete frequencies that correspond to the natural oscillation frequencies of the molecules included in the atmosphere.

water vapour:
22 GHz, 184 GHz, 324 GHz

oxygen:
60 GHz, 120 GHz

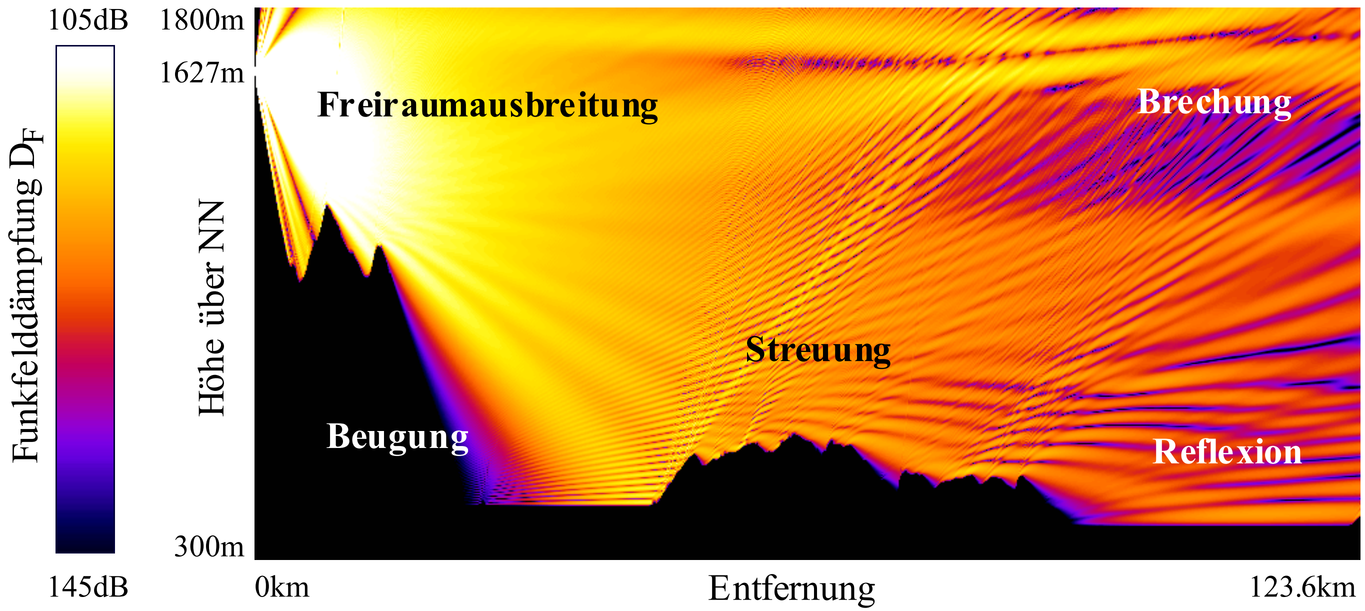
For future mobile radio systems partly intended for those frequencies, this effect has to be considered.



Source: N. Geng

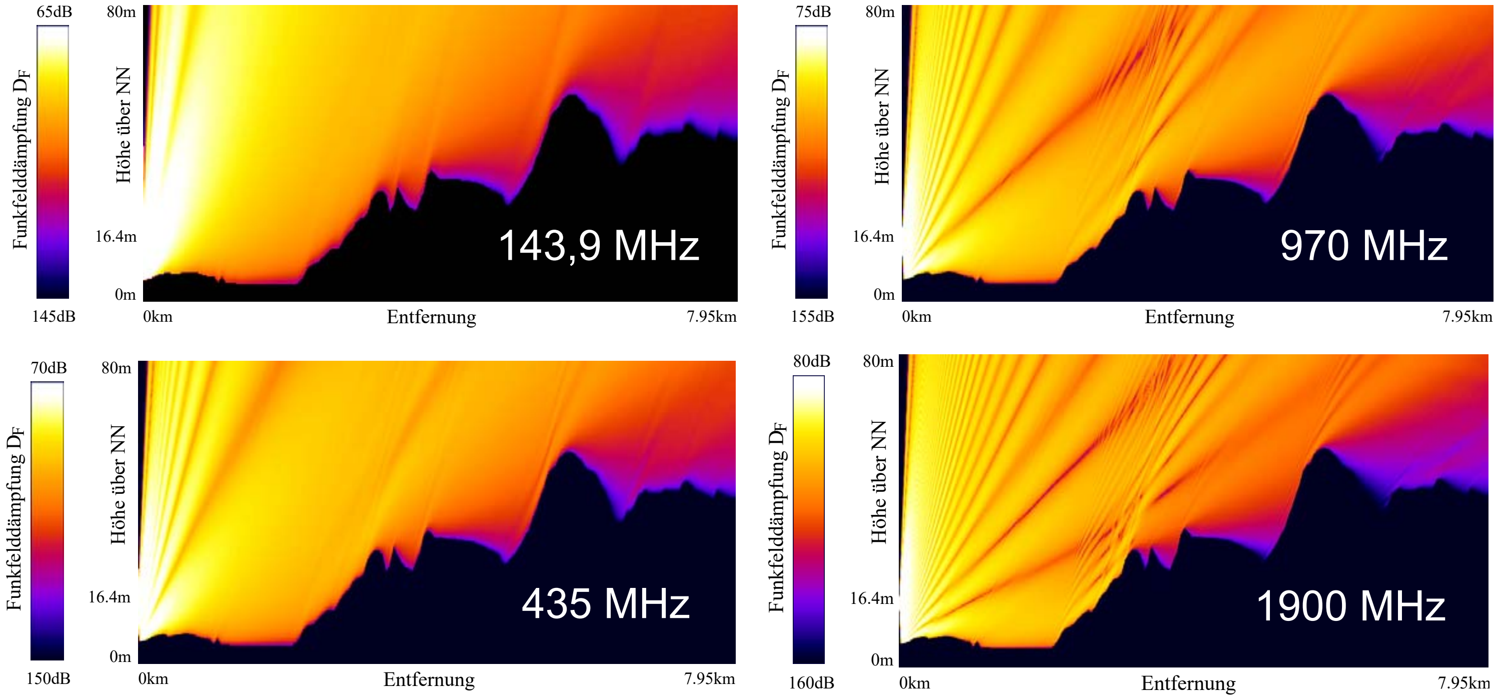
3.11 Superposition of the Propagation Effects

- Coherent superposition of the resulting multipath signals
  - example: propagation along a radio link at 300 MHz



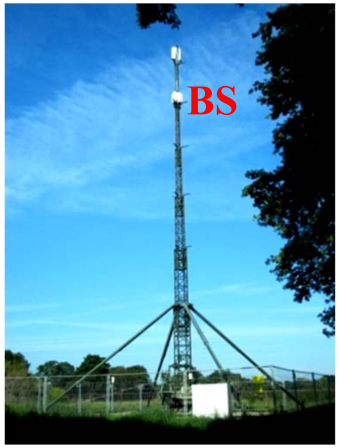
Source: N. Geng, W. Wiesbeck, Planungsmethoden für die Mobilkommunikation

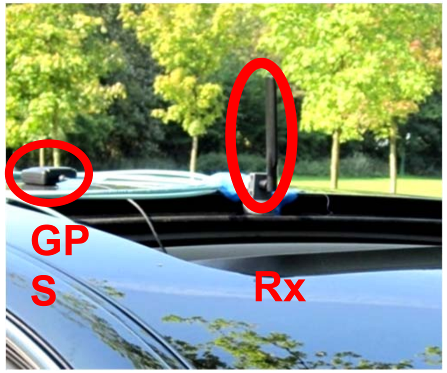
Frequency Dependence of the Propagation in a Hilly Terrain (v Pole)



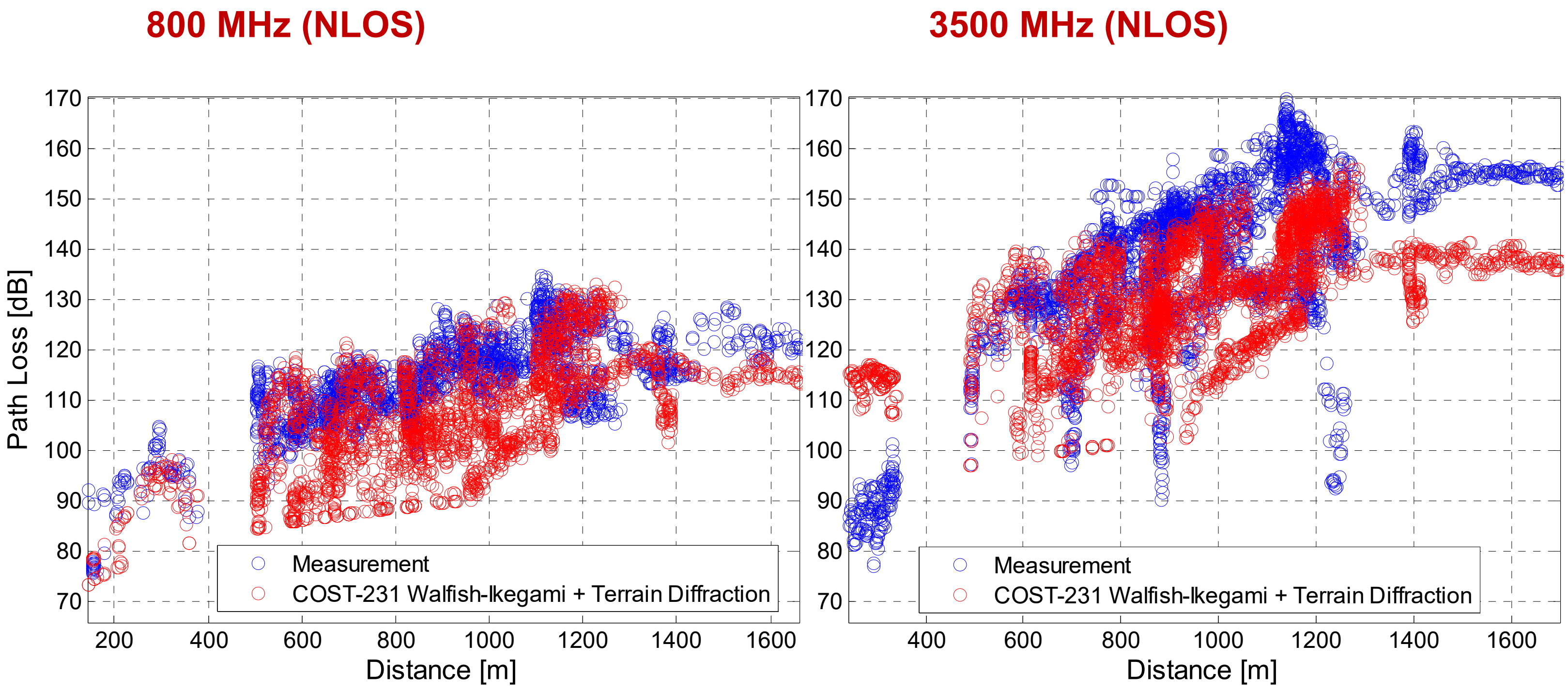
Source: N. Geng, W. Wiesbeck, Planungsmethoden für die Mobilkommunikation

Measurements at 800 MHz and 3500 GHz (WiMAX Pilot Test Lower Saxony)





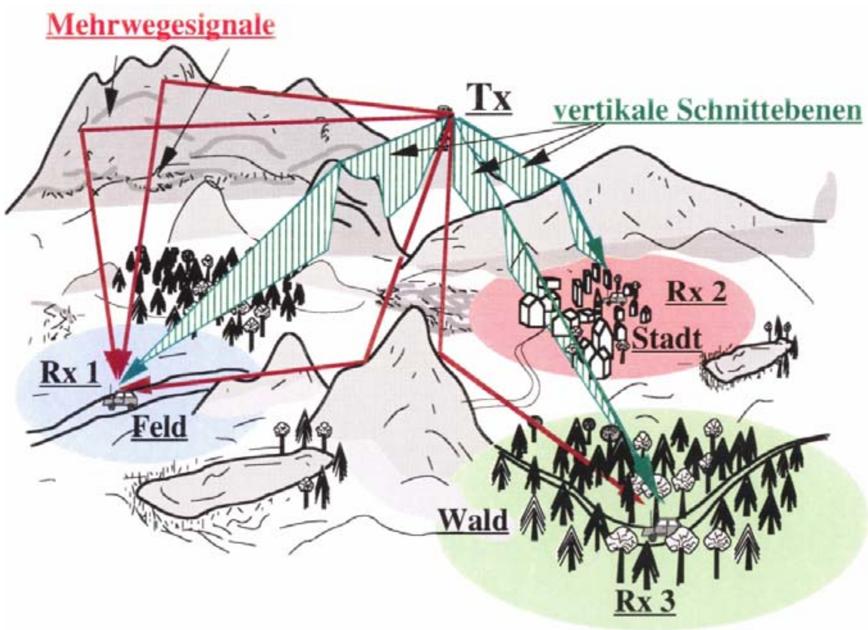
Path Loss at 800 MHz and 3500 GHz (Measurement at Foliation)



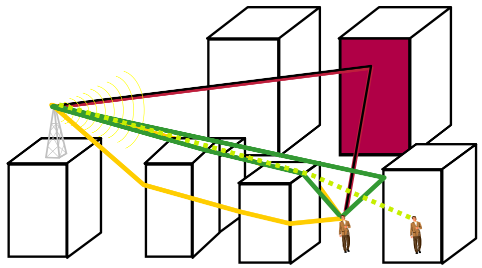
3.12 Propagation Models

- For the planning of radio networks, models for the determination of the propagation behaviour of electromagnetic waves are required.
- In order to calculate the attenuation including the respective terrain structure and buildings as precise as possible, numerous deterministic, empirical and semi-empirical propagation models were developed in recent years.
- In the following, some simple empirical and semi-empirical propagation models are introduced for a quantitative representation of the propagation behaviour in principle in realistic terrain structures.

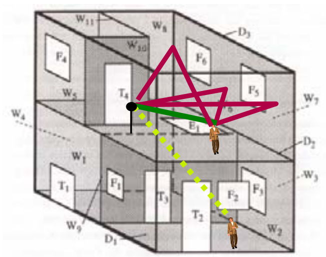
Typical Propagation Environments in Mobile Radio Communication



macro cell



small macro cell / micro cell



pico cell / femto cell

Simple Propagation Models for Macro Cells

- Attenuation ratios for macro cells (general equation)

$$L_{\mathrm{dB}}(r) = A + B\log\left(\frac{r}{\mathrm{km}}\right) + C + D \quad (2.45)$$

L_{dB}: distance-dependent attenuation in dB

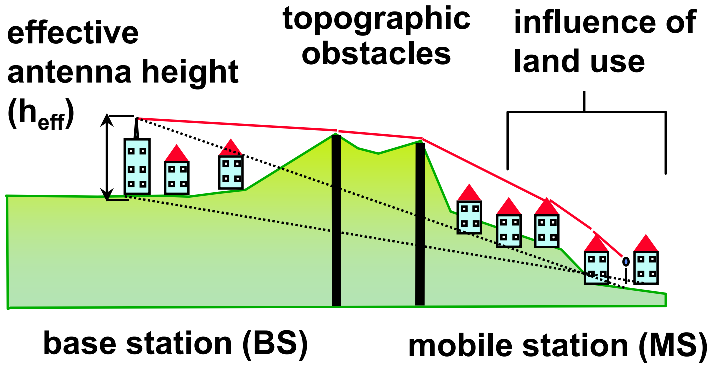
r: distance BS-MS in km

A: loss at a distance in 1 km

B: propagation coefficient (loss per decade)

C: diffraction loss through topographic obstacles

D: correction loss for land use (e. g. buildings)



Okumura-Hata Model and COST231-Hata Model, respectively

- For BS antenna heights (h_{BS}) between 30 and 200 m, a distance of 1 to 20 km and mobile station antenna heights (h_{MS}) of 1 to 10 m the following attenuation coefficients apply to urban areas:

  - from 150 MHz to 1000 MHz

$$A = 69.55 + 26.26\log\left(\frac{f}{\mathrm{MHz}}\right) - 13.82\log\left(\frac{h_{\mathrm{BS}}}{\mathrm{m}}\right) - a\left(\frac{h_{\mathrm{MS}}}{\mathrm{m}}\right) \quad (2.46)$$

  - from 1500 to 2000 MHz

$$A = 46.3 + 33.9\log\left(\frac{f}{\mathrm{MHz}}\right) - 13.82\log\left(\frac{h_{\mathrm{BS}}}{\mathrm{m}}\right) - a\left(\frac{h_{\mathrm{MS}}}{\mathrm{m}}\right) \quad (2.47)$$

  - for both a.m. frequency ranges

$$B = 44.90 - 6.55\log\left(\frac{h_{\mathrm{BS}}}{\mathrm{m}}\right) \quad (2.48)$$

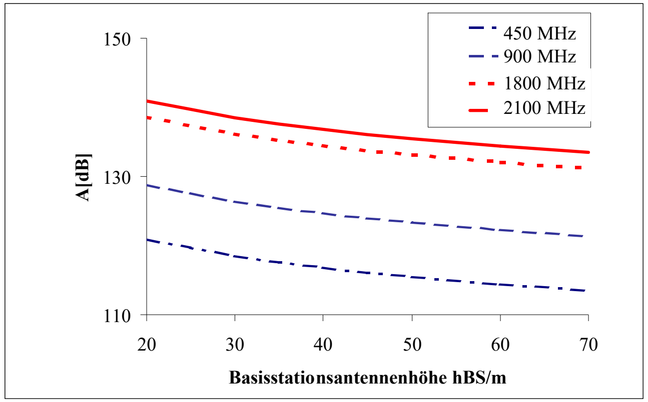
$$a(h_{\mathrm{MS}}) = \left(1.1\log\left(\frac{f}{\mathrm{MHz}}\right) - 0.7\right)\frac{h_{\mathrm{MS}}}{\mathrm{m}} - \left(1.56\log\left(\frac{f}{\mathrm{MHz}}\right) - 0.8\right) \quad (2.49)$$

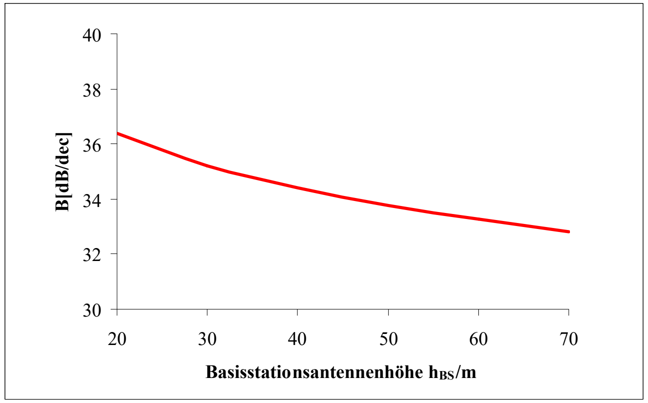
Attenuation Constants

- Examples of the values of *A* for 4 different frequencies and variations of the BS antenna height
- *B* is frequency independent
- *C* is usually described using the Knife-Edge model
- Determination of *D* for different land use classes

$$D = -9.42\log\left(\frac{f}{\mathrm{MHz}}\right) - 1.07 + E \qquad (2.50)$$

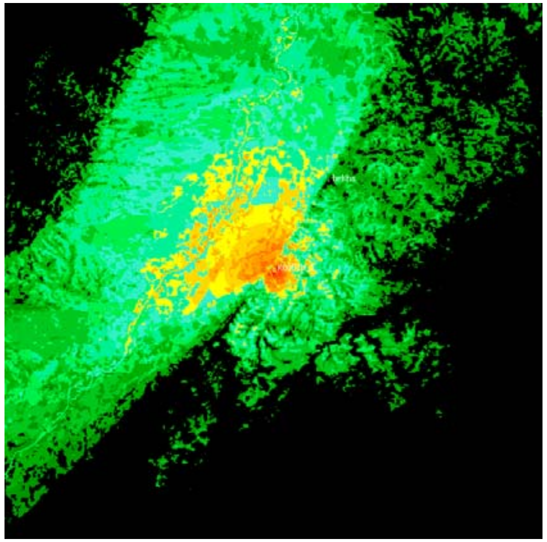
- The values of *E* depend on type and number of land use classes and have to be determined by calibration.
- Examples of *E* at 1800 MHz:
  - *E* = 19.6 dB in urban areas
  - *E* = 11.5 dB in open areas
  - *E* = 18.8 dB in forested areas



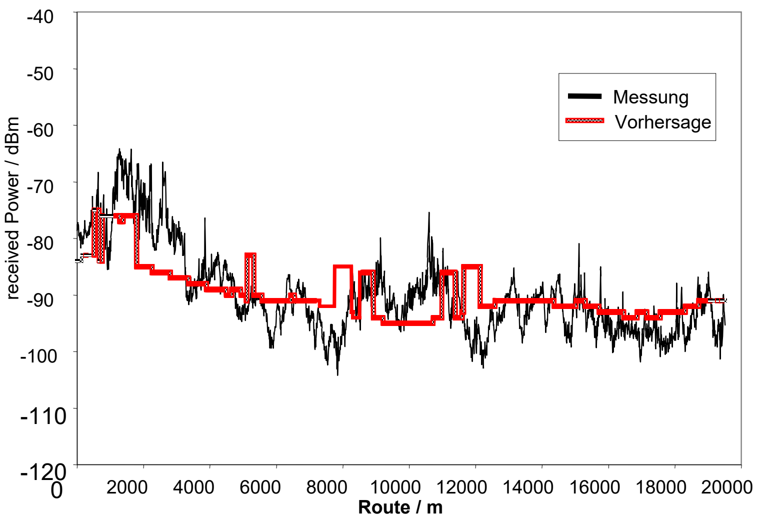


Example of Okumura-Hata Model

- Typical result based on a propagation model according to Okumura Hata + Knife Edge diffraction model + land use correction



Laminar prediction



Comparison prediction /measurement

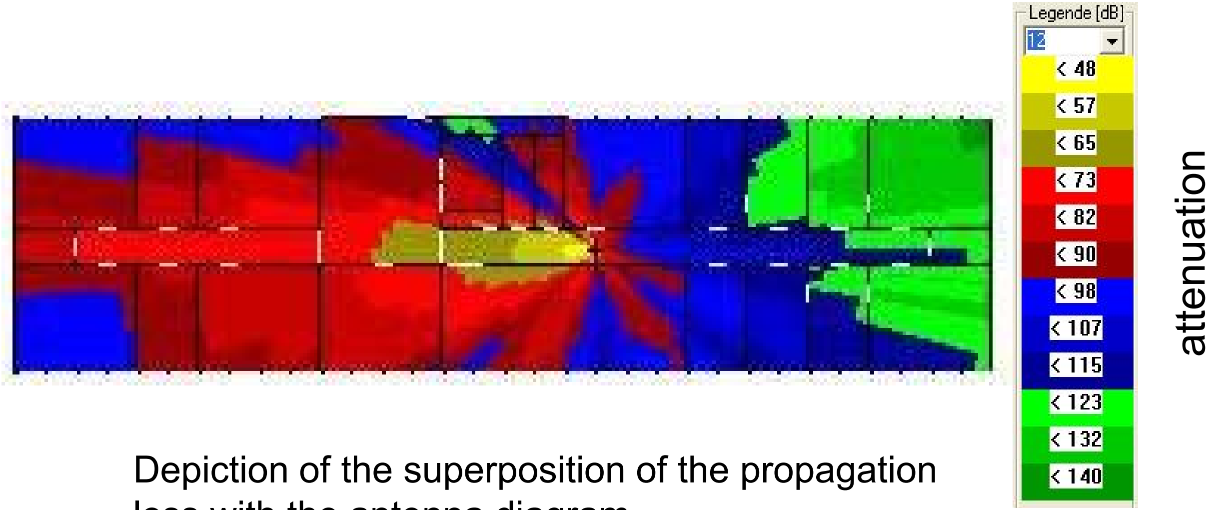
Simple Propagation Models for Indoor Coverage

- Multiwall model according to Motley-Keenan

$$L_{\mathrm{dB}} = L_{\mathrm{dB,FS}} + L_{\mathrm{dB,C}} + \sum_{i=1}^{I} k_{wi} L_{\mathrm{dB},wi} + \sum_{j=1}^{J} k_{fj} L_{\mathrm{dB},fj} \qquad (2.51)$$

$L_{\mathrm{dB,FS}}$	free-space attenuation
$L_{\mathrm{dB,C}}$	empirical determined constant
k_{wi}	number of penetrated walls of type *i*
k_{fj}	number of penetrated walls of type *j*
$L_{\mathrm{dB},wi}$	wall attenuation for wall of type *i*
$L_{\mathrm{dB},fj}$	floor attenuation for floor of type *j*
I	number of different types of walls
J	number of different types of ceilings

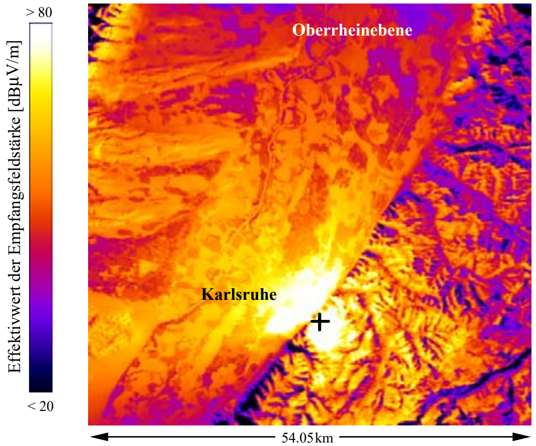
3.12 Propagation Models
Example of the Prediction of the Indoor Coverage Using the Multiwall Model



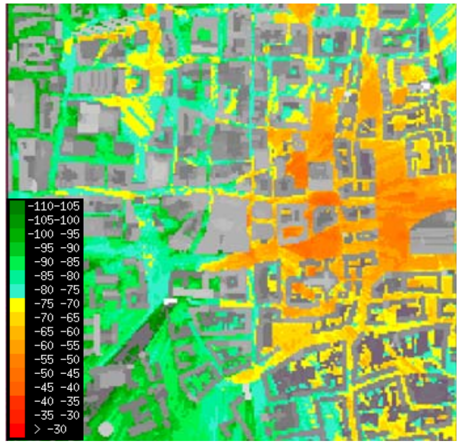
Depiction of the superposition of the propagation loss with the antenna diagram

Examples of Results Using more Komplex Models

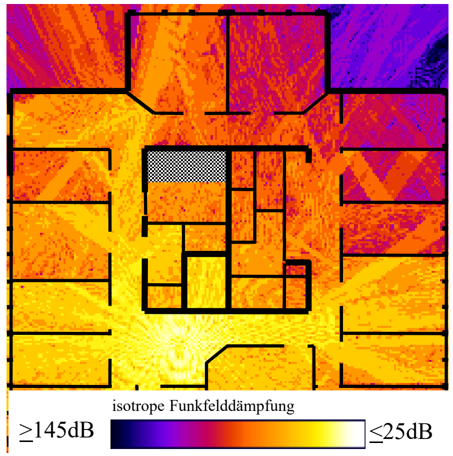
- For real radio network planning, deterministic propagation models are partly applied



macro cell

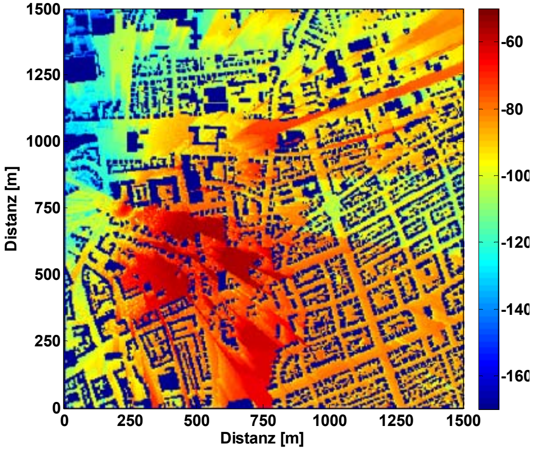


small macro cell

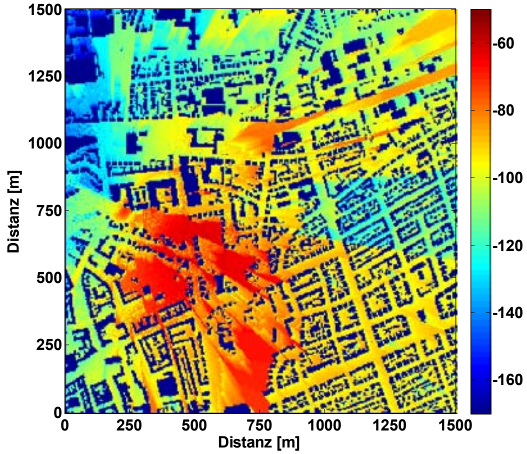


pico cell (indoor)

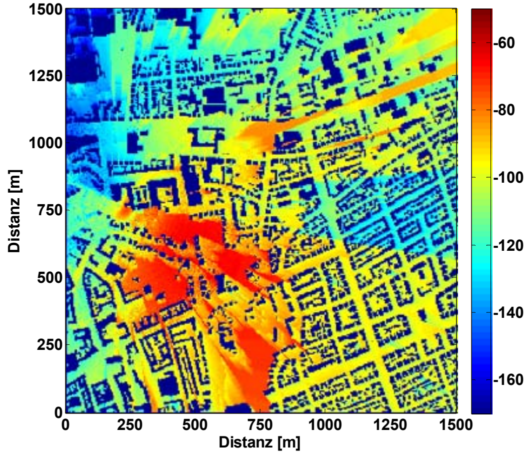
Prediction of the Received Power (Outdoor) on the Basis of Ray-Tracing



LTE800

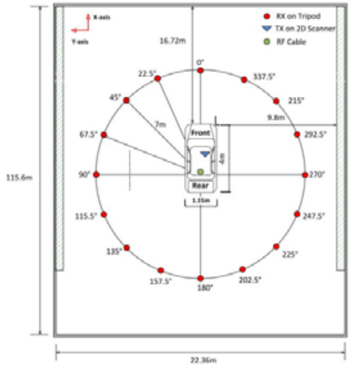


LTE1800

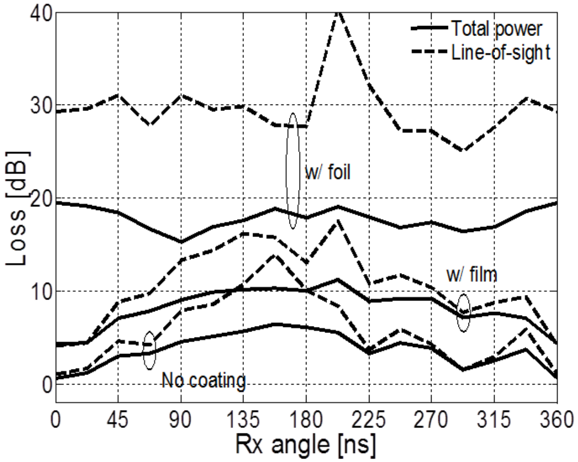


LTE2600

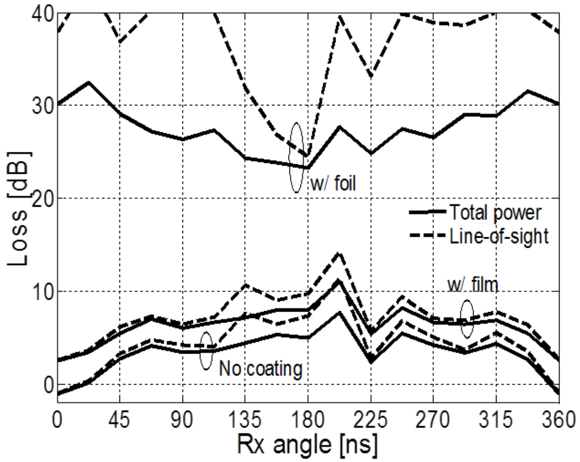
Penetration Loss at Radio Reception in a Vehicle without Outdoor Antenna



Source: Virk et. el, „Characterisation of Vehicle Penetration Loss at Wireless Communication Frequencies, EuCAP 2014



0.6 – 1.5 GHz

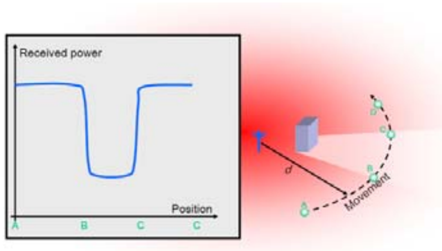


5.1 – 6 GHz

3.13 Fading Effects

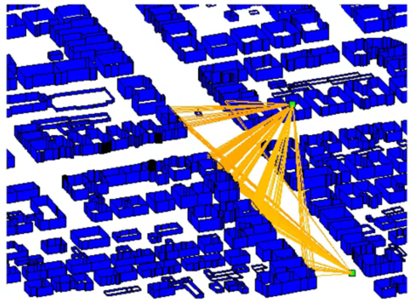
- The superposition of the different propagation paths results in additional statistical signal variations called fading.

  - Long-term fading:
    - deviations from the mean distance-dependent receive level due to varying shadowing effects (e.g. by buildings)
    - description of the variation of the attenuation in dB by a Gaussian normal distribution (lognormal fading)



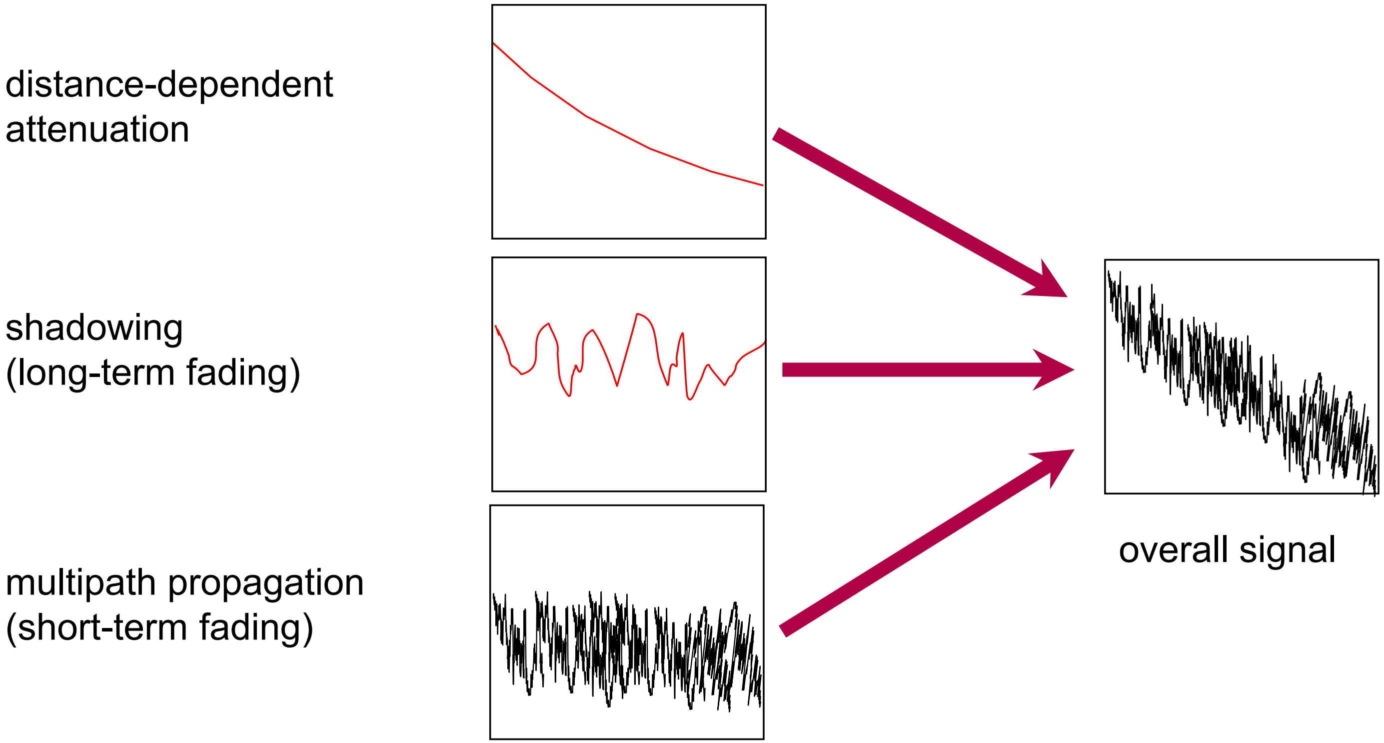
Source: Lecture slides for courses based on textbook A. F. Molisch, „Wireless Communications"

  - Short-term fading:
    - level fluctuations due to the coherent superposition of the multipath signals
    - description of the variation of the attenuation in dB by a Rayleigh distribution („Rayleigh-Fading")



- These two fading effects superpose the distance-dependent attenuation.

Superposition of Fading Effects with Distance-Dependent Attenuation

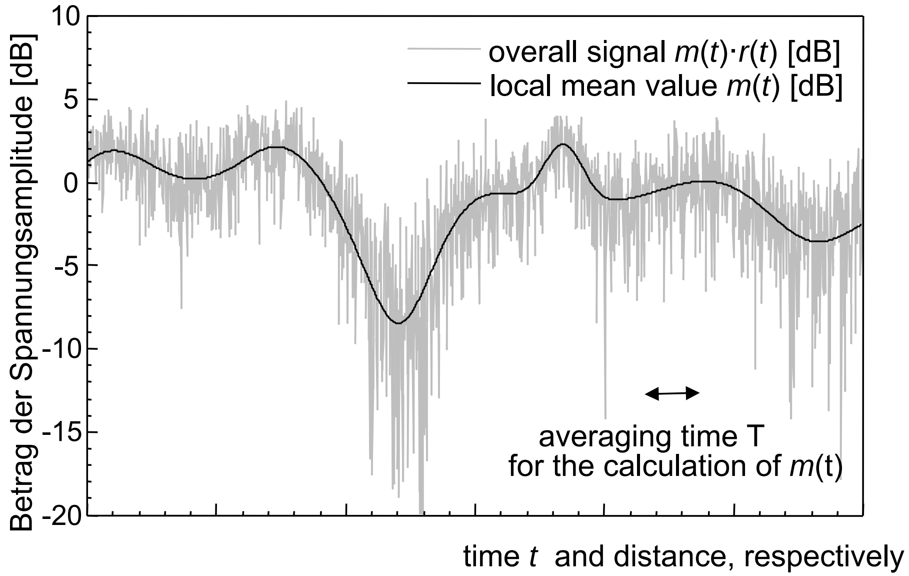


Superposition of Long-Term and Short-Term Fading

- Superposition of long-term and short-term fading
- A mobile station moving through the radio field experiences spacial fading effects.

At coverage measurements, but also for measurements carried out permanently by a mobile station for the handover decision, the long-term fading is determined.

Determination of the level characteristic of the long-term fading through averaging of the overall signal



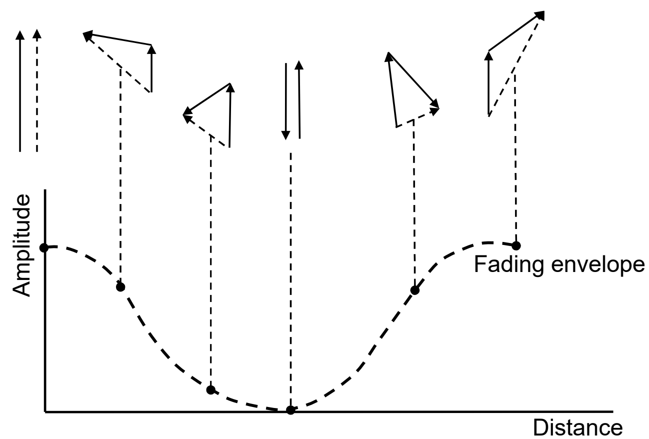
Source: N. Geng

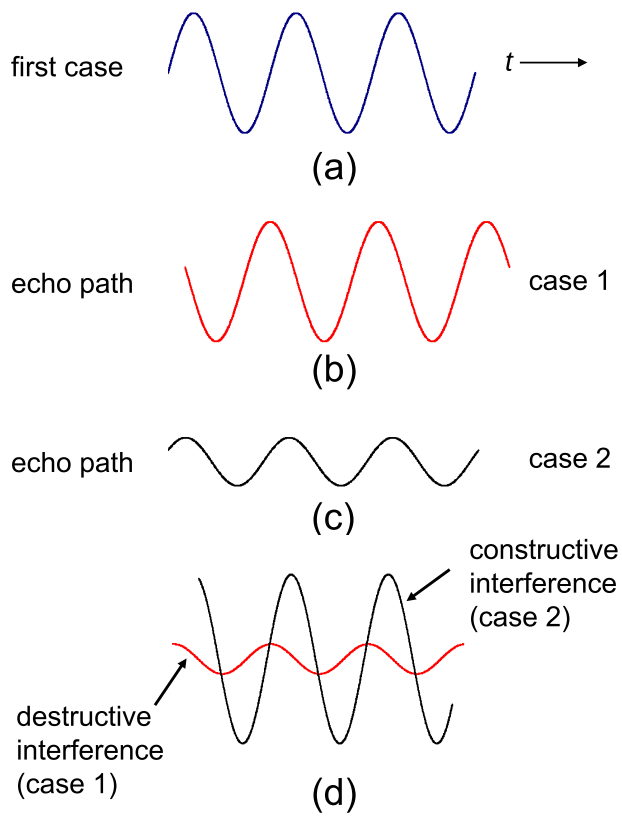
Technische Universität Braunschweig

Institut für Nachrichtentechnik

3.14 Superposition of Multipath Signals

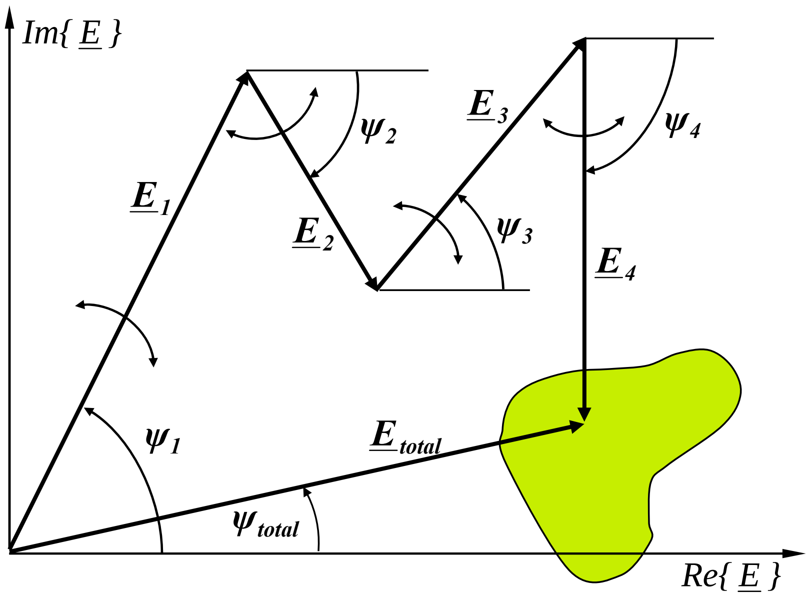
- Consideration of two-path propagation:
  - Depending on the amplitude and phase of both superposing signals, constructive and destructive interference can occur.

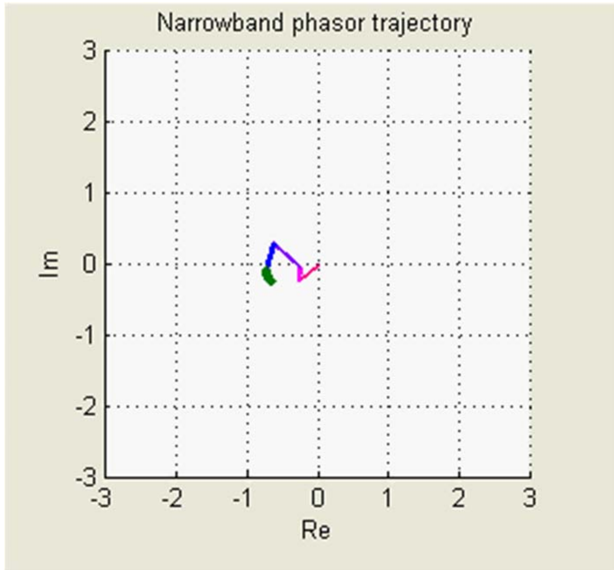




Superposition of Multipath Signals with Short-Term Fading

- Depiction of the signals as complex field strengths $\underline{E}_{\text{total}} = \sum_{i=1}^{n} \underline{E}_i = \sum_{i=1}^{n} E_i e^{j\psi_i}$ (2.52)





- Probability density of the resulting field strength depends on the statistical properties of the single signals

Probability Density Functions

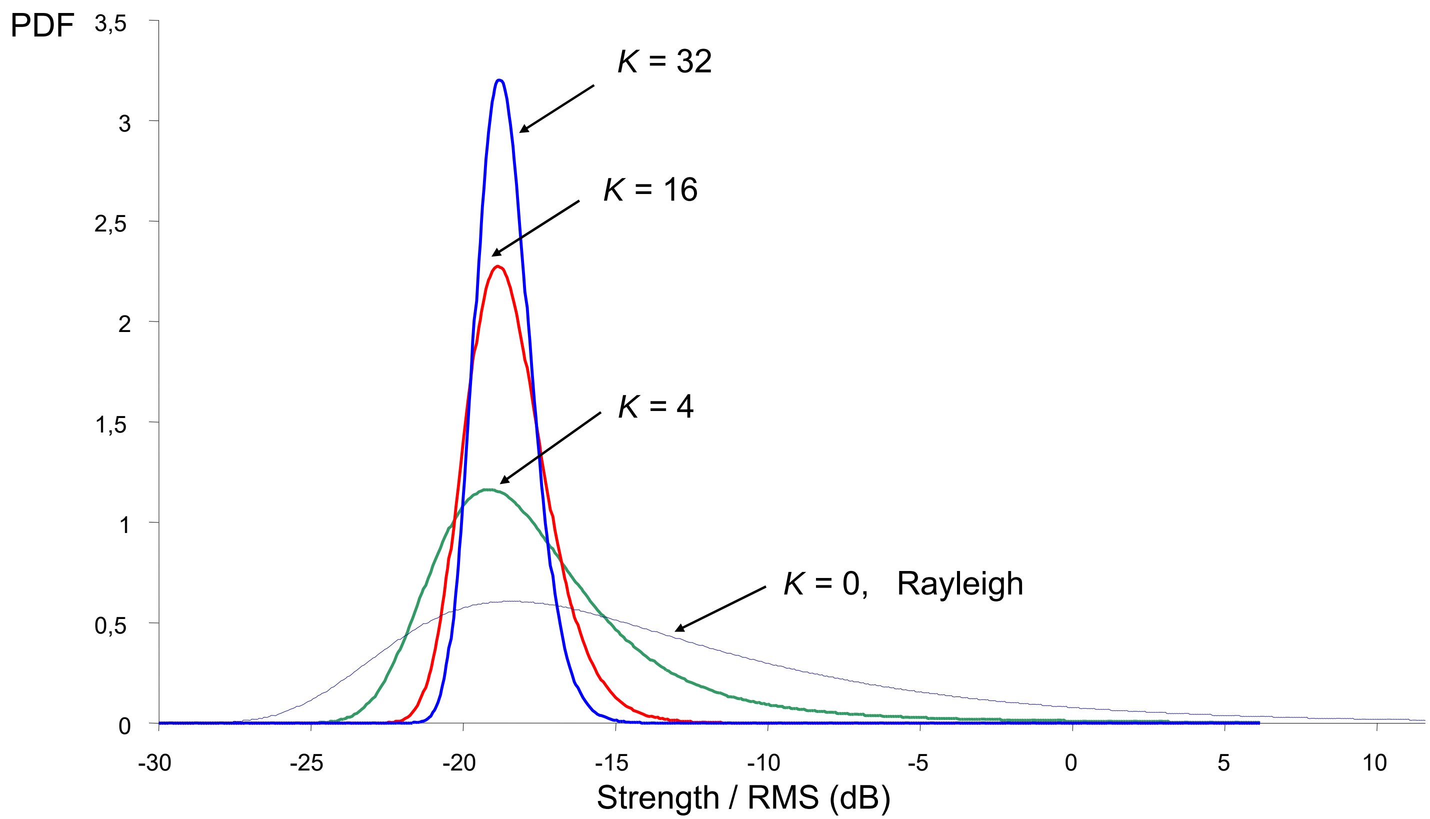
- In case that the field strength indicators of the multipath signals consist of a determined indicator E_1 and many statistically independent indicators E_i (from multipath signals with comparable absolute values and statistically varying phases y_i), for the real part and the imaginary part of E_{total} a two-dimensional Gaussian distribution due to the central limit theorem results.

- For the absolute value of the field strength in dB, a Rice distribution is generally obtained.

$$P(E) = \frac{E}{\sigma^2} \mathrm{e}^{-\frac{E^2}{2\sigma^2}} \mathrm{e}^{-K} I_0\left(\frac{E}{\sigma}\sqrt{2K}\right) \qquad (2.53)$$

with $$K = \frac{\text{power of the determined part}}{\text{power of the multipath signals}} \qquad (2.54)$$

Rice Distribution for Different Values of *K*



Special Cases of Rice Distribution

- 1. Special case: no determined signal, i.e. $K = 0$
  - Rice distribution passes into the Rayleigh distribution

$$P(E) = \frac{E}{\sigma^2} \mathrm{e}^{-\frac{E^2}{2\sigma^2}} \qquad (2.55)$$

- 2. Special case: determined signal is much stronger than the sum of the multipath signals, i.e. $K \rightarrow \infty$
  - Rice distribution passes into the Gaussian distribution

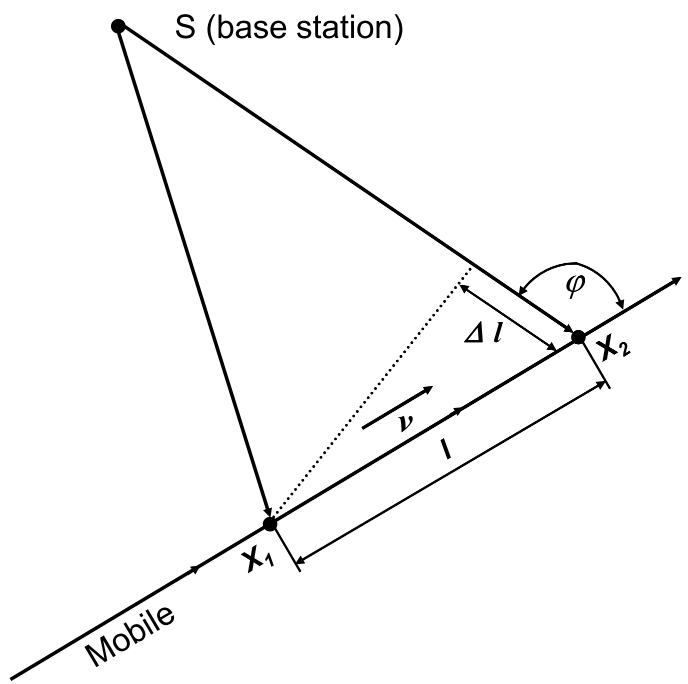
$$P(E) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{-\frac{\left(E-\overline{E}\right)^2}{2\sigma^2}} \qquad (2.56)$$

3.15 Doppler Shift

- In case of a moving receiver, for each multipath signal a Doppler shift occurs additionally.

$$f_\mathrm{D} = \frac{v}{\lambda}\cos\varphi \qquad (2.57)$$

v: speed of the receiver
λ: wave length



- Doppler shift results in a random frequency modulation

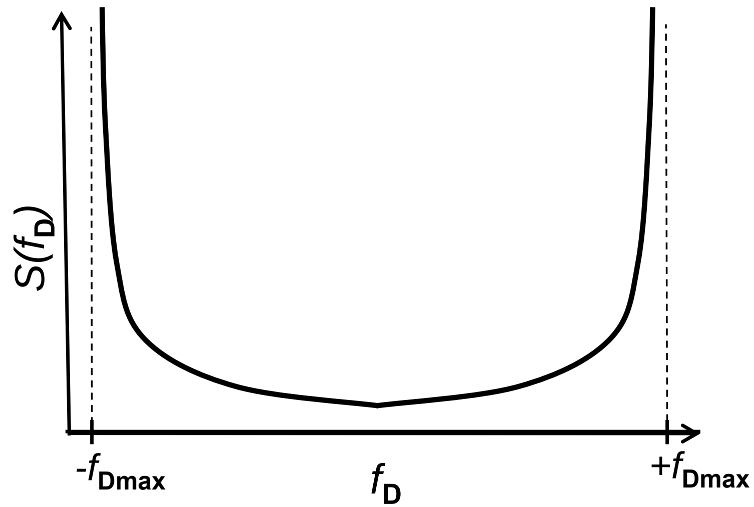
- Since the multipath signals arrive at different angles, a complete Doppler spectrum arises.

Doppler Spectrum (Example)

- The assumption of incoming multipath signals of the same amplitude uniformly distributed in the entire range of angles leads to the so-called Jakes spectrum

$$S(f_\mathrm{D}) = \frac{1}{\sqrt{1-\left(\frac{f_\mathrm{D}}{f_{\mathrm{Dmax}}}\right)^2}} \qquad (2.58)$$

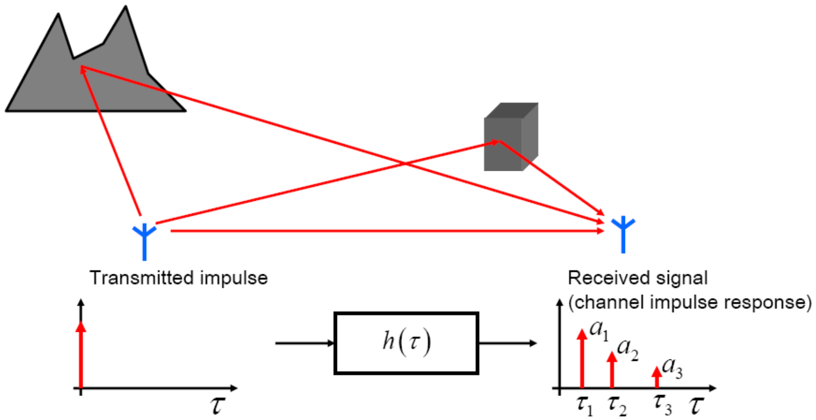
- f_{Dmax} is the maximum occurring Doppler frequency shift



- f_{Dmax} depends on the carrier frequency and determines the maximum velocity where a perfect reception of the signal is still possible.
- The higher the carrier frequency, the lower this maximum velocity

3.16 Broadband Radio Channel Characterisation

- Each multipath signal can be characterised by its amplitude, delay difference to the direct signal and its Doppler frequency shift.



Source: Lecture slides for courses based on textbook A. F. Molisch, „Wireless Communications“

- Due to the movement of the mobile station, the propagation conditions change location-dependently and thus time-dependently => the radio channel becomes time-dependent.

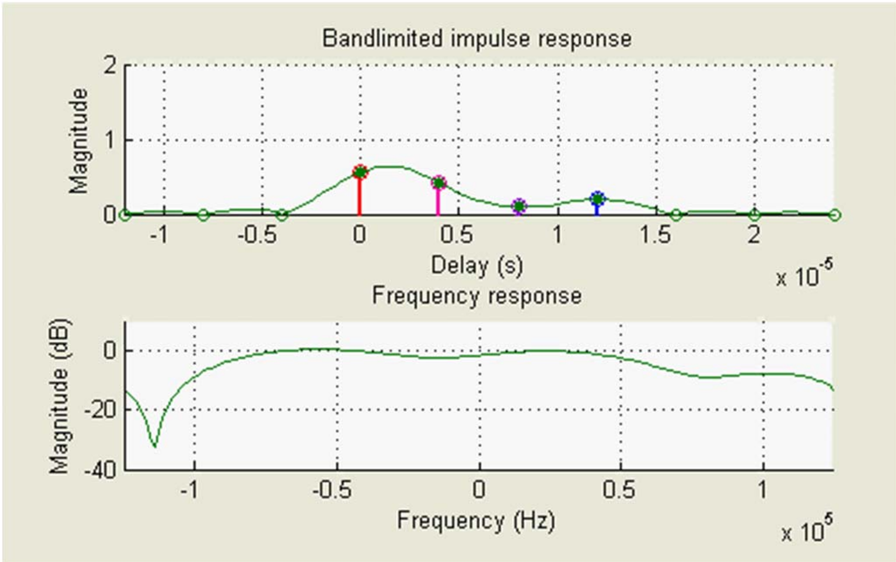
Effects on the Time and Frequency Domain

- The time-dependent impulse response $h(\tau,t)$ forms a Fourier pair with the time-dependent transfer function $H(f,t)$:

$$h(\tau,t) \;\circ\!\!-\!\!\!-\!\!\!-\!\!\bullet\; H(f,t) \qquad (2.59)$$

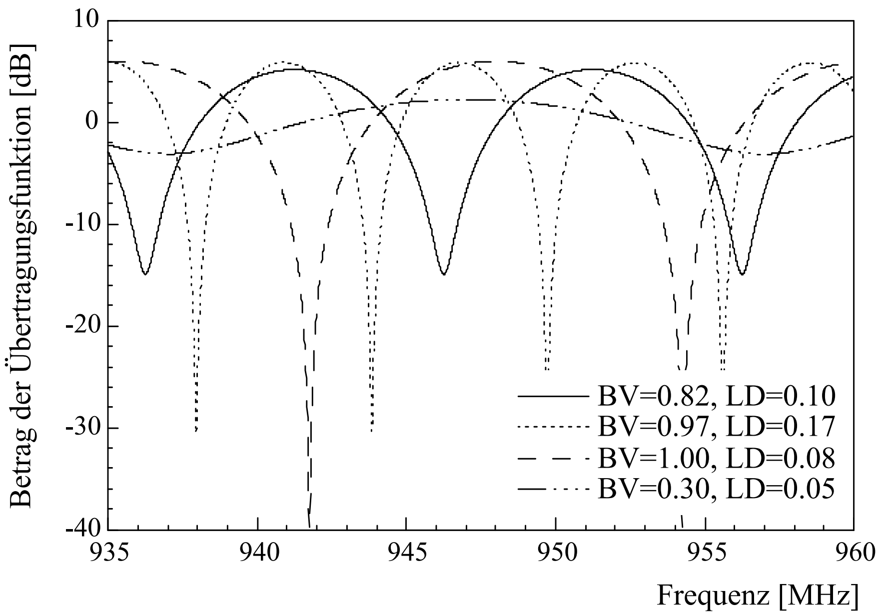
$h(\tau,t)$

$H(f,t)$



Characteristics of the Transfer Function

- Constructive and destructive interferences arise with different frequencies.



Special case of the two-path propagation
BV = a_2/a_1
LD = $\Delta t/\mu s$

Source: N. Geng

3.17 Diversity

- Method for the averaging of fading notches (and interferences) are called diversity methods
  - Basic principle of all diversity methods: Redundant information arrives at the receiver via statistically independent radio channels.

- Time diversity
  - The data to be transferred are split into blocks of a definite length that are transferred temporally one after another.

- Frequency diversity
  - Averaging of the frequency-dependent short-term fading in the frequency range, e. g. through large transmission bandwidth or by using frequency-hopping methods.

- Antenna diversity
  - Reception of the signal with several antennas (direction, polarisation and space diversity)
  - In the following, different antenna diversity methods are explained.

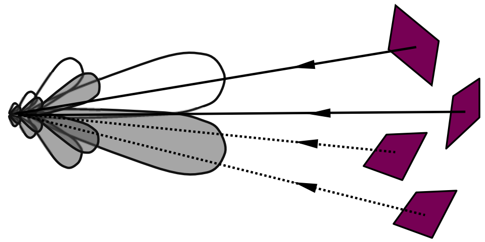
Direction Diversity

- The multipath signal starting from the MS arrives at the BS from different directions with different fading behaviour.

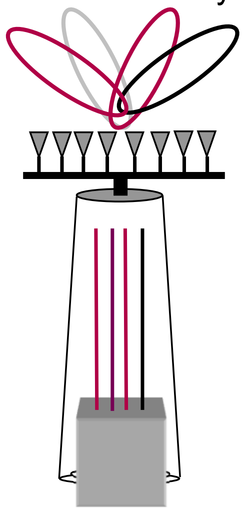
- By application of special antenna techniques, firstly separate reception and later combination

- Application for smart antennas providing several advantages:

  - higher antenna gain by bunching
  - reduction of fading
  - capacity gain by reducing interferences



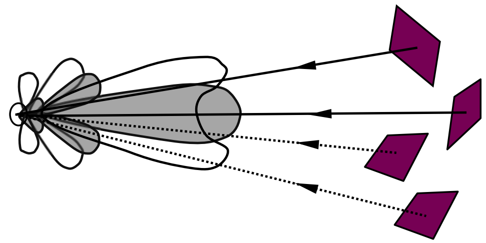
Direction diversity



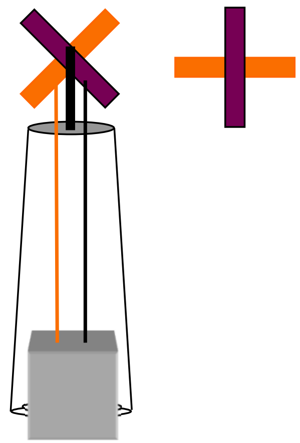
Combination

Polarisation Diversity

- In general, the polarisation changes with scattering processes.
- In environments with very distinctive scattering (e. g. urban areas), signals with different polarisation arrive at the receiver.
- Space-saving possibility for the realisation of diversity



Polarisation diversity as **X** or as cross



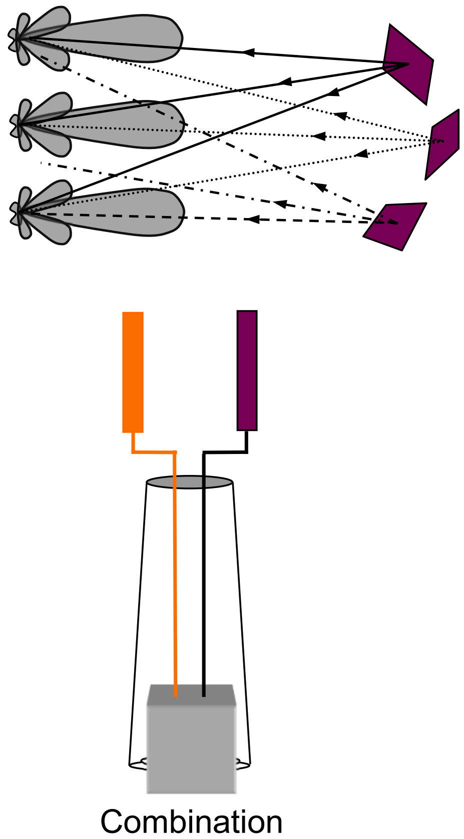
Combination

Space Diversity

- Reception via – normally two – spacially separated antennas

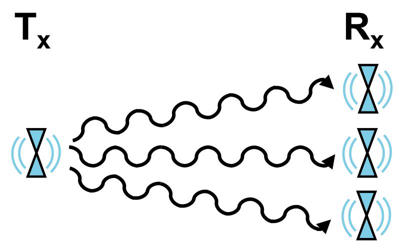
- Efficiency of space diversity depends on
  - number of antennas
  - method for the combination of the single signals
  - distance between the antennas

- Distinction of horizontal and vertical space diversity



Combination Methods

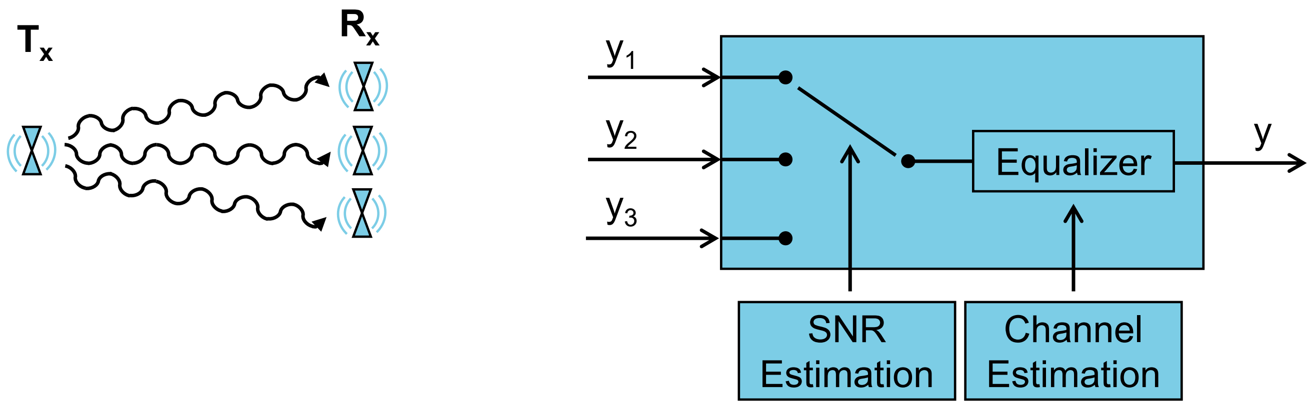
- There are different methods for combination of the single signals received via different radio channels.



- These methods are most commonly used:
  - Selection Combining
  - Maximum-Ratio Combining
  - Equal Gain Combining

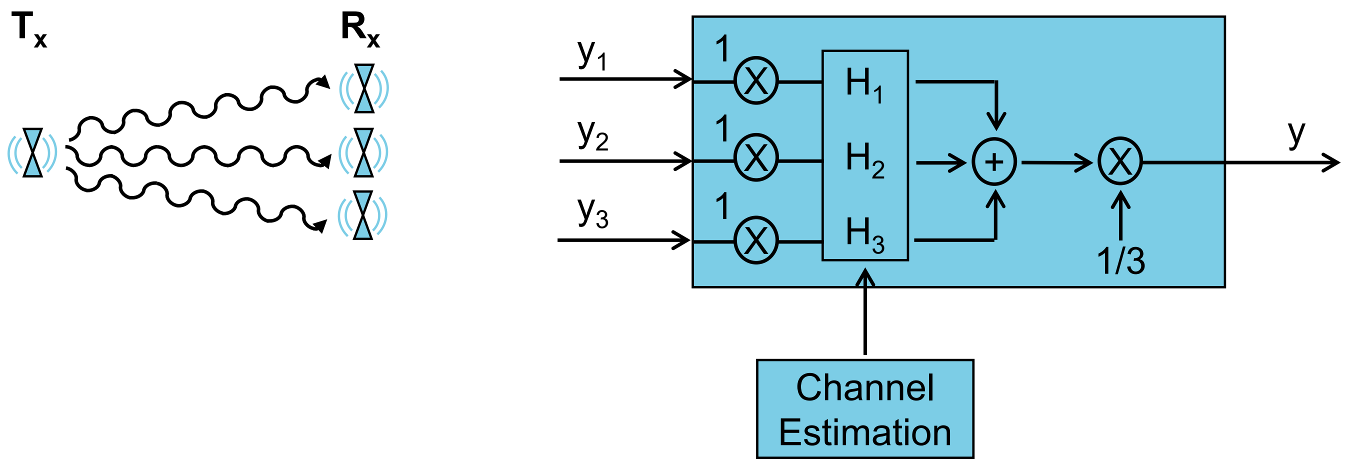
Selection Combining

- Selection of a transmission channel
- Selection criterion: SNR conditions of the channels



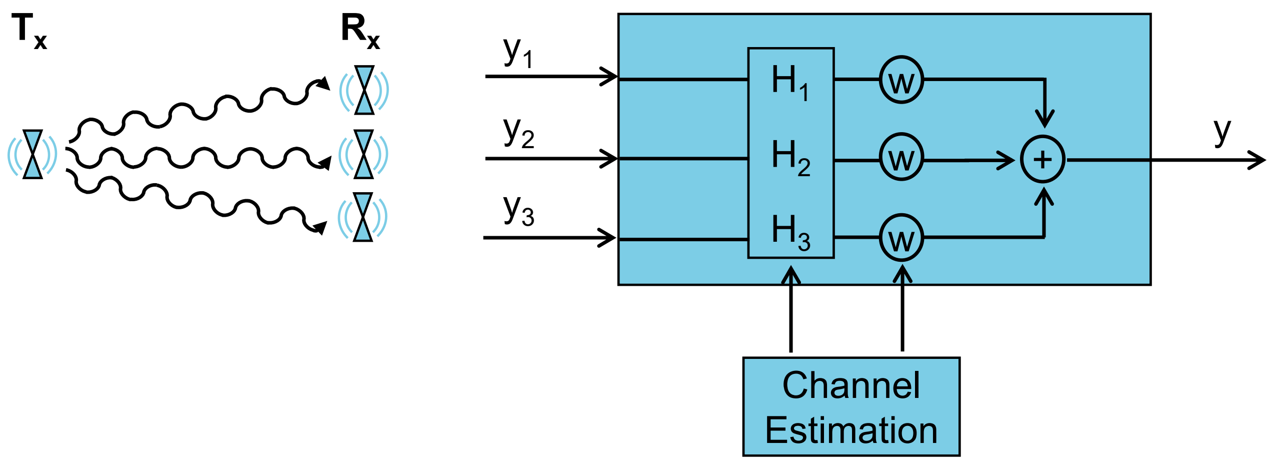
Equal Gain Combining

- All receive signals are considered.
- All channels have the same weighting factor.

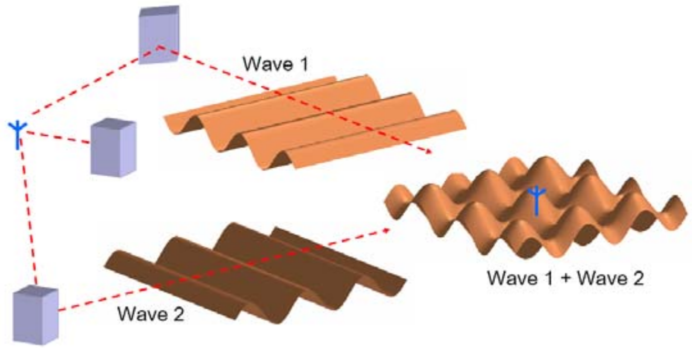


Maximum-Ratio-Combining Method

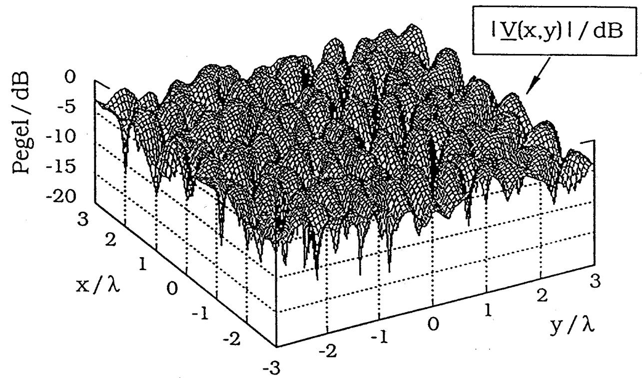
- All receive signals are considered.
- Weighting depends on the channel estimation.
- Sum of the weighting factors = 1



Example of Space Diversity

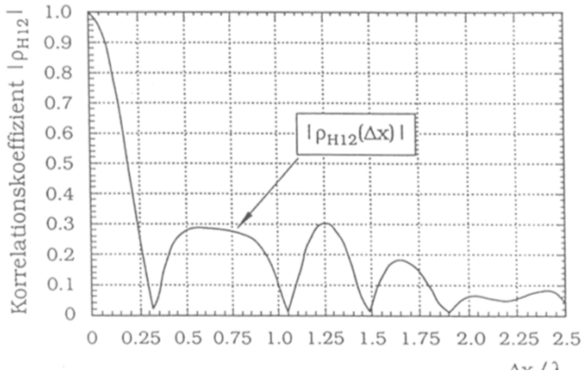


Source: Lecture slides for courses based on textbook A. F. Molisch, „Wireless Communications“



spatial field distribution

- Diversity gain
  - A diversity gain is only possible in case of uncorrelated signals.
  - Diversity gain can only be stated as estimated value for the gain to be expected.



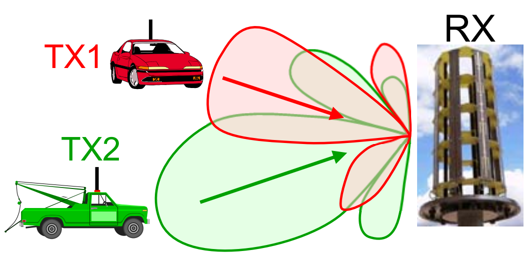
Source: Norbert Geng

envelope cross correlation coefficient

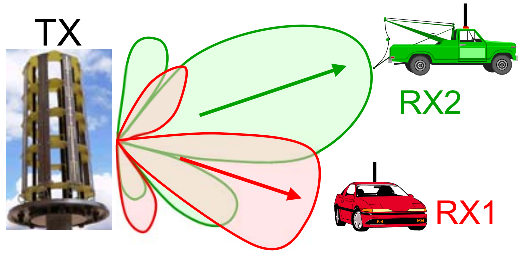
Source: N. Geng

3.18 Multi Antenna Systems

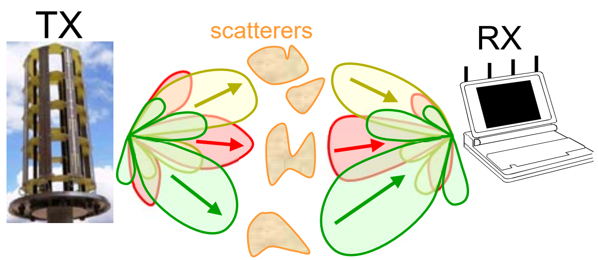
- Rough classification of smart antenna systems
- Input-output classification takes place from the viewpoint of the radio channel



SIMO: Single Input Multiple Output



MISO: Multiple Input Single Output

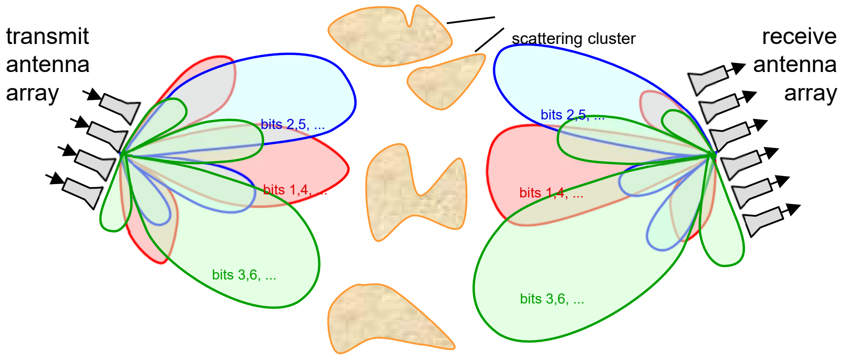


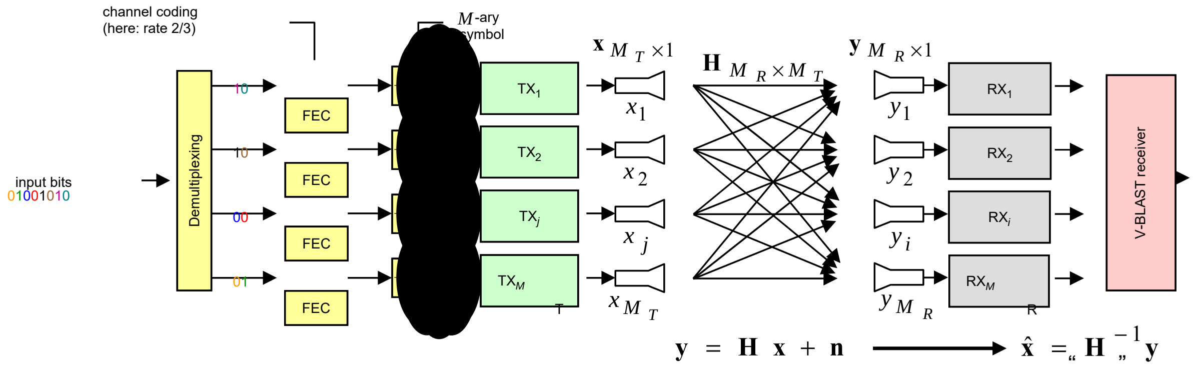
MIMO: Multiple Input Multiple Output

Increase in Capacity by Space-Division Multiplex

- Simplified model for
  optimal space-division multiplex

- Channel capacity increases with
  increasing multipath propagation



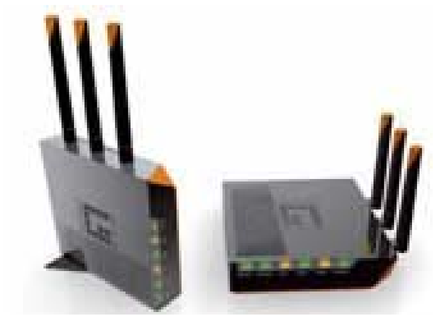


Source: Prof. Dr. Norbert Geng

Examples of MIMO Antennas

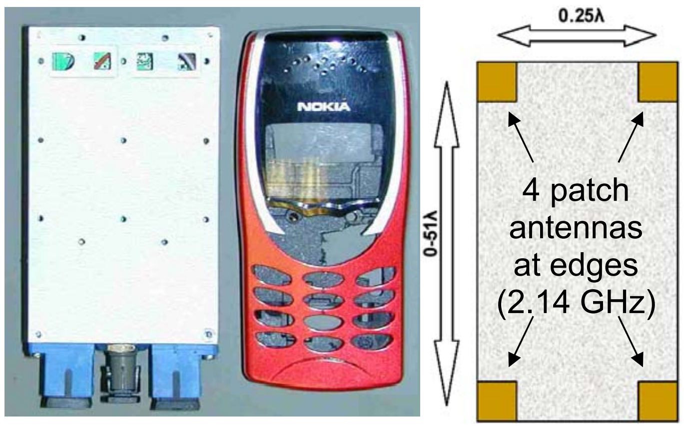
Smart antenna
TD-SCDMA base station
(Roke Manor)

2-element Yagi
for LTE800



Source: http://www.chip.de

WLAN router



4-Element
MIMO terminal
(Univ. of Aalborg
and Nokia)

3.20 Link Budget

- Available power at the output of the receiving antenna under ideal conditions:

$$P_{\mathrm{dBm,R}} = P_{\mathrm{dBm,T}} + G_{\mathrm{dBm,R}} + G_{\mathrm{dBi,T}} - L_{\mathrm{dB,F}} \qquad (2.60)$$

- Required minimum received power level at the input of the receiverf P_{rmin} (corrsponds noise level + required signal-to-noise-ratio)
- Require´ment on isotropic path loss $L_{dB,F}$ under real conditions:

$$L_{\mathrm{dB,F}} \leq L_{\mathrm{dB,F,max}} = P_{\mathrm{dBm,T}} - P_{\mathrm{dBm,R,min}} + G_{\mathrm{dBi,R}} + G_{\mathrm{dBi,T}} + \text{other gains} - \text{other losses} - \text{safety margin}$$

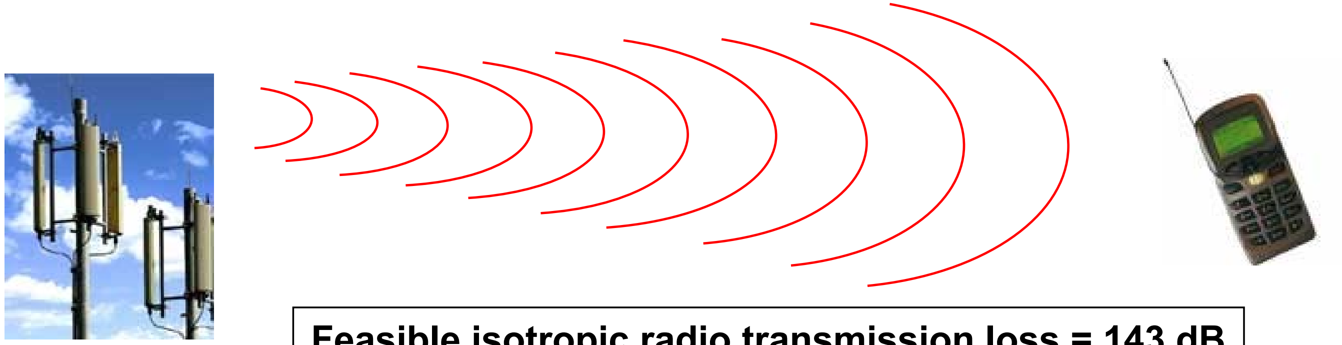
(2.61)

- Other losses: for example lien losses between outpower of the power amplifier and the input of the antenna, imkpedance mismatch

Other Gains

- Other gains: e. g. diversity, antenna preamplifier
- Taking special measures, as mentioned in „other gains“ above, the feasible transmission loss can be increased.
- The link budget has to be set up for UL and DL separately.
- With GSM, a balanced link budget for UL/DL is mandatory.

Link Budget in the Downlink

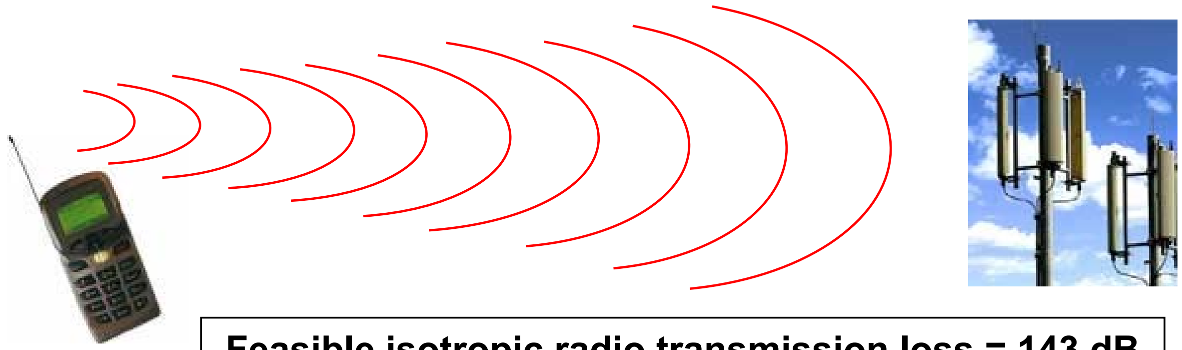


Feasible isotropic radio transmission loss = 143 dB

transmit power	42 dBm	receive antenna gain	0 dBi
cable losses	2 dB	diversity gain	0 dB
transmitter losses	3 dB	losses antenna-human	3 dB
transmit antenna gain	18 dBi	fading margin	6 dB
		interference margin	3 dB
		minimum receive power	-100 dBm

GSM Linkbudget UL/DL; ETSI Technical Report ETR103, GSM03.30

Link Budget in the Uplink



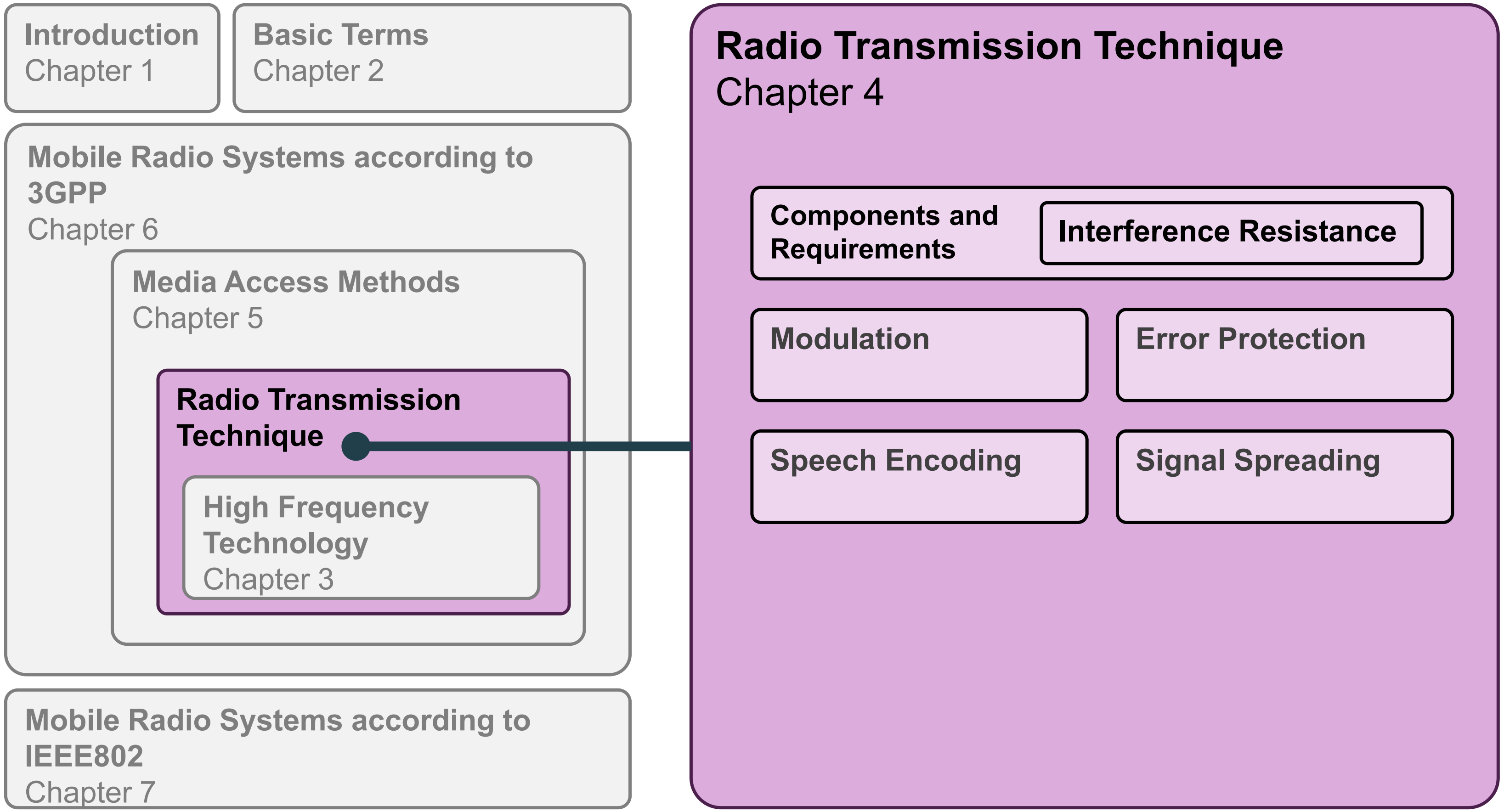
Feasible isotropic radio transmission loss = 143 dB

transmit power	30 dBm
transmit antenna gain	0 dBi
losses antenna-human	3 dB
further losses	0 dB

receive antenna gain	18 dBi
diversity gain	5 dB
cable losses	2 dB
fading margin	6 dB
interference margin	3 dB
minimum receive power	-104 dBm

GSM Linkbudget UL/DL; ETSI Technical Report ETR103, GSM03.30

Chapter 4 – Radio Transmission Technique



4 Radio Transmission Technique
4.1 Basic Requirements

- Application of digital transmission techniques
  - Voice transmission with a data rate of about 10 kbit/s
    - Required bit error rate (BER) < 10^{-3} for acceptable speech quality
  - Data transmission with data rates of up to some Mbit/s
    - Required bit error rate partly < 10^{-6} for acceptable transmission quality

- Due to interferences and variations of the receive level, radiocommunication is considerably more error-prone than wired transmission

- Frequency spectrum is limited

Task of Radiocommunication Techniques

- Warranty of a high net data rate
  - with a low bit error rate,
  - with a high interference immunity and
  - using a preferably small frequency spectrum

- These three objectives are competing objectives which normally cannot be fulfilled at the same time.

- Favourable compromises for the respective mobile radio systems with their different fields of application have to be found.

Components of a Radiocommunication System

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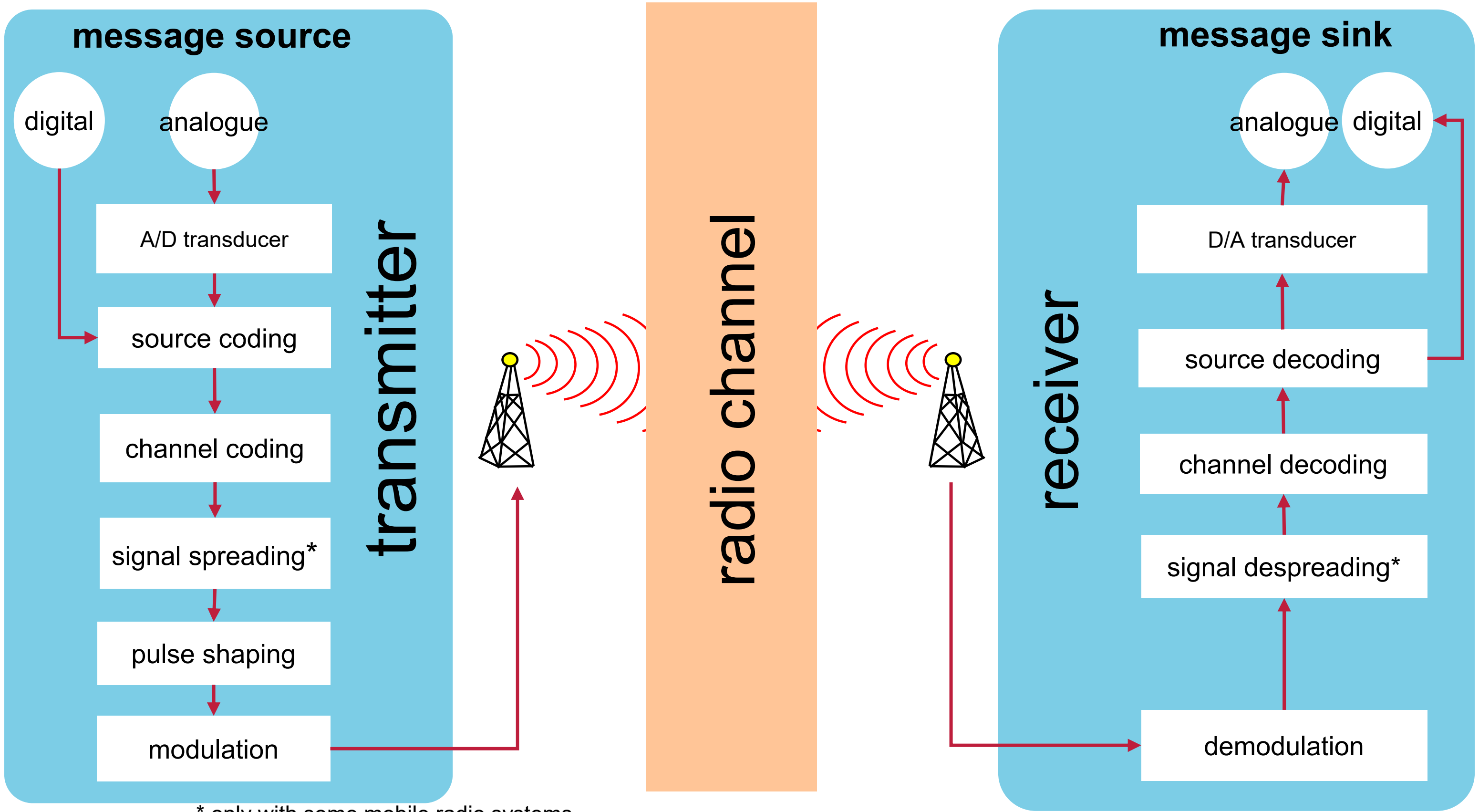


* only with some mobile radio systems

Tasks of the Transmitter (1)

- Steps for the signal transmission (transmit side)
  - A/D conversion
    - Conversion of an analogue signal into a digital signal
  - Source coding
    - Preferably compressed coding of the digital signal
  - Channel coding
    - Adding of redundant bits for the automatic error detection or correction at the receiver
  - Signal spreading (only with some mobile radio systems)
    - Spreading of the signal in the frequency domain to reduce the effects of short-term fading

Tasks of the Transmitter (2)

- Pulse shaping
  - Signal filtering, that serves, inter alia, to avoid unwanted emissions to adjacent channel frequencies or to reduce intersymbol interferences

- Modulation
  - Transformation of the signal into the favoured frequency domain (carrier frequency)
  - Conversion of the signal to an electromagnetic wave

- At the receiver side, the single steps have to be done again **(???, s. deutsches Skript)** in reverse order.

4.2 Interference Immunity

- The relevant interfering sources with mobile radio transmission are:
  - Receiver noise
  - Co-channel and adjacent-channel interferences
  - Intersymbol interferences with multipath propagation

- Receiver noise
  - evolves from random thermal motions of the electrons in the electronic devices of the receiver
    - Spectral noise power density N_0 (noise power per frequency interval Df) is independent from the frequency (white noise)

$$N_0 = \mathrm{k} \cdot T \cdot z \qquad (4.1a)$$

z: noise factor of the receiver (typical values for noise factor Z = 3 dB ...10 dB),

T: ambient temperature in Kelvin,

k: Boltzmann‘s constant (1.38 10^{-23} Ws/K)

Noise Power

- Complete noise power *N* depends on the bandwidth *B* of the receiver input filter

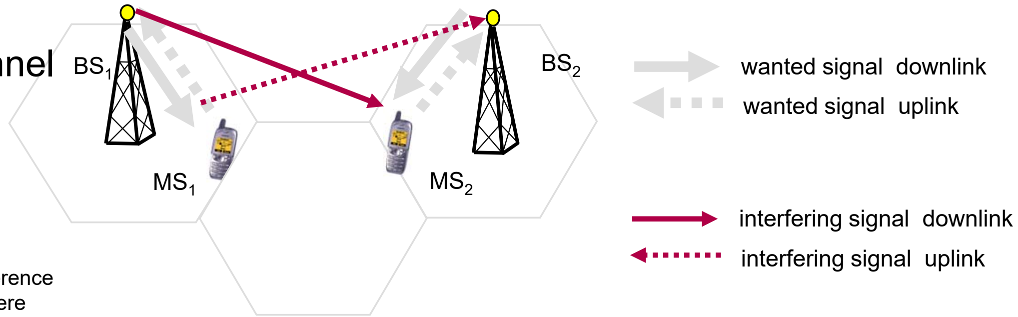
$$N = N_0 B = \mathrm{k}BTz \qquad (4.1b)$$

  - *z*: noise factor of the receiver
  - *T*: ambient temperature in Kelvin
  - k: Boltzmann's constant (1.38 10^{-23} Ws/K)
  - *B*: bandwidth

- Co-channel and adjacent-channel interferences
  - Interferences are particularly caused by subscribers using the same frequency at the same time (co-channel interferences).
  - Due to non-ideal filters, there are also interferences caused by subscribers using adjacent frequencies at the same time (adjacent-channel interferences).
  - This type of noise is called interference.

Co-Channel Interference

example of co-channel interference



For clarity reasons, only the interference BS_1/MS_1 -> BS_2/MS_2 is depicted here

- Overall interference power

$$I_{\mathrm{dB,Ges}} = N_{\mathrm{dB}} + I_{\mathrm{dB}} = N_{\mathrm{dB}} + I_{\mathrm{dB,c}} + I_{\mathrm{dB,a}} \qquad (4.2)$$

with $I_{\mathrm{dB,C}}$*: co-channel interfere in dB*

$I_{\mathrm{dB,a}}$*: adjacent-channel interference in dB*

Consideration of Extreme Cases

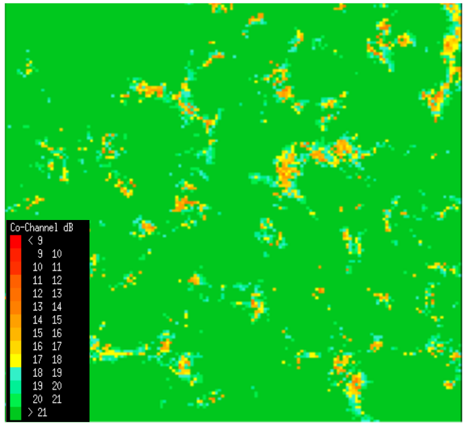
- Noise limitation:
  - Noise power dominates compared to the co-channel and adjacent-channel interference: $N >> I$
  - Typical situation for sparsely populated rural areas, but also for indoor coverage

- Interference limitation:
  - Co-channel and adjacent-channel interference dominates compared to the noise power : $N << I$
  - Typical situation for dense urban areas with small cells and a high rate of telephone traffic

Signal Power and Interference Power

- Ratio of signal power and interference power
  - For the quality of the received signal, the ratio of signal power and interference power is crucial.
  - For this ratio, the abbreviations C/I (carrier-to-interference ratio) for interference limitation and SNR (signal-to-noise ratio) for noise limitation, respectively, can often be found.

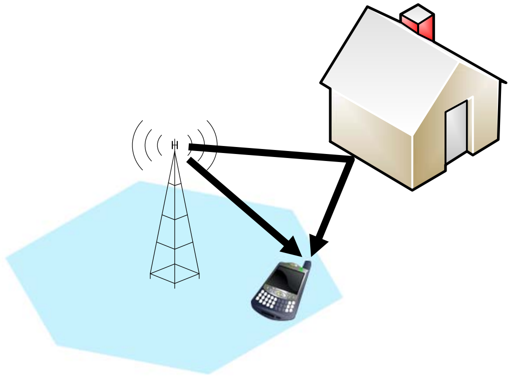
- Interference immunity
  - The interference immunity of a method is described by C/I_{min} and SNR_{min}, respectively, that at least has to be kept to fulfil a required bit error rate criterion.
  - For the determination of C/I, only local mean values (without short-term fading) are considered.

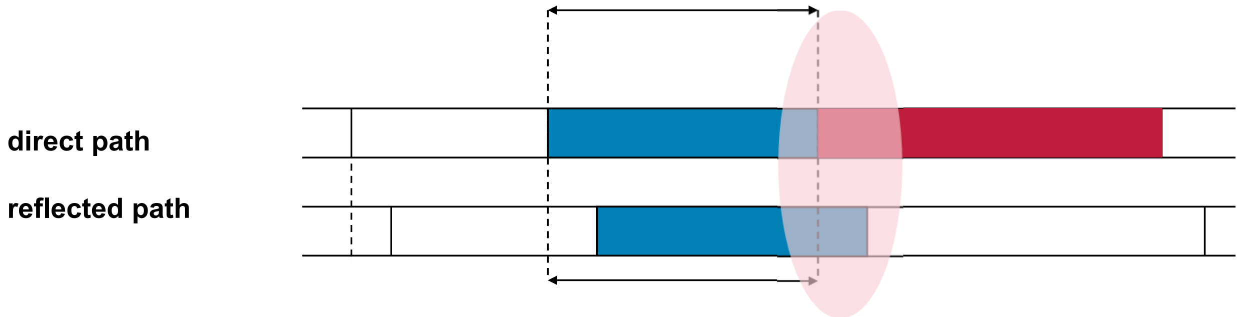


Example of the C/I distribution in a GSM network

Intersymbol Interference

- With multipath propagation, delay differences of the single multipath signals can occur that are in the order of magnitude of the symbol duration (intersymbol interference).
- The longer delay τ of reflected or scattered multipath signals causes intersymbol interference:
  - Symbols of the preceding symbol arriving later interfere with the current symbol arriving via the direct path.





Intersymbol Interference

- Description of the dispersion of the radio channel through the RMS delay spread τ_{RMS}:

$$\tau_{\mathrm{RMS}} = \sqrt{\frac{1}{\sum_{i=1}^{n} P_i} \sum_{i=1}^{n} \tau_i^2 P_i - \left(\frac{\sum_{i=1}^{n} (\tau_i P_i)}{\sum_{i=1}^{n} P_i}\right)^2} \qquad (3.3)$$

τ_i: time delay of the i-th path

n: number of multipath signals

P_i: receive level of the i-th path

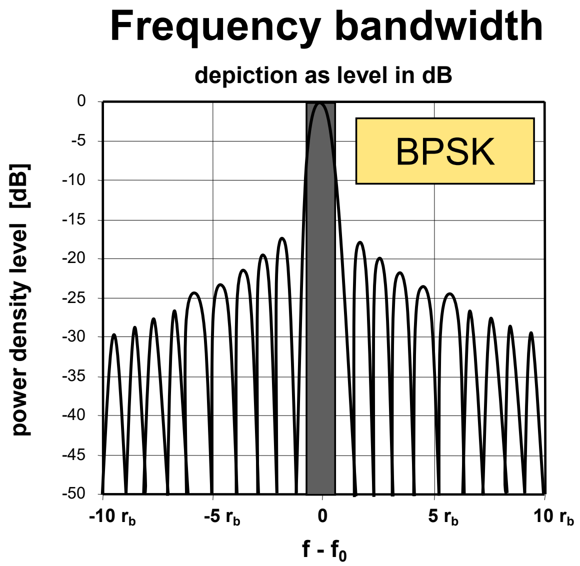
RMS: root mean square

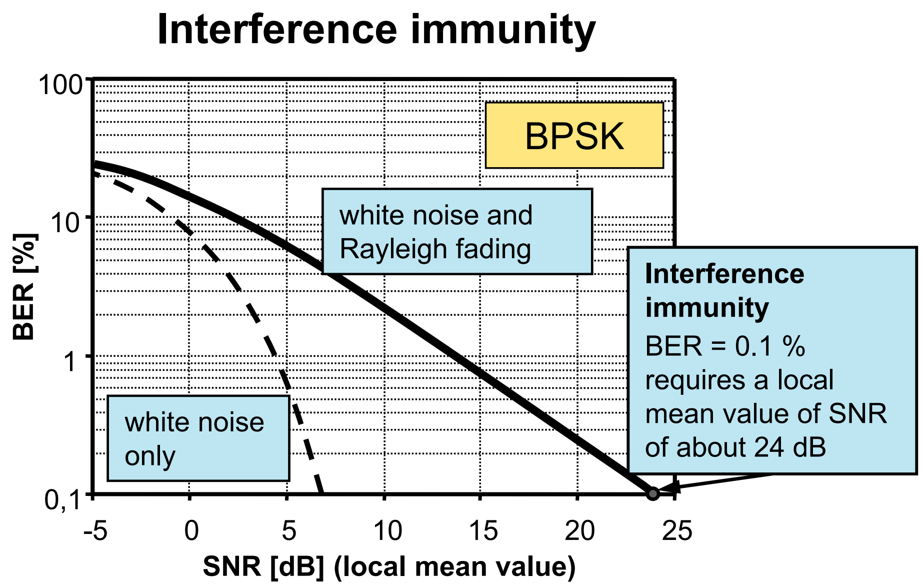
- In case that the value of the RMS delay spread exceeds a system-dependent quantity, it is assumed that error-free reception is no longer possible.

4.3 Modulation

- Modulation: conversion of the real wanted signals into an electromagnetic wave with a high carrier frequency
- Modulation is discussed in detail in the lecture „Signalübertragung II“
- The following digital modulation techniques are normally applied in current mobile radio systems:
  - Binary Phase Shift Keying (BPSK)
  - Higher-Order Phase Shift Keying (M-PSK)
  - Quadrature Amplitude Modulation (QAM)
  - Gaussian Minimum Shift Keying (GMSK)
- Due to fading effects, amplitude modulation is less suitable for mobile communications
- Criteria for the application of modulation techniques in mobile communications
  - Required frequency bandwidth (spectral efficiency, adjacent-channel interferences)
  - Interference immunity with regard to typical interferences

Frequency Bandwidth / Interference Immunity





Quelle: nach C. Lüders, Mobilfunksysteme

The signal power within the bandwidth B is concentrated in the range of the carrier frequency, however, adjacent-channel interferences cannot be neglected.

Problem: In typical radio networks, values of SNR< 10 dB often occur!
$\Rightarrow$ further measures for error protection required

Higher-Order Modulation Techniques

- The spectral efficiency (ratio between data bit rate r_b and required bandwidth B) for simple modulation techniques as BPSK is low:

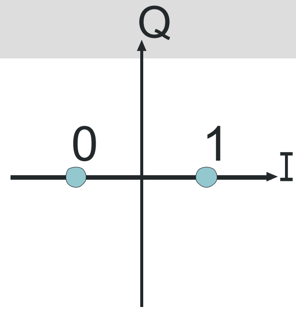
$$\epsilon = \frac{r_b}{B} = \frac{1\text{bit/s}}{1\text{Hz}} = \frac{1\text{kbit/s}}{1\text{kHz}} = \frac{1\text{Mbit/s}}{1\text{MHz}} \qquad (3.4)$$

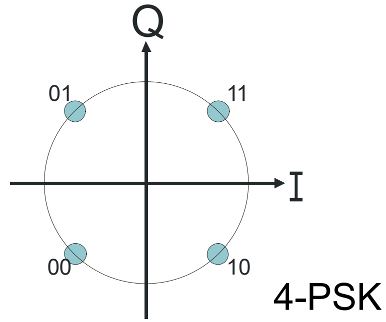
- Enhancement of the spectral efficiency using higher-order modulation techniques (example M-PSK):

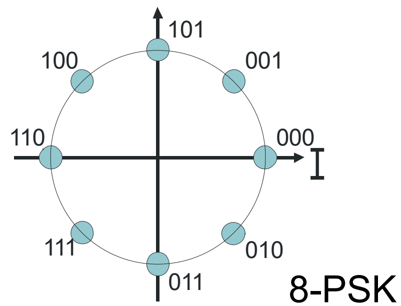
$$\epsilon = \frac{m r_b}{B} = m\frac{1\text{bit/s}}{1\text{Hz}} = m\frac{1\text{kbit/s}}{1\text{kHz}} = m\frac{1\text{Mbit/s}}{1\text{MHz}} \qquad (3.5)$$

  - Bundling of *m* bits to one symbol with $M=2^m$
  - The larger the value for *m*, the better the spectral efficiency but the smaller the interference immunity!
  - Interference immunity depends on the distance between adjacent symbols

=> Balancing between the criteria spectral efficiency and interference immunity

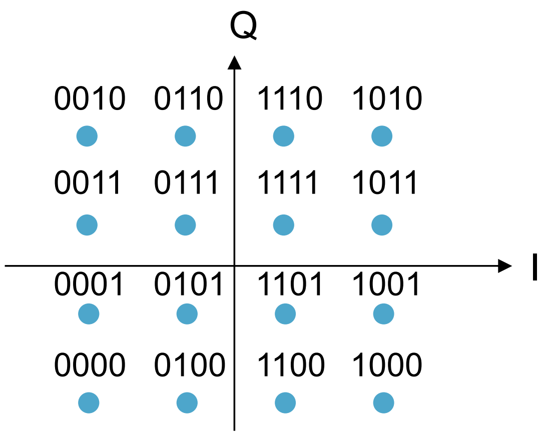




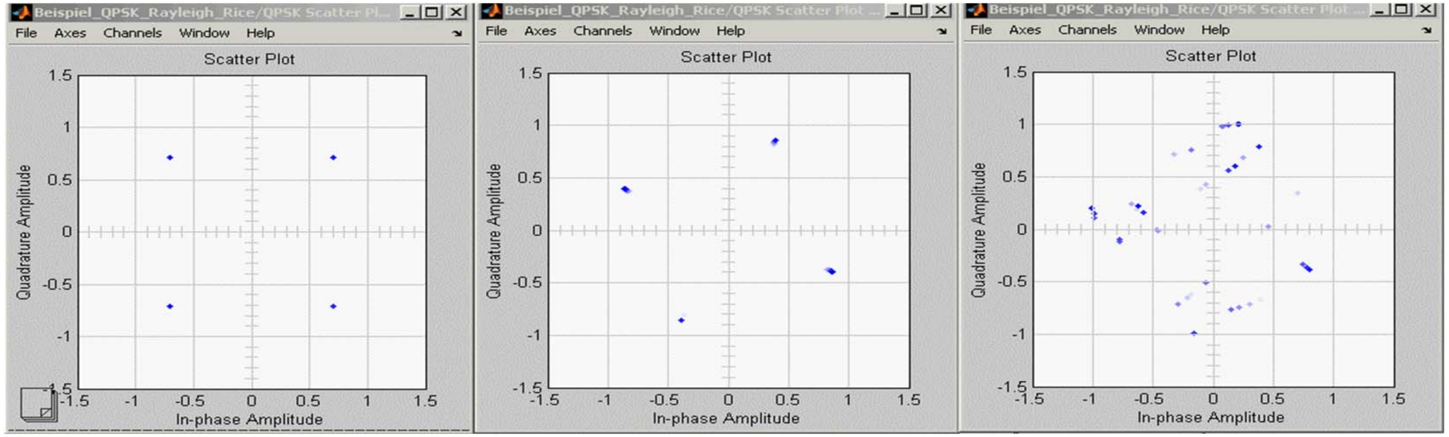


Quadrature Amplitude Modulation (QAM)

- Representation of different symbols by different phase and amplitude values
- Application only in those cases, in which large amplitude variations are not expected.
- In case of only small amplitude variations, however, M-QAM is considerably more fail-safe than M-PSK with the same spectral efficiency.



Example: Effect of Short-Term Fading on a QPSK Signal



initial signal constellation

signal constellation with Rice fading

signal constellation with Rayleigh fading

Gaussian Minimum Shift Keying (GMSK)

- Minimum Shift Keying (MSK):
  - Phase is increased within the bit time linear with the time

$$\varphi(t) = \varphi_0 \pm \frac{\pi t}{2T_{\mathrm{b}}} \qquad (3.6)$$

- Gaussian Minimum Shift Keying (GMSK)
  - Additionally, a Gaussian filter is preconnected to the MSK modulation

$$\varphi(t) = \varphi_0 \pm \sum_i k_i \phi(t - iT) \qquad (3.7)$$

with $\begin{cases} k_i = 1, & \text{in case } \mathrm{d_i} = \mathrm{d_{i-1}} \\ k_i = -1, & \text{in case } \mathrm{d_i} \neq d_{i-1} \end{cases}$ (3.8)

and d_{i-1}, d_i, d_{i+1} representing an infinite bit stream

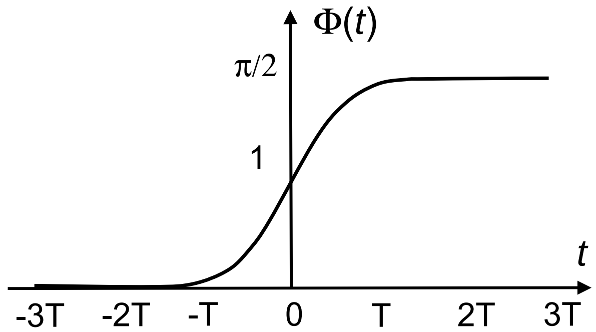
$$\phi(xT) = \frac{\pi}{2}\left(G\left(x + \frac{1}{2}\right) - G\left(x - \frac{1}{2}\right)\right) \qquad (3.9)$$

GMSK (2)

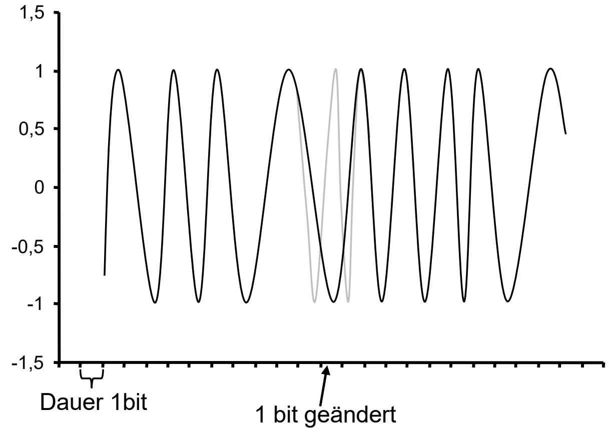
$$T = \frac{48}{13}\,\mu s \qquad (3.10)$$

$$\sigma = \frac{\sqrt{\ln 2}}{2\pi BT} = \frac{\sqrt{\ln 2}}{2\pi 0.3} = 0.441684 \qquad (3.11)$$

$$G(x) = x \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{t^2}{2\sigma^2}}\, dt + \frac{\sigma}{\sqrt{2\pi}} e^{-\frac{t^2}{2\sigma^2}} \qquad (3.12)$$



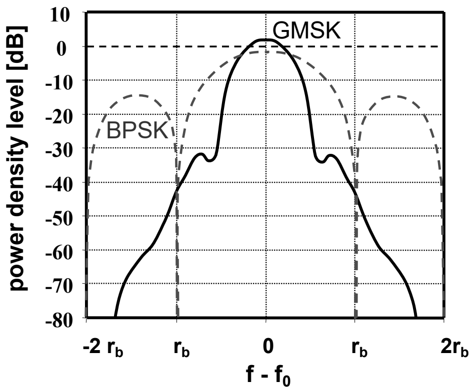
$\Phi(t)$ with GMSK modulation



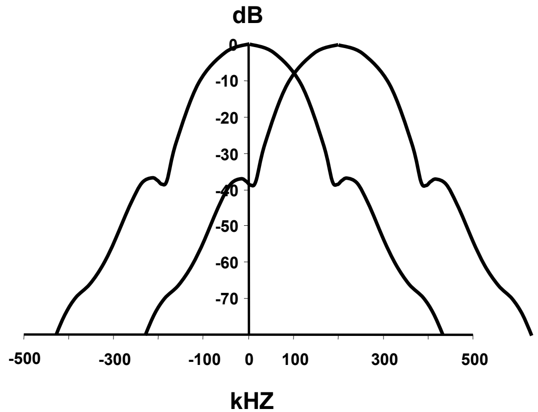
Effect of the alteration of a bit on the modulated signal

Spectral Efficiency of GMSK

- Spectral efficiency at about 1 bit/s/Hz
- No phase shifts
- Stronger decline of the power density spectrum in comparison with BPSK (stronger interference resistance to adjacent channel interferences)
- Interference immunity to BPSK about 1.5 dB worse



$r_b = 1/T_b$: bit rate
f_0: carrier frequency



Source: nach C. Lüders, Mobilfunksysteme

Comparison: spectrum BPSK/GMSK

Adjacent channel interference with GMSK

Application of Digital Modulation Techniques

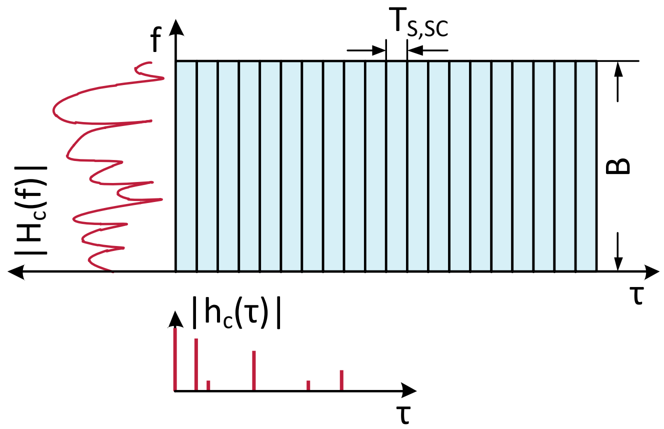
- Application of digital modulation techniques to mobile radio systems:
  - GSM: GMSK, 8-PSK (with EDGE)
  - DECT: GMSK
  - UMTS: QPSK, 16-QAM, 64-QAM
  - LTE: OFDM*, BPSK, QPSK, 16-QAM, 64-QAM
  - 5G: QPSK, 16-QAM, 64-QAM, 256-QAM
  - IEEE 802.11: OFDM*, BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM 1024-QAM
  - WiMAX: OFDM*, BPSK, QPSK, 16-QAM, 64-QAM
  - Bluetooth: GFSK (Gaussian Frequency Shift Keying)

* see section 4.4

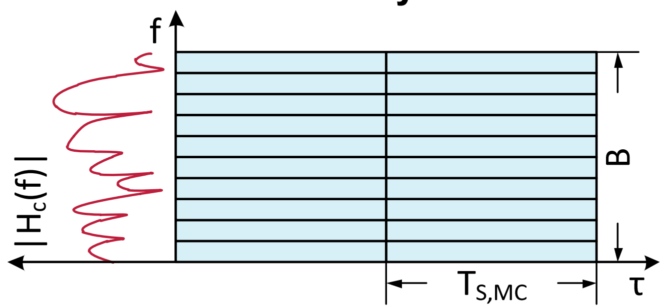
4.4 Orthogonal Frequency Division Multiplexing (OFDM)

- Transition from the single carrier system (SC) to the multicarrier system (MC):
  - With SC systems, an **increase of the data rate** with constant spectral efficiency is only possible if the bandwidth is increased
  - This leads to a **reduction of the symbol duration**, so that intersymbol interferences (ISI) occur
  - Multicarrier systems modulate the information to single **subcarriers that are transmitted in parallel**
  - With constant bandwidth and data rate, **the symbol duration is extended** compared to SC systems
  - The influence of ISI is decreased.

single carrier system

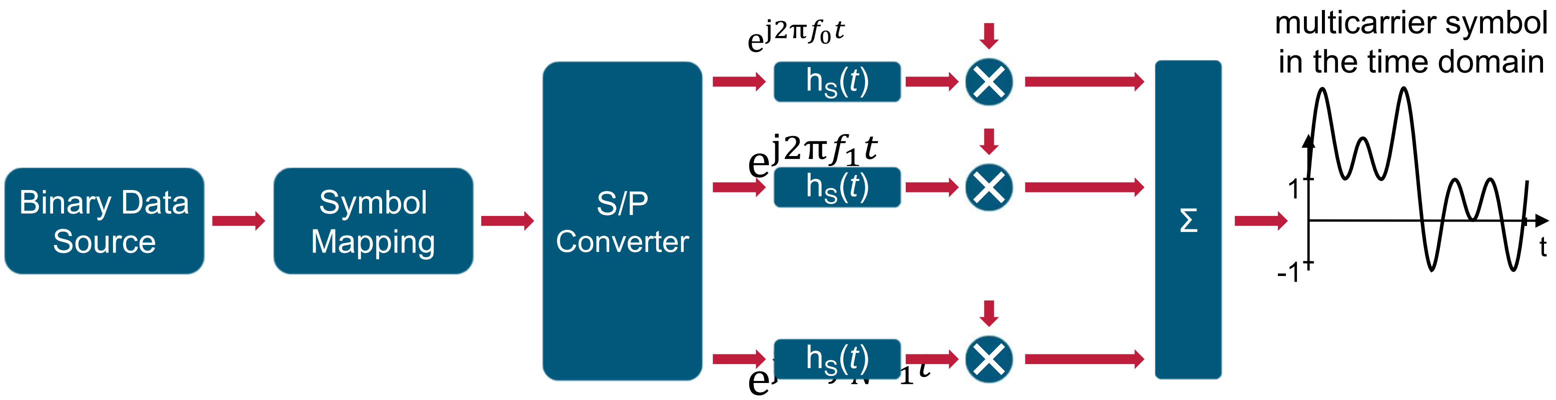


multicarrier system



Realisation of a Multicarrier System

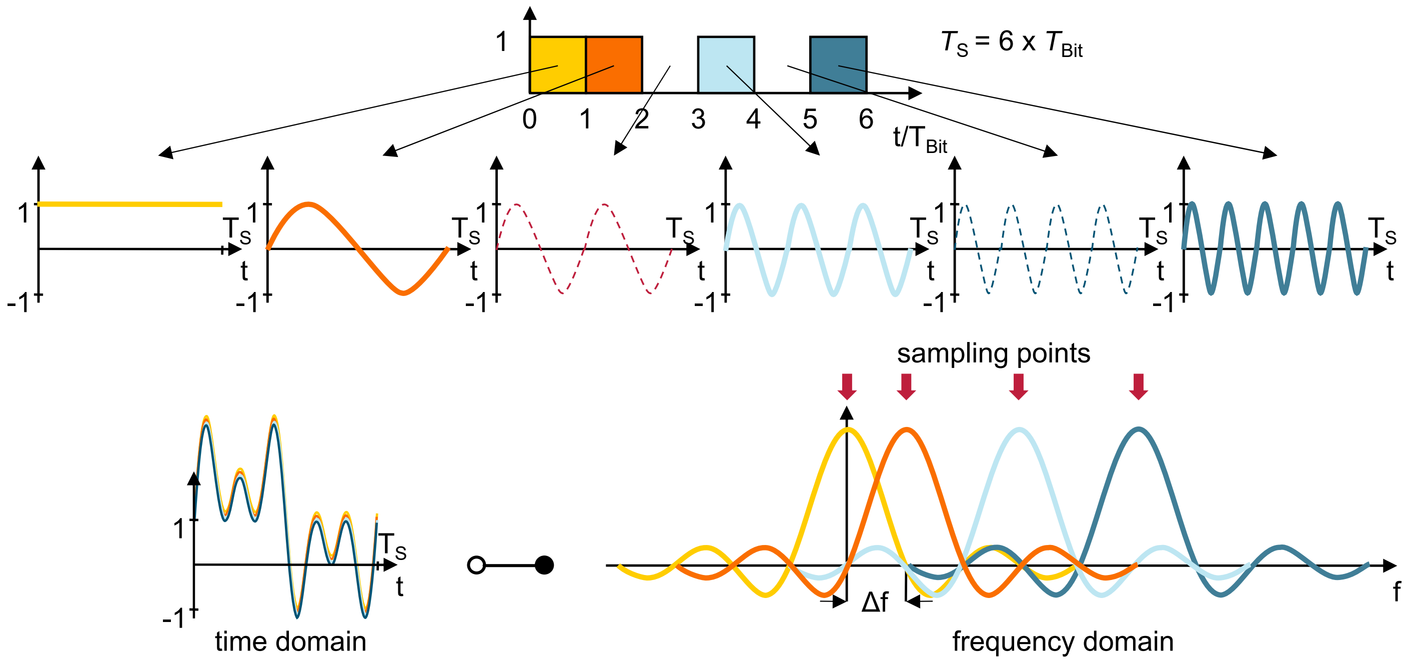
- At first, the bit stream is mapped to complex symbols and then is parallelised
- Each symbol passes a pulse shape filter and is transformed to the respective subcarrier frequency
- After superposition of the single partial signals, a multicarrier symbol is obtained



- With this approach, with a large number of subcarriers the implementation effort would make a practical realisation impossible (costs!)
- By means of the inverse FFT (**Fast Fourier Transform**), the same result of the parallel-connected oscillators may be obtained (efficient realisation possible!)

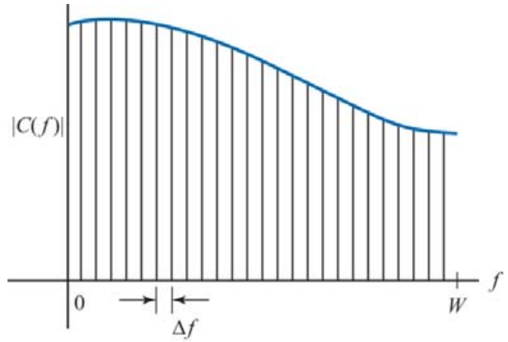
Orthogonality of the Subcarrier

- Further essential requirement for a multicarrier system: interferences between the subcarriers at the sampling points have to be avoided
- As the **subcarriers are orthogonal to each other**, this boundary condition is fulfilled:
  - Pulse shape is rectangular → correspondence with si function in the frequency domain
  - Symbol duration T_S determines subcarrier separation: $\Delta f = 1/T_S$
- Illustration by the following example:



OFDM and Multipath Propagation

- Distribution of the existing channel bandwidth *B* to $K = B/\Delta f$ subchannels in order to reduce the effects of multipath propagation (frequency-selective fading)
- With a small Δf, the characteristics of the frequency response of the subchannels are almost ideal

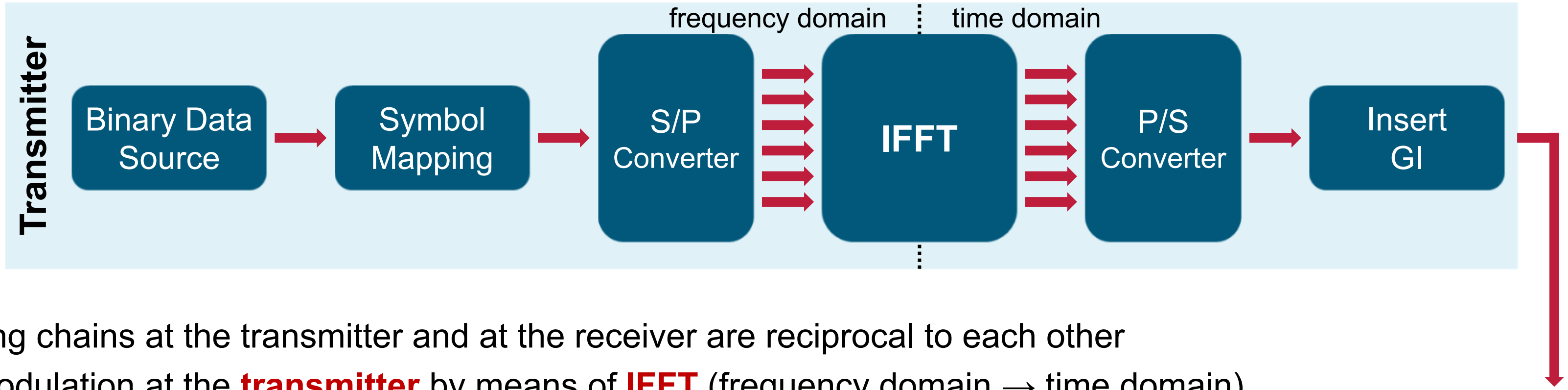


- A carrier is assigned to each subchannel: $x_k(t) = \sin 2\pi f_k t$, k=0,1,2,…,K-1 (3.13)
- Selection of the symbol rate 1/*T* for each subcarrier so that the subcarriers over the symbol interval *T* are orthogonal

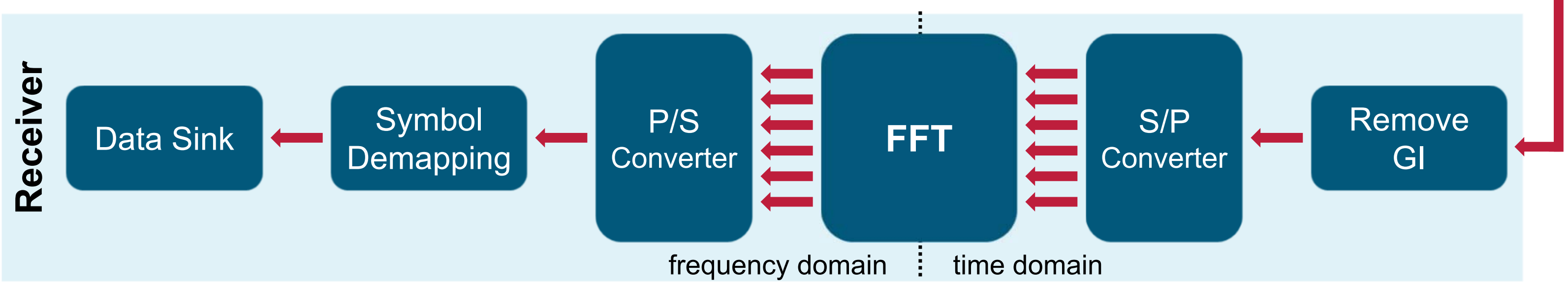
$$T = KT_s \tag{3.14}$$

- T_S: symbol interval of a single carrier system that requires the total bandwidth *B* and transmits the data with the same rate as the OFDM system
- By selection of *K*, *T* can be made much larger than the time of the channel impulse response

Model of the OFDM Transmission Chain in the Equivalent Baseband

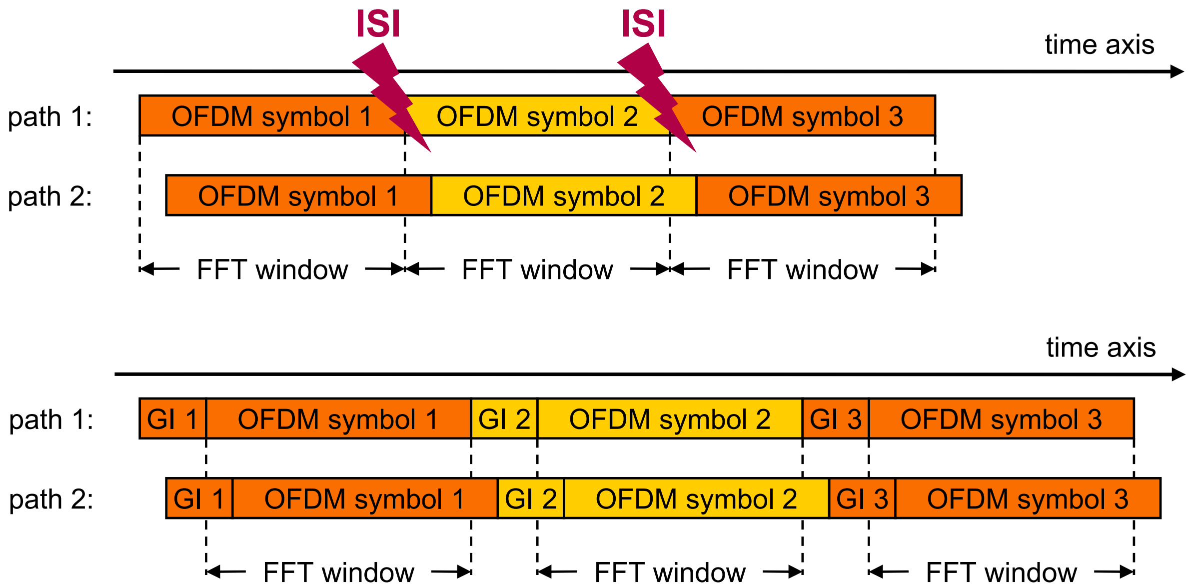


- Processing chains at the transmitter and at the receiver are reciprocal to each other
- OFDM modulation at the **transmitter** by means of **IFFT** (frequency domain → time domain)
- OFDM demodulation at the **receiver** by means of **FFT** (time domain → frequency domain)
- The so-called Guard interval (GI) is dealt with later
- For reasons of clarity, blocks at the receiver such as frequency and time synchronisation, channel estimation, equalisation etc. are not represented



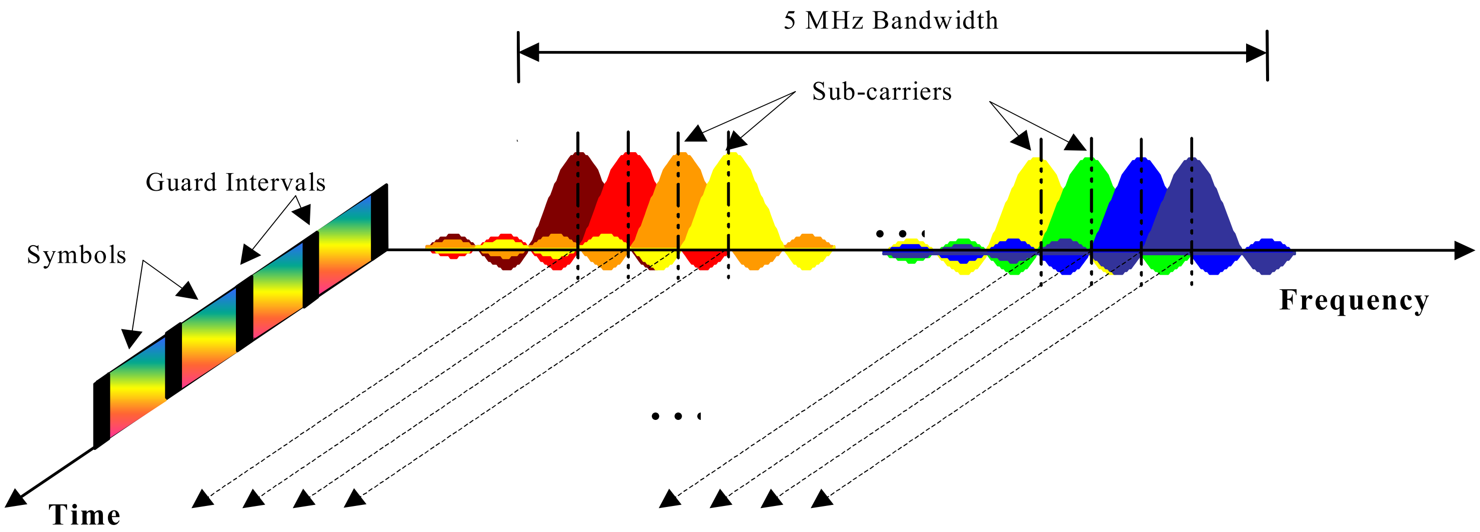
Intersymbol Interferences and the Introduction of the Guard Interval

- Intersymbol Interference (ISI) is caused by superposition of different symbols
- ISI leads to a violation of the orthogonality condition and thus reduces the performance of the system
- By means of the Guard interval (realised at LTE as Cyclic Prefix), ISI can be avoided



- But: GI reduces the spectral efficiency of the system

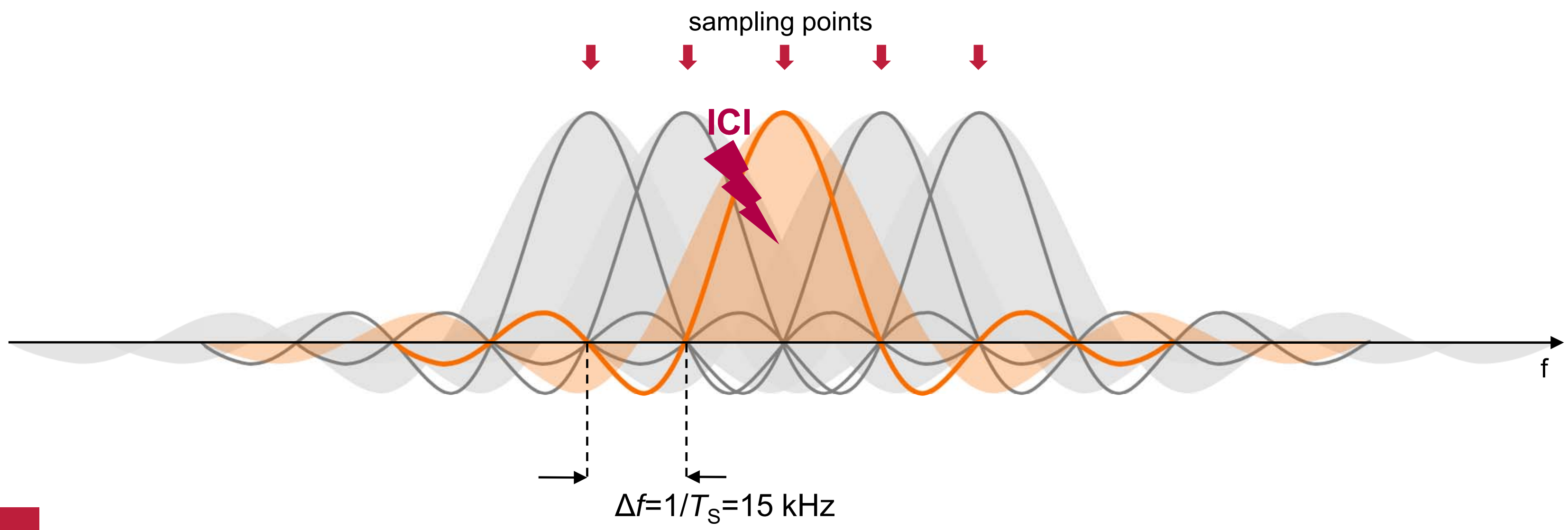
Representation of the OFDM Signal in the Time-Frequency Domain



Source: 3GPP TR 25.892, V6.0.0

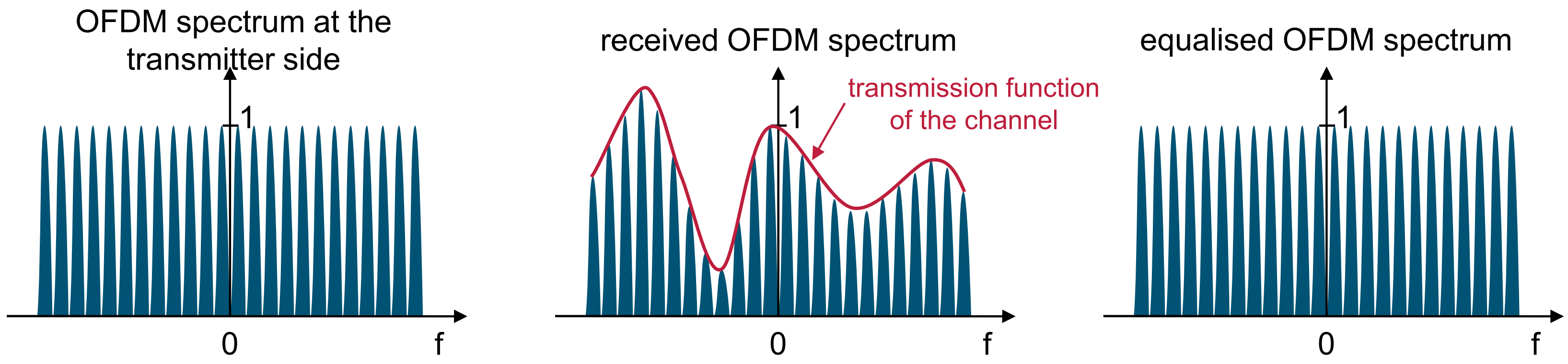
Intercarrier Interference (ICI) and the Subcarrier Separation

- With OFDM, the subcarrier separation is given by the symbol duration
- So as not to affect the performance of the system, interferences between adjacent subcarriers (Intercarrier Interferences, ICI) have to be avoided
- Due to the **Doppler shift** of single multipaths, spectra of the subcarriers can be spread (frequency dispersion)
- With regard to the maximum Doppler spread to be expected, the **subcarrier separation** has to be chosen **sufficiently large to avoid ICI**



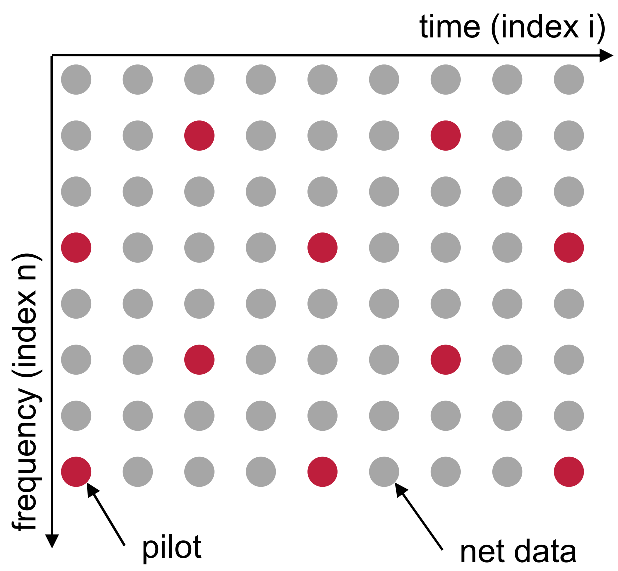
Channel Estimation and Channel Equalisation with OFDM Systems

- By transmission via a fading channel, **distortion of the subcarrier occurs in amplitude and phase**
- For correct decoding, the received signal has to be equalised
- For this, **knowledge of the channel transmission function is required** (channel estimation)
- Since the channel varies in dependence of the time (time variance), the channel estimation has to be repeated and updated at regular intervals



Channel Estimation and Channel Equalisation with OFDM Systems

- Channel estimation and equalisation are efficiently performed in the **frequency range**
- Frequently, in the frequency-time raster at the receiver known **pilot signals** are placed
- The more pilot signals are available, the higher the goodness of estimate (spectral efficiency!)
- Also, blind estimation methods getting along without reference signals are possible (complexity!)



received signal in the frequency range:

$$Y_{n,i} = H_{n,i} \cdot X_{n,i} + N_{n,i} \qquad (3.15)$$

Least-Squares channel estimation:

$$\hat{H}_{n,i} = \frac{Y_{n,i}}{X_{n,i}} \qquad (3.16)$$

Zero-Forcing equalisation:

$$\hat{Y}_{n,i} \stackrel{!}{=} \frac{Y_{n,i}}{\hat{H}_{n,i}} = X_{n,i} \qquad (3.17)$$

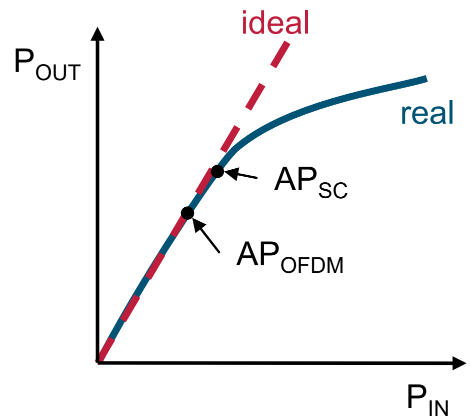
Advantages and Disadvantages of OFDM at a Glance

- Advantages:
  - In partial data streams, data are split to narrow-band subcarriers at a low data rate and transmitted in parallel
  - Considering each subcarrier, the channel is not frequency-selective → **simple equalisation**
  - Resulting overall symbol duration is extended with the same data rate → influence of **ISI is reduced**
  - Subcarriers are closely arranged and orthogonal to each other (do not overlap at the sampling points) → **more efficient exploitation of the spectrum** in comparison to SC
  - Efficient realisation by means of FFT and IFFT, respectively

- Disadvantages:
  - **Strong vulnerability to frequency shift**
    → exact frequency synchronisation
  - **High Peak-to-Average Power Ratio** (PAPR)
    → lower efficiency of the transmit amplifier

$$\mathrm{PAPR} = \frac{P_{\max}}{\bar{P}} \qquad (3.18)$$

principal response curve



4.5 Measures for Error Protection

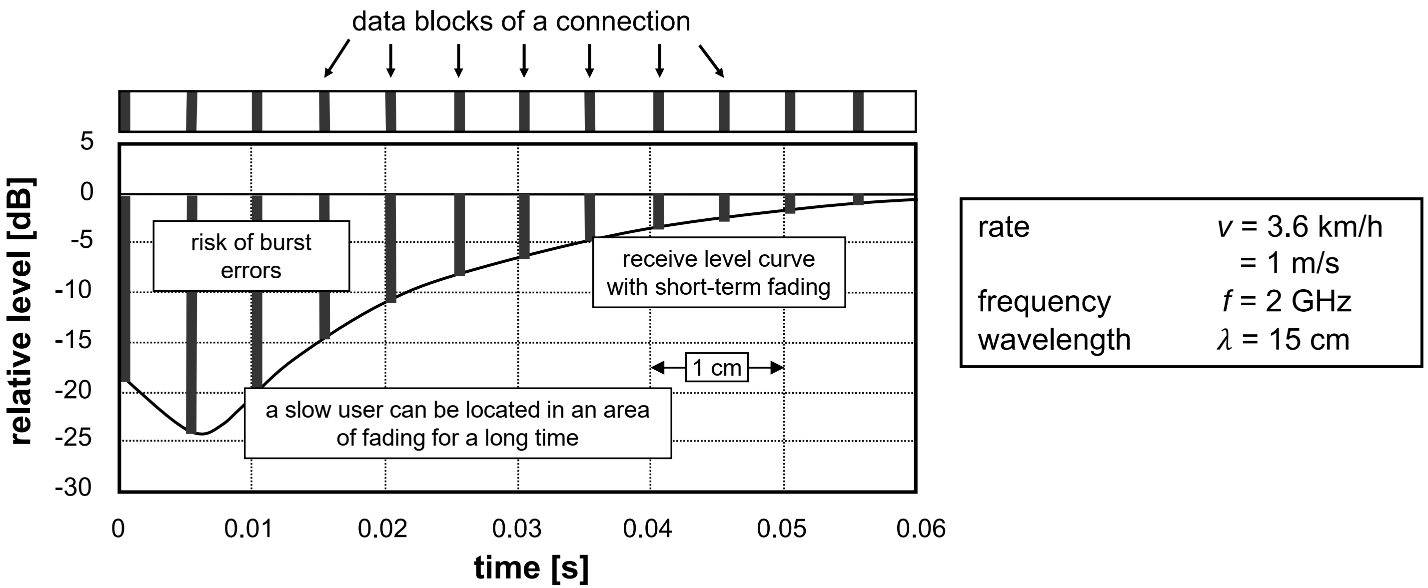
- Channel Coding to improve the interference immunity:
  - Adding of redundancy bits that allow error detection and correction

  - Code rate $$r_{\text{Code}} = \frac{\text{data bits}}{\text{data bits+redundancy bits}} \qquad (3.19)$$

- Channel coding is discussed in detail in the lecture „Codierungstheorie“
- Methods for error protection:
  - Forward error correction (FEC)
    - application of error correcting codes
    - correction of errors carried out independently by the receiver
  - Automatic Repeat Request (ARQ)
    - application of error detecting codes; receiver requests again a data packet recognised as erroneous
  - Hybrid ARQ methods

Burst Errors

- Due to short-term fading, burst errors often occur in mobile communications.



Source: nach C. Lüders, Mobilfunksysteme

- Suitable counter measures are frequency-hopping methods and interleaving, respectively, as well as non-binary codes, as e.g. Reed-Solomon codes.

Forward Error Correction

- Sufficient redundancy is added to a data word so that a certain number of errors can be corrected by the receiver (no return channel required).

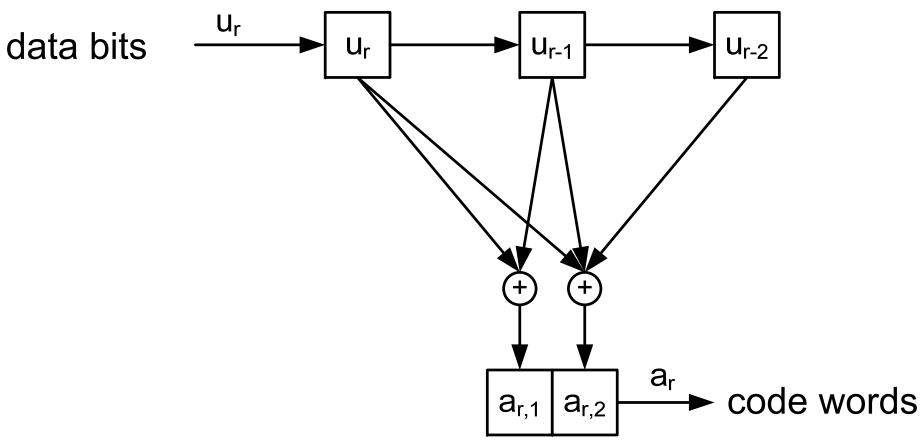
- Differentiation of two code families for forward error correction:

  - Linear block codes
    - Calculation of redundant bits that are also transmitted (see **slide 204**), e. g.
      - Bose-Chaudhuri-Hocquenghem codes (BCH codes)
      - Reed-Solomon codes (RS codes); particularly suitable in case of burst errors
      - Low Density Parity Check codes (LDPC codes)
      - Polar codes (developed in 2009; now part of the 5G standard)

  - Convolutional codes
    - Insertion of redundancy bits by a convolutional operation (see **slide 207**)
    - also provides the basis for the turbo codes (concatenation of two convolutional codes with an interleaver)

Convolutional Coding (1)

- Code with memory
- Code word depends on the active data bit and on several earlier data word positions
- Realisation through shift registers, multipliers and summing units
- Number of registers is characterised as memory length



Code table

u_r	u_{r-1}	u_{r-2}	$a_{r,1}$	$a_{r,2}$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	0
1	0	0	1	1
1	0	1	1	0
1	1	0	0	0
1	1	1	0	1

Convolutional Coding (2)

- Decoding is effected by Viterbi algorithm and Maximum-Likelihood decision
- Convolutional codes work efficiently in case of single errors
- Burst errors are not adjusted by the decoder
- Increase of the code rate by puncturation of convolutional codes:

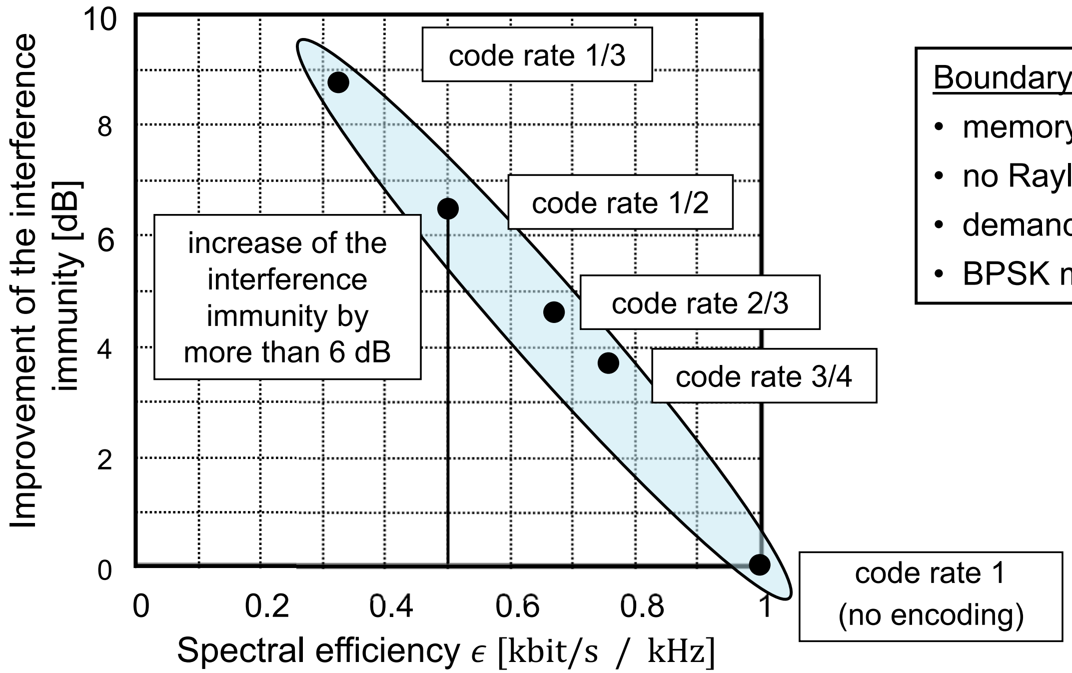
- Cancellation of some encoded bits
- Application: increase of the data rate with the mobile data transmission (e. g. with GPRS)

- Spectral efficiency decreases with the code rate
- Example BPSK modulation

$$\epsilon = \frac{r_{\text{Code}} r_{\text{b}}}{B} = \mathrm{r}_{\text{Code}} \frac{1\text{bit/s}}{1\text{Hz}} \qquad (3.20)$$

4.5 Measures for Error Protection

Coding Gain by Convolutional Codes



<u>Boundary conditions</u>

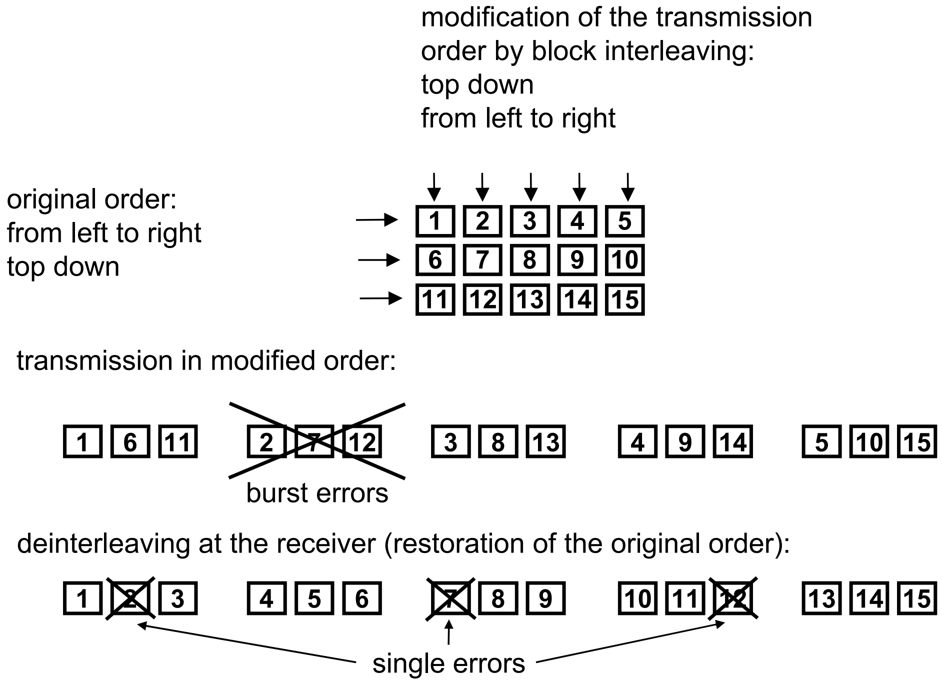
- memory length K=6
- no Rayleigh fading
- demanded BER: 0.1 %
- BPSK modulation

decreasing net data rate ⟷ increasing interference immunity

Source: nach C. Lüders, Mobilfunksysteme

Interleaving

- Re-sorting of the original transmission order after the encoding and before the transmission
- Deinterleaving at the receiver before the decoding => burst errors turn to single errors



Source: nach C. Lüders, Mobilfunksysteme

Error Detection

- With error detection it can be determined whether a received data word is a valid code word or not.
  - no correction of wrongly identified data words
  - The linear block codes employed for error correction can also be employed for error detection.
    - In doing so, the number of detectable errors is usually larger than the number of corrigible errors
  - Data words identified as wrong have to be transmitted again
    - For this, ARQ methods are deployed
- In the use of **forward error correction**
  - the **data throughput** is **constant** and independent of the channel quality
  - **Residual-error rate** due to non corrigible errors **dependent on the channel quality**
- In the use of **error detection**
  - the **data throughput depends on the channel quality due to the repetitions required**
  - Due to repetitions, **residual-error rate** is **theoretically at zero** (if infinitely many repetitions were admitted)

4.6 ARQ Methods

- Blocks recognised by the receiver as erroneous are requested again by the transmitter
- Efficiency in frequency spectrum use, especially in case of very good receive conditions
- Disadvantage: Due to repetitions, incalculable delays can occur => for voice transmission, no application possible
- Return channel between transmitter and receiver is required for sending an acknowledgement
- Transmitter has to maintain a copy of the transmitted packet until it is notified as error-free

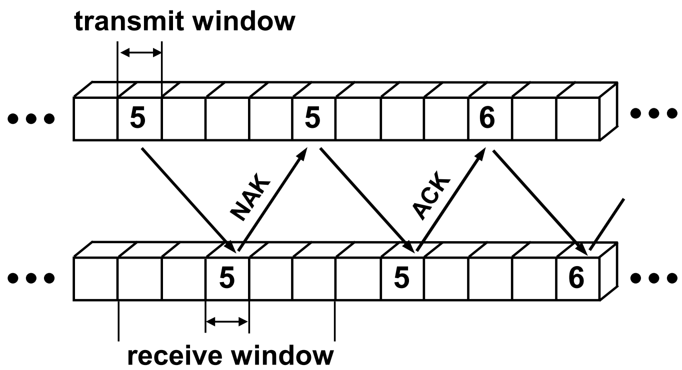
Send-and-Wait ARQ Protocol

- For every data packet received, the receiver has to send back an acknowledgement

  - in case of error-free reception, as acknowledgement (ACK)
  - in case of fault, as negative acknowledgement (NAK)
  - In case of NAK, the packet sent as the latest one has to be sent for the second time
  - New packet is allowed to be sent only after receipt of ACK for the active packet
  - *Round Trip Delay* t_{rd}: minimum delay for an acknowledgement

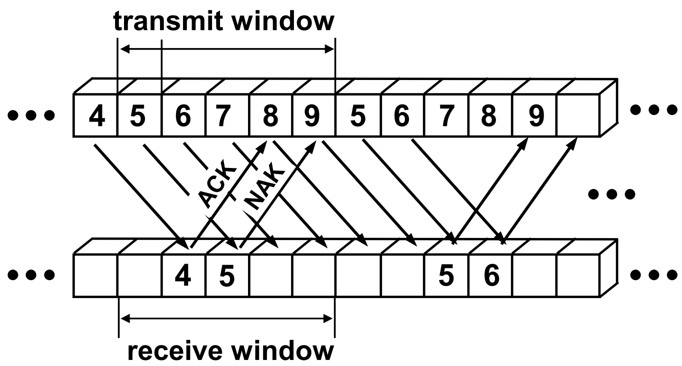
$$t_{\mathrm{rd}} = 2t_{\mathrm{f}} \qquad (3.22)$$

t_f: transfer time for the channel



Go-back-N ARQ Protocol

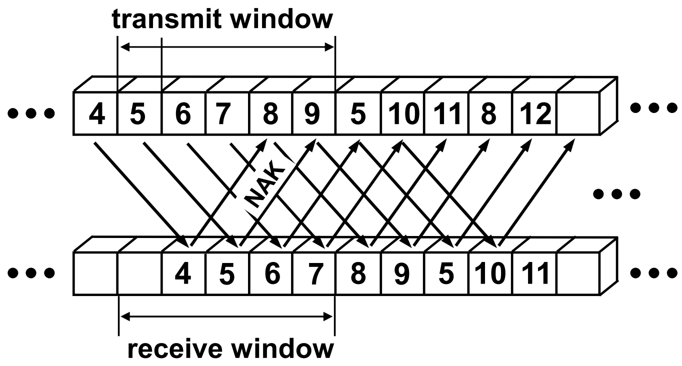
- Transmitter can send several data packets one after the other without waiting for an acknowledgement.
- The maximum number of unconfirmed data packets is defined through the size of the transmit window.
- After receipt of a certain number of data packets (receive window), the receiver sends ACK and NAK, respectively.
- In case of fault, only those packets are transmitted which were sent after the last packet confirmed by ACK.
- In case the receive window > 1, the positive and negative acknowledgements are transmitted piggy-back in a data packet.



Selective-Reject ARQ Protocol

- Prevention of the repetition of error-freely received packets by a more detailed ACK (quotation which packets were transmitted error-free and which were not)

- Larger scope and more complex structure of the ACK messages
- Storage of the packets received in the meantime in a buffer storage
- Intermediate storage of a packet at the receiver until all packets with lower packet numbers have been received correctly
- Transmitter has to buffer the data packets until a positive acknowledgement has been sent.



Data Throughputs

- Send-and-Wait

$$D_{\mathrm{SW}} = \frac{n(1-PER)}{n+t_{\mathrm{rd}}v} \qquad (3.23)$$

- Go-back-N

$$D_{\mathrm{GBN}} = \frac{n(1-PER)}{n+PER\,t_{\mathrm{rd}}v} \qquad (3.24)$$

- Selective-Reject*

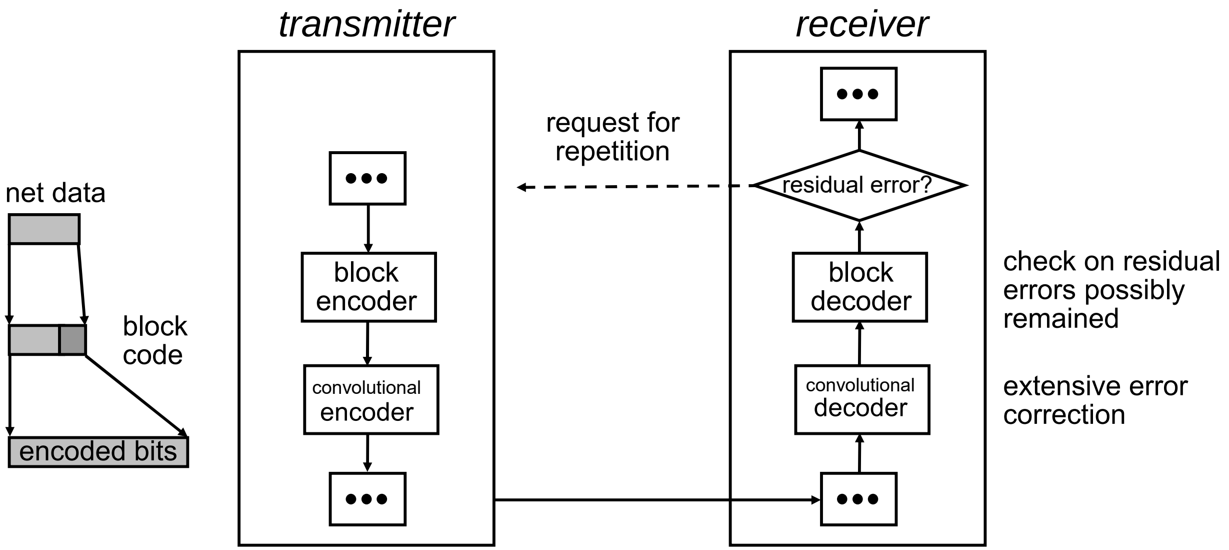
$$D_{\mathrm{SR}} = (1-PER) \qquad (3.25)$$

with n packet length in bit
PER packet error probability
v transmission rate in bit/s

* assumption of an unlimited receive memory

Hybrid ARQ

- Application of combinations of forward error correction and ARQ methods



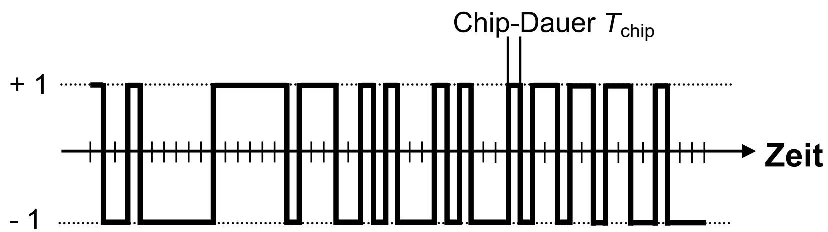
Source: nach C. Lüders, Mobilfunksysteme

- Hybrid ARQ and Link adaption
  - In dependence on the receive conditions, the transmitter chooses one from several convolutional codes *(Automatic Link Adaption - ALA).*

4.7 Signal Spreading (Code Multiplex)

- Superposition of multipath signals results in frequency-dependent fading of the receive level.
- The larger the bandwidth of the signal to be transferred, the higher the interference immunity against those interferences.

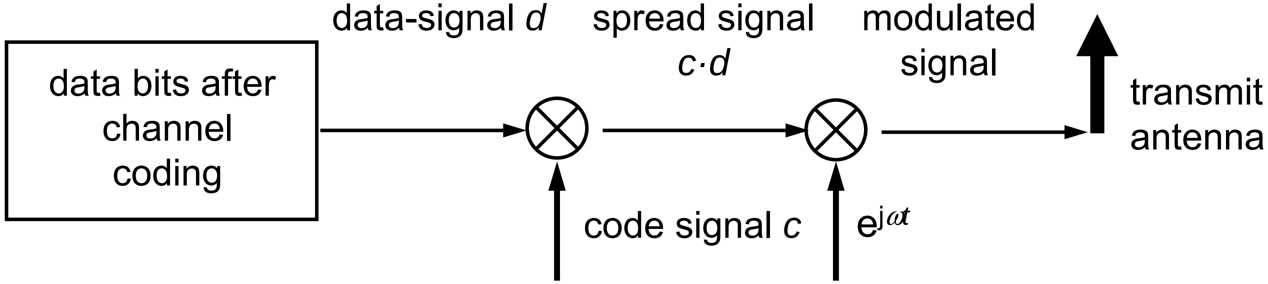
- Application of signal spreading
  - Multiplication of the digital data signal before the modulation with a code signal c



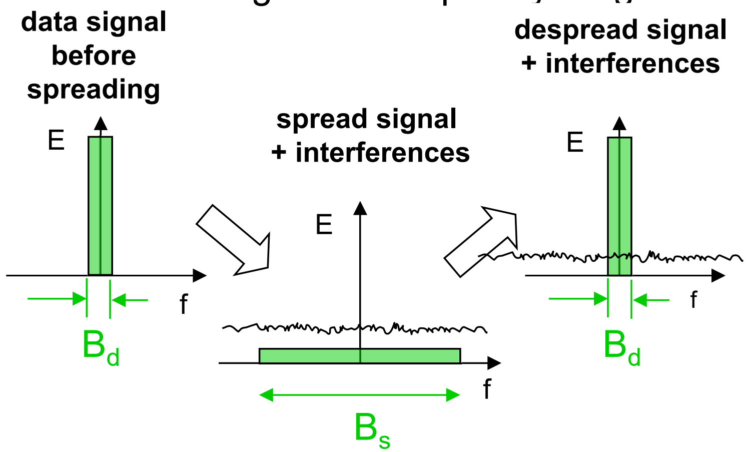
Quelle: nach C. Lüders, Mobilfunksysteme

- Code signal
  - Quasi-random sequences of „-1“ and „+1“ (pseudo-noise sequences and scrambling codes, respectively)
  - Orthogonal codes for variable spreading (Orthogonal Variable Spreading Codes - OVSF)
  - The bits of the code signal are called chips.

Procedure of Signal Spreading at the Transmit Side



- Consequences of signal spreading in the frequency range



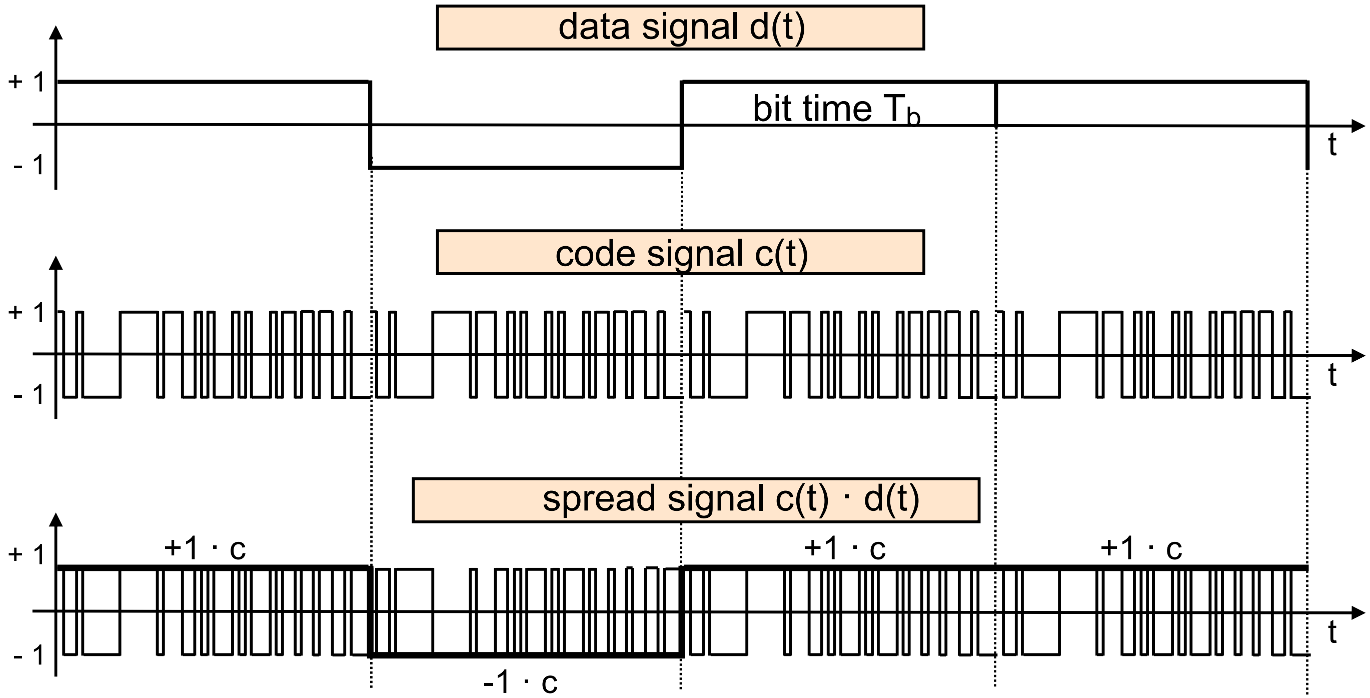
- spread factor

$$SF = \frac{r_{\text{Chip}}}{r_{\text{bit}}} = \frac{T_{\text{bit}}}{T_{\text{Chip}}} \approx \frac{B_S}{B_d} \qquad (3.26)$$

- process gain

$$G_{\text{dB,sp}} = 10 \log SF \qquad (3.27)$$

Transmission Procedure with Code Multiplex



Source: nach C. Lüders, Mobilfunksysteme

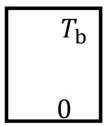
Despreading

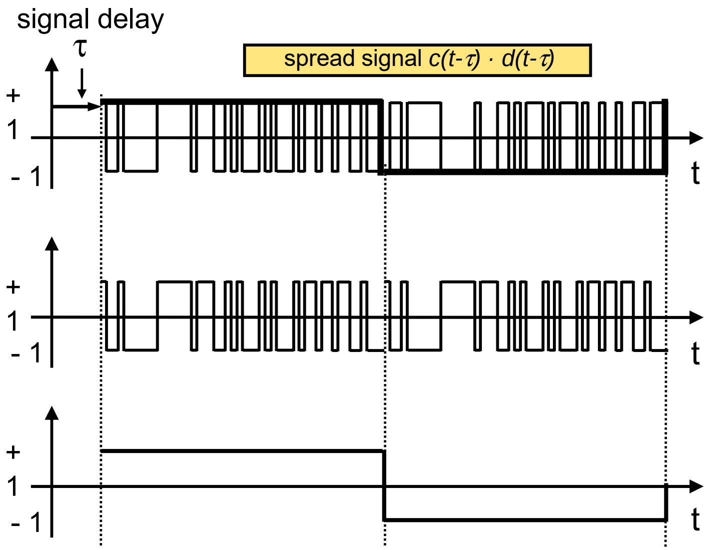
- Multiplication of the demodulated signal by the same signal as with transmission taking into account the signal delay (chip-synchronal)

- Reduction of interferences (other users, deviations of the synchronism) by averaging over the time of the data bit

- Correlator:
  code signal multiplication + averaging

- Multiplication by the code signal $c(t - t_r)$
  with the correct clock pulse: $t_r = \tau$
- Subsequent averaging over the time
  of the respective data bit
- Averaging symbolised by: $\frac{1}{T_\mathrm{b}} \int$





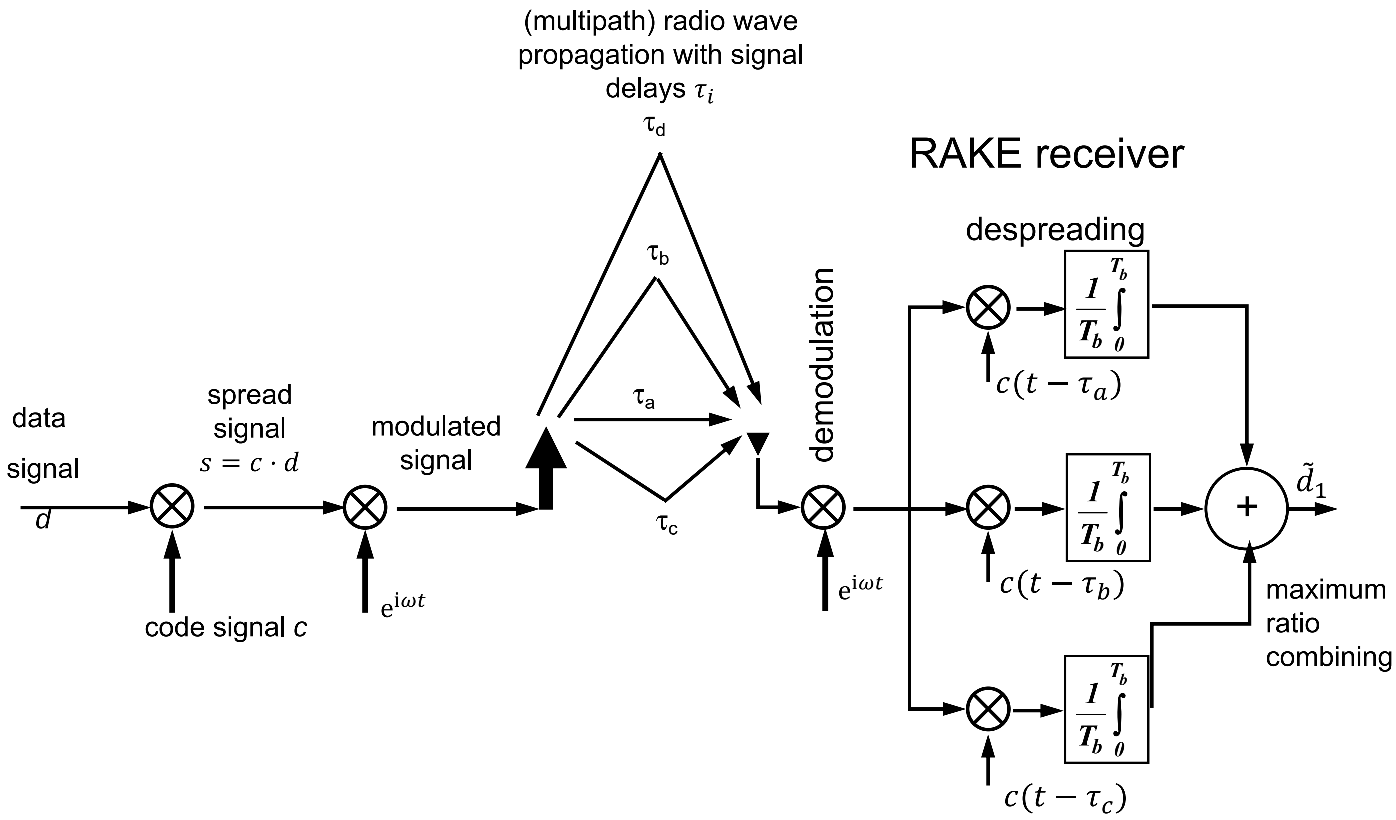
Source: nach C. Lüders, Mobilfunksysteme

Rake Receiver

- Due to multipath propagation, synchronisation on several signal delays required
  - Application of several correlators
  - Channel estimation from the pilot channel
  - Combination of the despread signals by maximum ratio combining
- The structure of a receiver looks like a rake
- Term for a single correlator: RAKE finger
- Normally, receivers with about 4 RAKE fingers are employed
- After despreading, the ratio of signal power to interference power is increased by the process gain compared to the received SNR before despreading:

$$SNR_{\mathrm{dB,desp}} = G_{\mathrm{dB,sp}} + SNR_{\mathrm{dB}} \qquad (3.28)$$

RAKE Receiver



Source: nach C. Lüders, Mobilfunksysteme

4.8 Speech Encoding

- ISDN (basis for DECT):
  - Puls Code Modulation (PCM); sampling with 8 kHz and quantisation with 8 bit => speech bit rate of 64 kbit/s
- In mobile radio systems, a reduction of the data rate is required
  - Modelling of the generation of human speech by excitation coefficients and parameterizable filters
  - Transmission of coefficients
  - Reconstruction of the speech signal at the receiver
- Speech codecs in GSM
  - Full Rate Codec (FR): speech bit rate 13 kbit/s
  - Half Rate Codec (HR): speech bit rate 5.6 kbit/s
  - Enhanced Full Rate (EFR): speech bit rate 12.2 kbit/s
  - Considering the channel coding as well as the application of several bits for organisational purposes, a channel data rate of 22.8 kbit/s (FR, EFR) and 11.4 kbit/s (HR), respectively, results for GSM.
- With LTE, AMR codec (Adaptive Multirate and the EVS codec (Enhanced Voice Services) are used („HD Voice“).

Chapter 5 – Multiple-Access Methods

Introduction
Chapter 1

Basic Terms
Chapter 2

Mobile Radio Systems according to 3GPP
Chapter 6

Multiple-Access Methods

Radio Transmission Technique
Chapter 4

High Frequency Technology
Chapter 3

Mobile Radio Systems according to IEEE802
Chapter 7

Multiple-Access Methods
Chapter 5

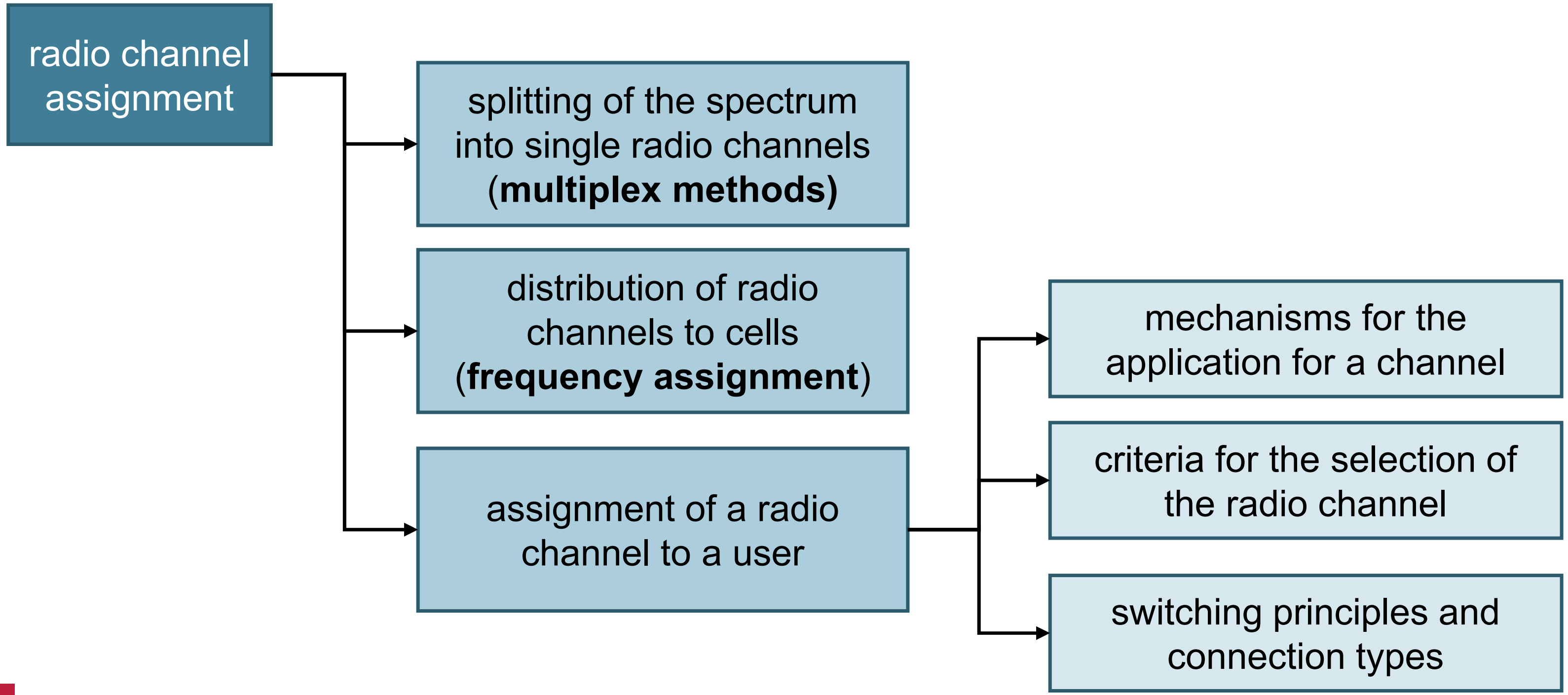
Multiplex and Duplex Methods
- **Channel Access Methods**
- **Switching Principles**

Channel Allocation Strategies

Power Control

5 Multiple-Access Methods

- Limited spectrum for each mobile radio system
- For single radio links, radio channels have to be assigned to the mobile radio subscribers if required.



5.1 Multiplex and Duplex Methods

- Considering multiple-access methods, mobile radio systems differ in terms of the applied duplex and multiplex methods

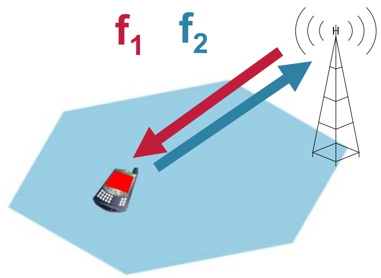
- Duplex method:
    - describes the splitting of the radio channels for the use in UL and DL

- Multiplex method:
    - describes the way of splitting the whole frequency range in radio channels
    - combination of multiple-access technologies and spectrum splitting

Duplex Methods

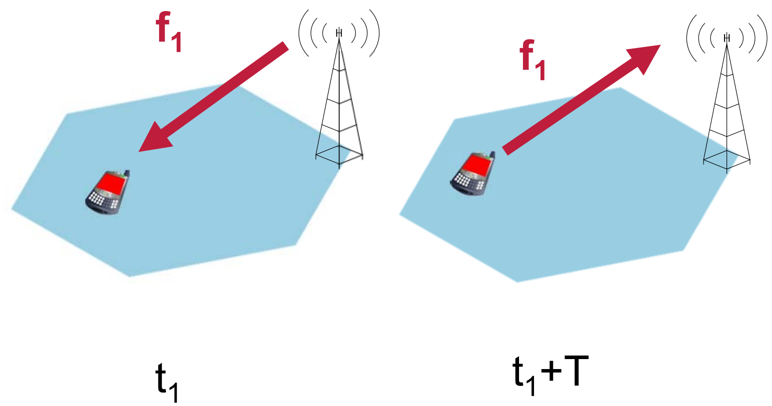
Frequency duplex

- FDD: Frequency Division Duplex
- For uplink and downlink, separated frequency bands are used over which simultaneous transmission is possible
- Use of paired frequency bands with a fixed distance (duplex separation)



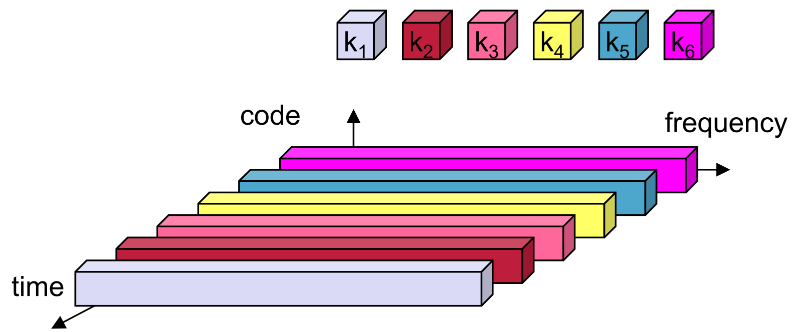
Time duplex

- TDD: Time Divison Duplex
- Uplink and downlink use the same frequency
- Sequential use
- Use of unpaired frequency bands



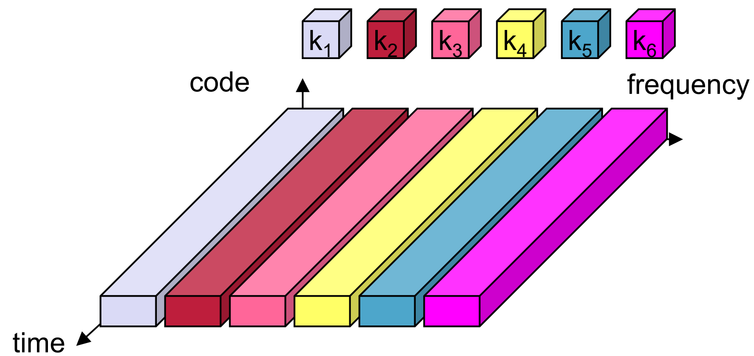
Time Division Multiple Access (TDMA)

- Splitting of the frequency carrier in *N* time slots
- Every time slot corresponds to one connection.
- All users use the same frequency.
- *N* time slots are called a TDMA frame.
- Advantages: transmitting and receiving via an antenna without duplex filter
- Time for adjacent channel measurements (efficient hand-over methods)



Frequency Division Multiple Access (FDMA)

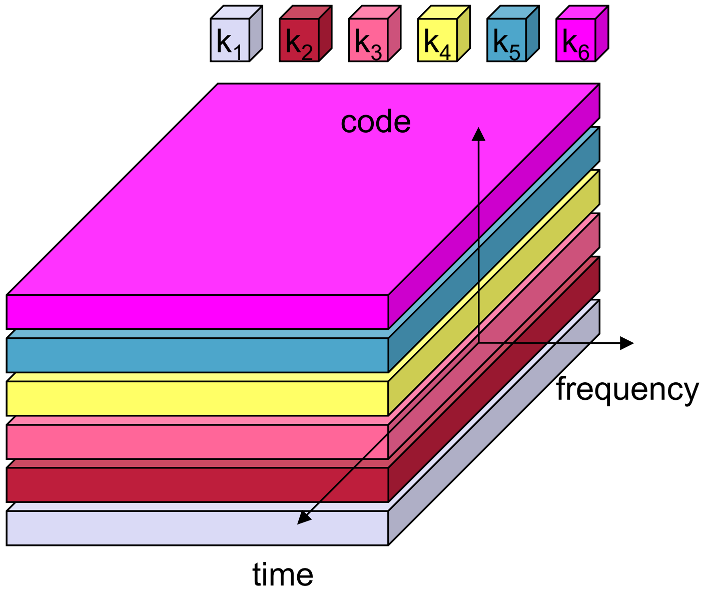
- Splitting of the complete spectrum into subbands (frequency carrier)
- Carrier separation in the order of magnitude of the modulation bandwidth
- Directional separation UL/DL can be effected over the frequency (FDD)
  - Assignment of 2 frequency bands with a gap
  - Duplex separation: distance between UL carrier and DL carrier
    - Examples of duplex separations:
      - GSM900: 45 MHz
      - GSM1800: 95 MHz
      - UMTS-FDD: 190 MHz



Code Division Multiple Access (CDMA)

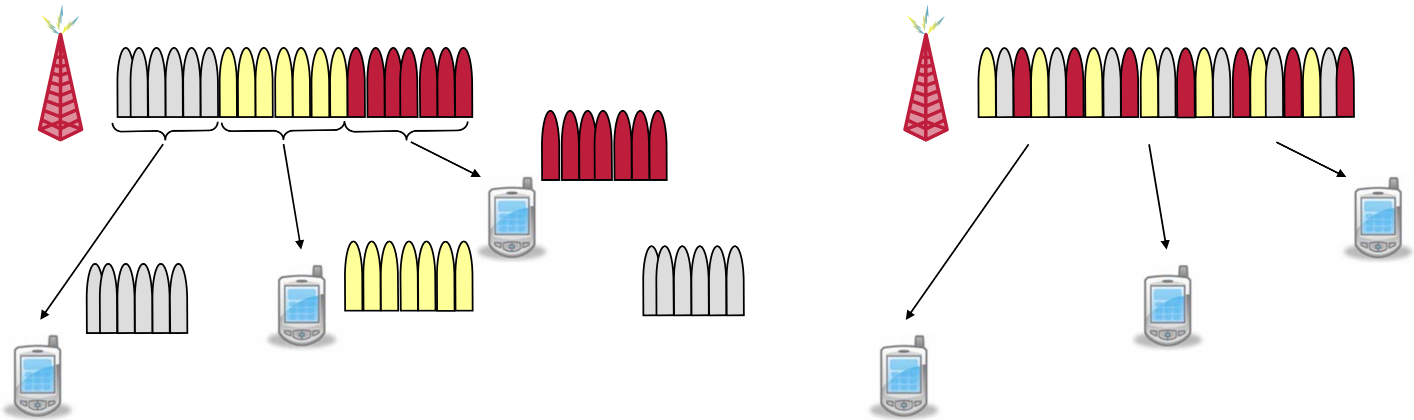
- All users send at the same time and with the same frequency.

- Separation of the users via codes
  - Application of spread spectrum technique
  - Every bit of the transmit bit sequence is multiplied by a connection-specific code signal and thus spread in the frequency range.



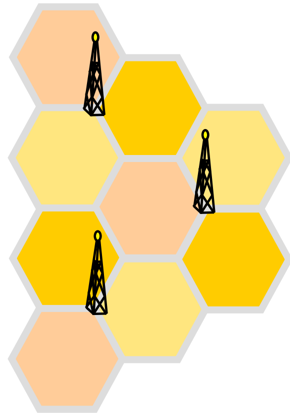
Orthogonal Frequency Division Multiple Access (OFDMA)

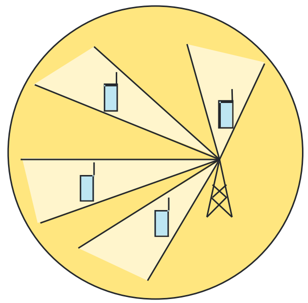
- OFDM can also be used as multiple-access technology where the subcarriers are distributed to different mobile users



Space Division Multiple Access (SDMA)

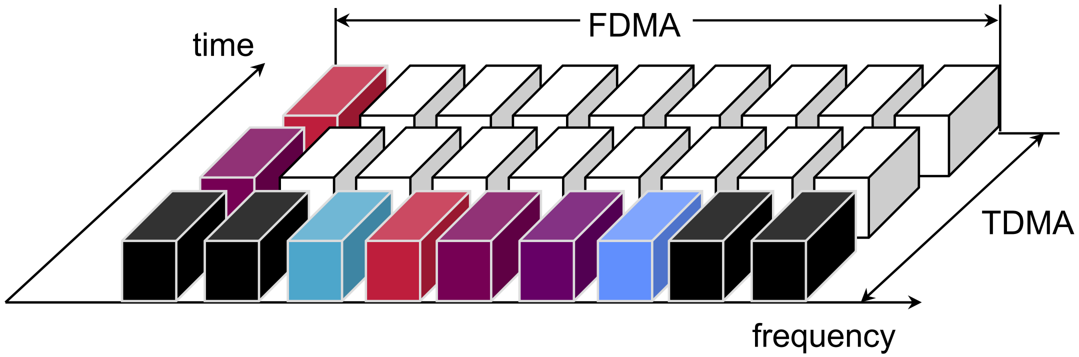
- Application in all mobile radio systems for multiple use of radio channels in different, spacially separated radio cells
  - Standard use case: spatial frequency repetition
  - Special case: application of smart antenna systems
    - Forming of narrow antenna beam lobes by special signal processing techniques
    - Direction of the antenna beam lobe to the respective mobile station





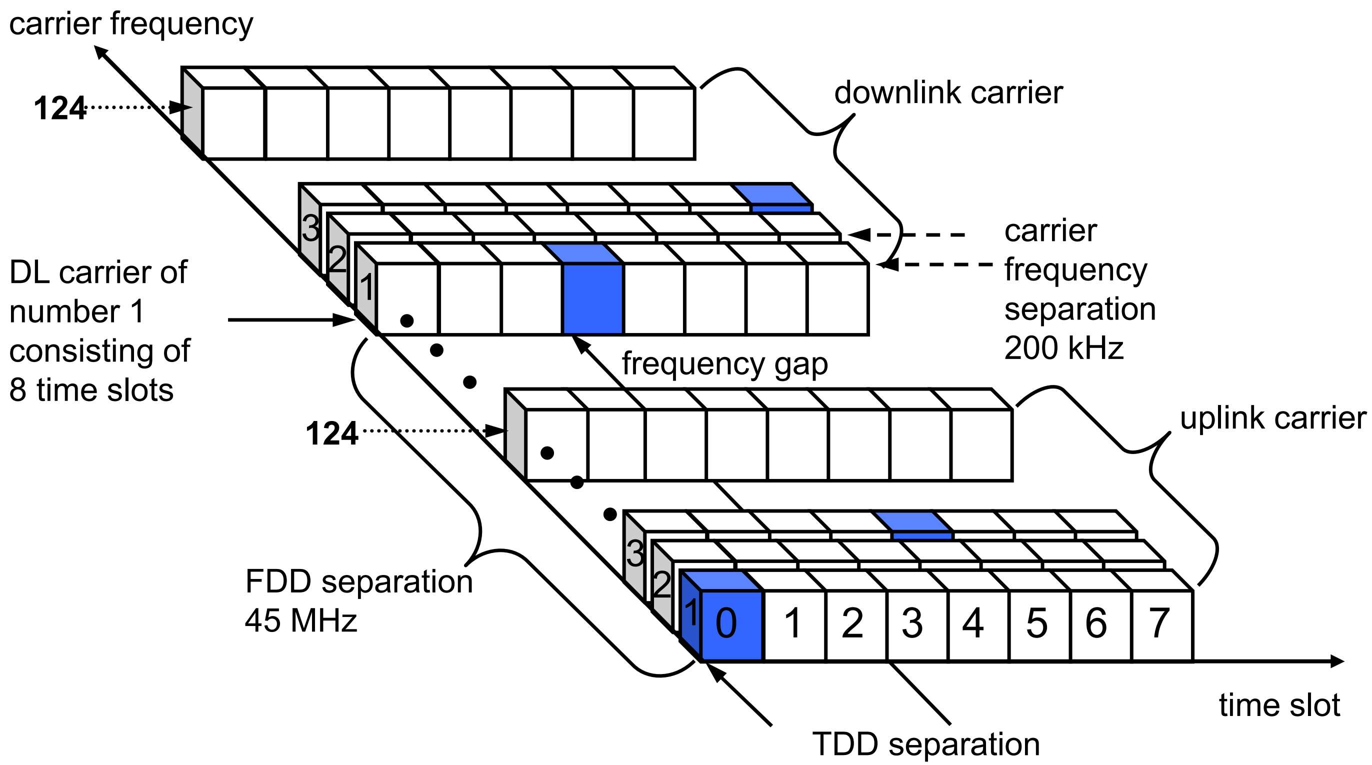
5.2 Realisation of Multiplex Methods

- Combination of TDMA and FDMA
  - Splitting of the complete spectrum in N_f frequency carriers by means of frequency division multiplex
  - Subdivision of every frequency carrier into N_t time slots
  - Total number of channels $N_k = N_f N_t$
  - Characterisation of the radio channel by time slot number and frequency number
  - Application of this principle for DECT and GSM, respectively



FDMA/TDMA Combination for GSM

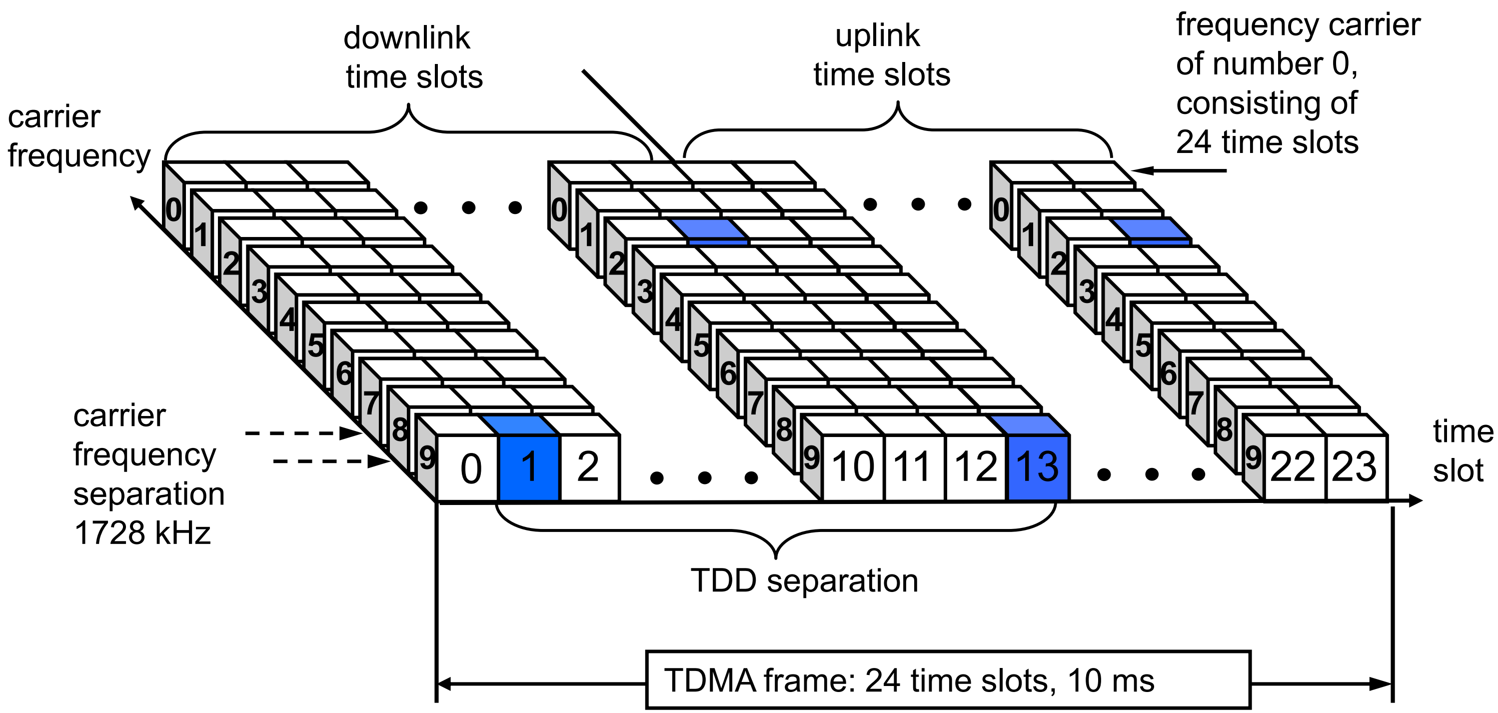
- Application of frequency duplex with time shift (UL and DL at different frequencies and shifted by 3 time slots)



Source: nach J.Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

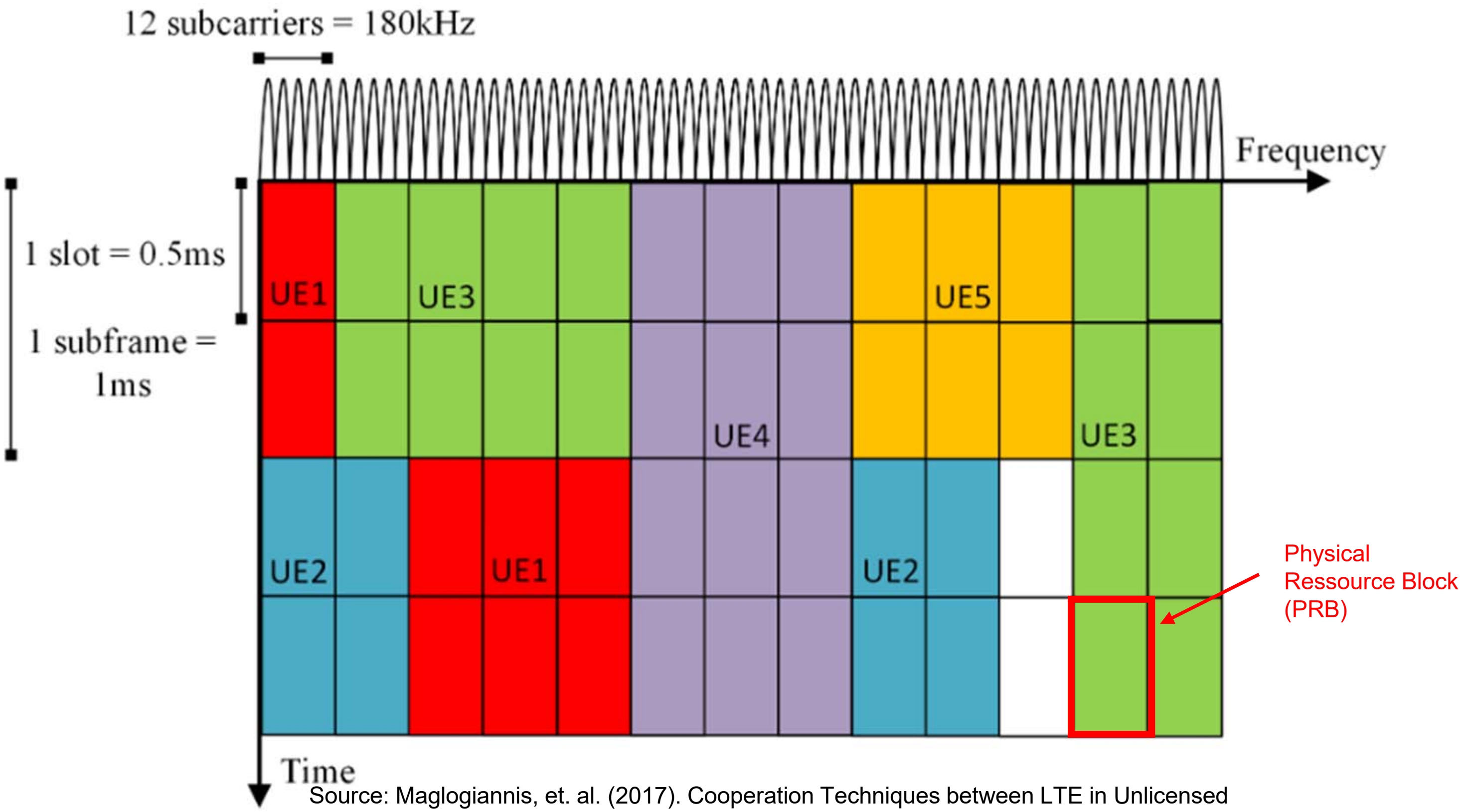
FDMA/TDMA Combination for DECT

- Application of a pure time duplex (UL, DL at the same frequency)



Source: nach J.Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

OFDMA with LTE/5G

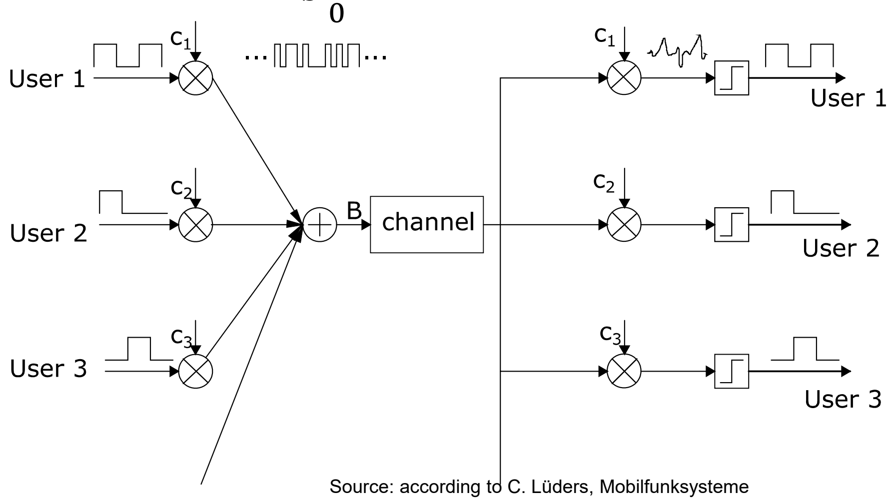


Source: Maglogiannis, et. al. (2017). Cooperation Techniques between LTE in Unlicensed Spectrum and Wi-Fi towards Fair Spectral Efficiency. Sensors. 17. 10.3390/s17091994.

CDMA

- For separation of the users by correlation with their connection-specific code, the code signals have to be orthogonal.
- Condition for orthogonality of the code signals c_n, c_m:

$$\frac{1}{T_b}\int_0^{T_b} c_n(t)c_m(t)\,\mathrm{d}t = 0 \qquad (4.1)$$

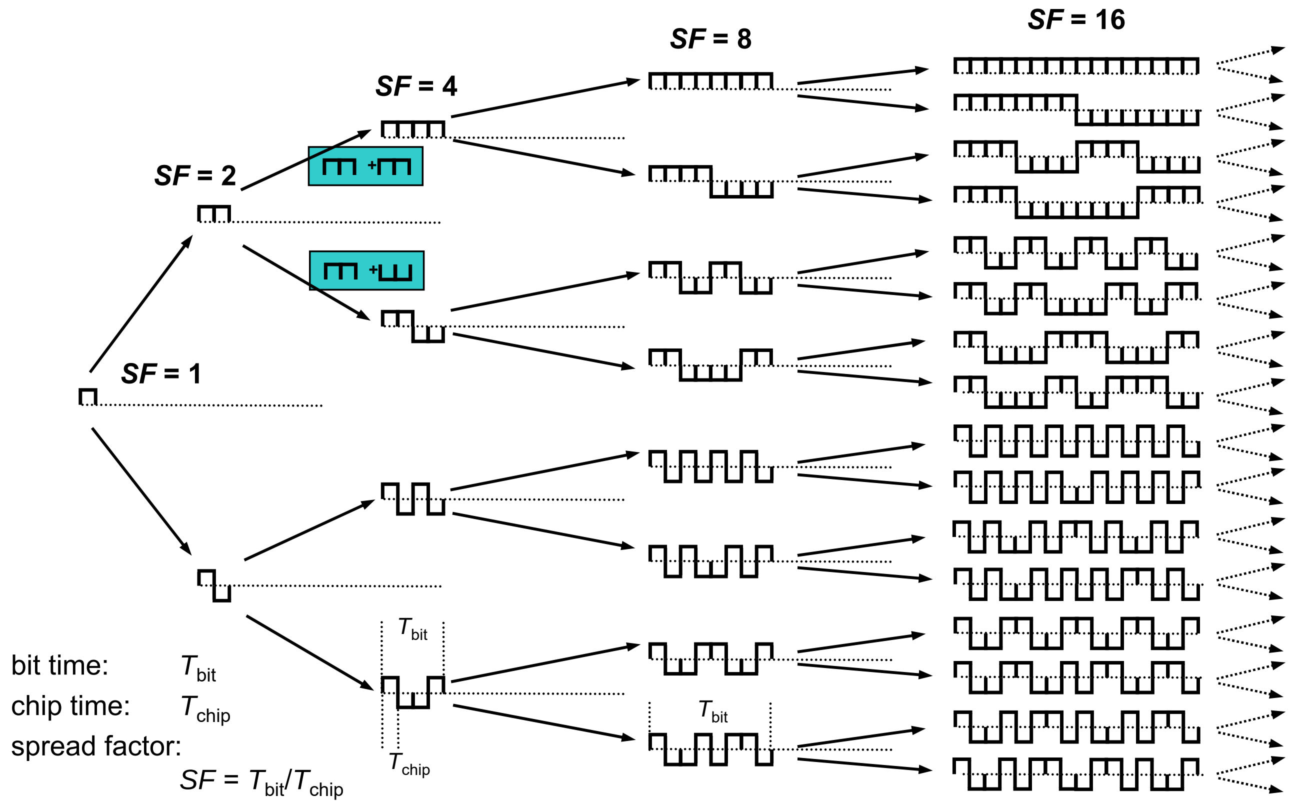


Source: according to C. Lüders, Mobilfunksysteme

- Orthogonality through OVSF codes (orthogonal variable spreading factor codes) in case of perfect synchronisation between transmitter and receiver

OVSF Codes (1)

- Orthogonal codes of variable length; example Walsh Hadamard codes



OVSF Codes (2)

- Application of codes for different data rates
  - Signal with a small data rate: code signal with a large spread factor
  - Signal with a large data rate: code signal with a small spread factor
- Codes within the same step are orthogonal in pairs
- Transmission of information of different data rates
  - Prevention of simultaneous assignment of those codes, which are the anchestors and descendants, respectively, of a code already assigned, since orthogonality is not guaranteed
- Disturbances of orthogonality:
  - Multipath propagation
  - No perfect synchronisation in the uplink
  - Degree of orthogonality is described by the orthogonality factor α
    - total orthogonality: $\alpha = 0$
    - total loss of orthogonality: $\alpha = 1$

5.3 Random Access Methods

- Request for call set-up (=> request for a radio channel) of the mobile stations at any unspecified time

- Rules and procedures to control the access to the network

- Possibilities for access:
  - Assignment mode with central control
    - Query of the subordinate slaves (mobile station) by a master (base station)
    - Reasonable for a small number of slaves (e. g. with bluetooth)
  - Competition mode
    - Stations may have access at any time
    - Collisions are possible
    - Repetitions and strategies to break up and prevent collisions

Reservation Mode

- Combination of assignment mode and competition mode
- Frequent application in mobile radio systems
- Differentiation of 2 phases
  - Application phase
    - Mobile station requests a channel using a competition mode procedure
    - Access on channels especially allocated for this purpose
    (e. g. Random Access Channel RACH in GSM)
  - Transmission phase
    - A channel for the transmission is assigned exclusively to the successfully connected mobile station

ALOHA

Classical ALOHA

- Mobile stations may transmit data at any time.
- Collided packets have to be resend after a random delay.
- New packets are sent immediately.

Slotted ALOHA

- Data packets have a definite length.
- Transmission is only possible in certain time slots of the length T_{RACH}
- Access attempts take place uncoordinatedly.
- MS is successful in case BS can decode the access attempt; BS sends an acknowledgement to MS
- In case an acknowledgement is missing, retry of access attempt after random delay
- Interruption after a maximum number of repetitions
- Capture effect: In case of collision, the MS with the strongest signal may become accepted, provided that the received power is much larger than the sum of the received powers of the other mobile stations.

Data Throughput at Slotted ALOHA (number of successful access attempts per time)

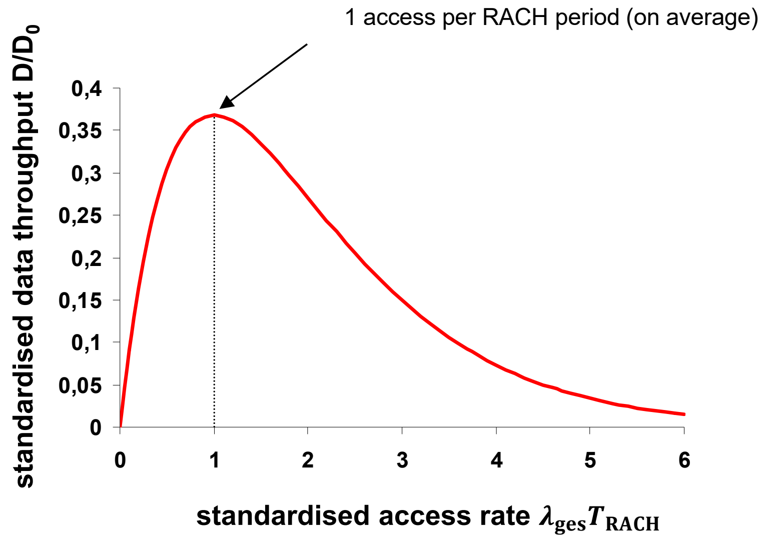
$$D = \lambda_{\mathrm{ges}} \mathrm{e}^{-\lambda_{\mathrm{ges}} T_{\mathrm{RACH}}} \qquad (4.2)$$

λ_{ges}: access rate, i.e. total number of successful access attempts per time

maximum channel capacity of RACH :

$$D_0 = 1/T_{\mathrm{RACH}} \qquad (4.2)$$

maximum throughput at slotted ALOHA is 37 % of the channel capacity of RACH

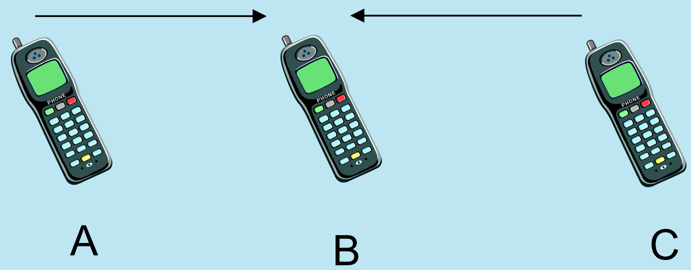


Carrier Sense Multiple Access (CSMA)

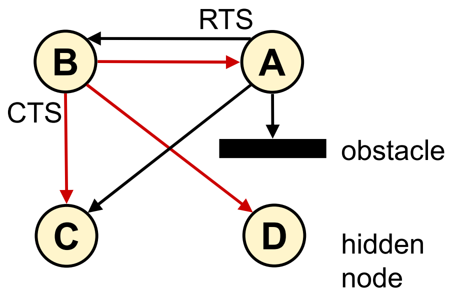
- Extension of the ALOHA method
- Monitoring of the radio channel and access only if the channel is free
- Problem of the hidden terminals (*hidden node*)
- Application with wireless networks

Problem of the hidden terminals (Hidden Node Problem)

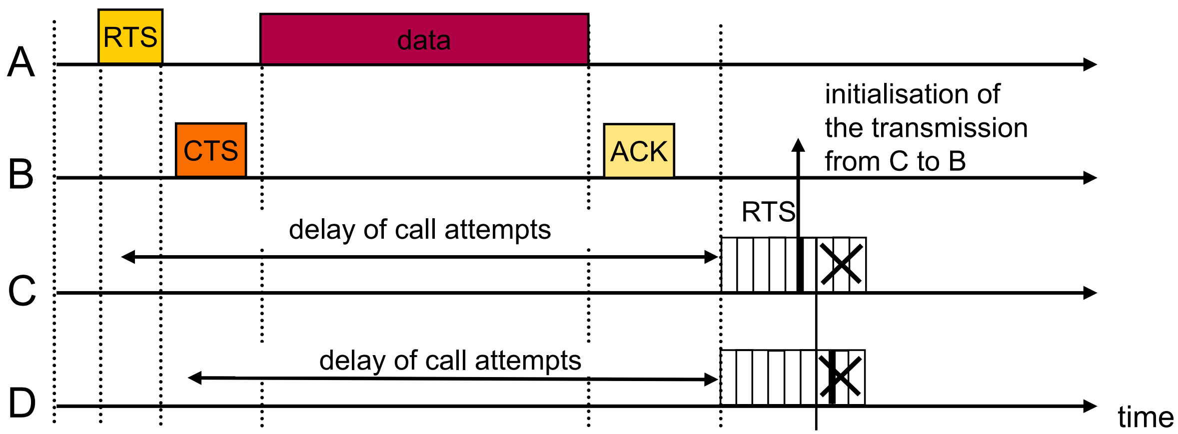
A and C would like to transmit to B at the same time, but cannot see each other because the coverage is too large, i. e. they are “hidden” from each other.



Advanced CSMA Method



RTS: Request To Send
CTS: Clear To Send
ACK: Acknowledgement



Source: nach C. Lüders, Mobilfunksysteme

5.4 Channel Assignment Strategies

- Fixed and dynamic channel assignment is distinguished

- Fixed channel assignment (FCA)

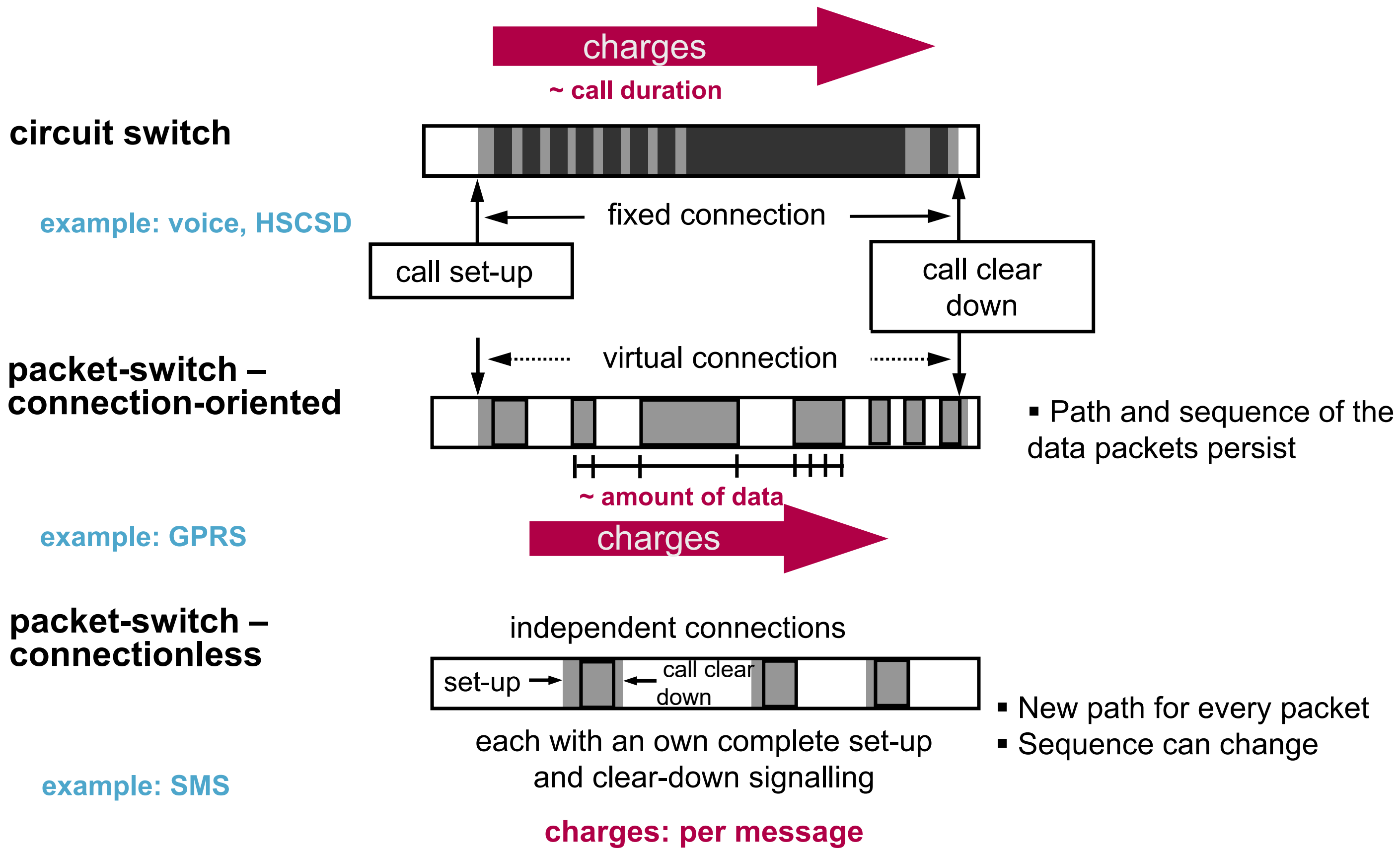
  - Every cell obtains a set of firmly allocated frequencies according to its channel requirements.
  - Assignment can be done according to a fixed regular re-use pattern (not relevant in practice)
  - Assignment within the scope of radio network planning by means of automated frequency assignment methods based on interference calculations that are based on propagation models
  - Application of frequency-hopping methods possible to reduce the re-use separation
  - With GSM, fixed channel assignment is applied.

Dynamic Channel Assignment

- Dynamic channel assignment (DCA)

  - In principle, every cell can use every radio channel.
  - No frequency planning required
  - System determines the frequencies independently on the basis of the active interference
  - Use of different radio channels possible (intracell handover), e. g. in case the interference situation degrades
  - Differentiation of the DCA methods according to:
    - Adoption rate (second, modifications dependent on time of day and weekday, respectively etc.)
    - Criteria for the channel selection (C/I, traffic load etc.)
    - Responsibility for the channel selection (BS, MS, central unit)
  - Application e. g. with DECT

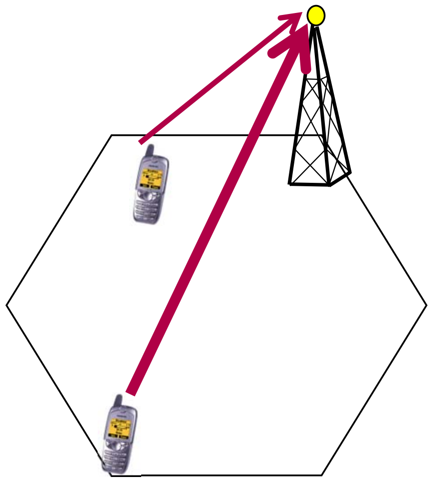
5.5 Switching Principles



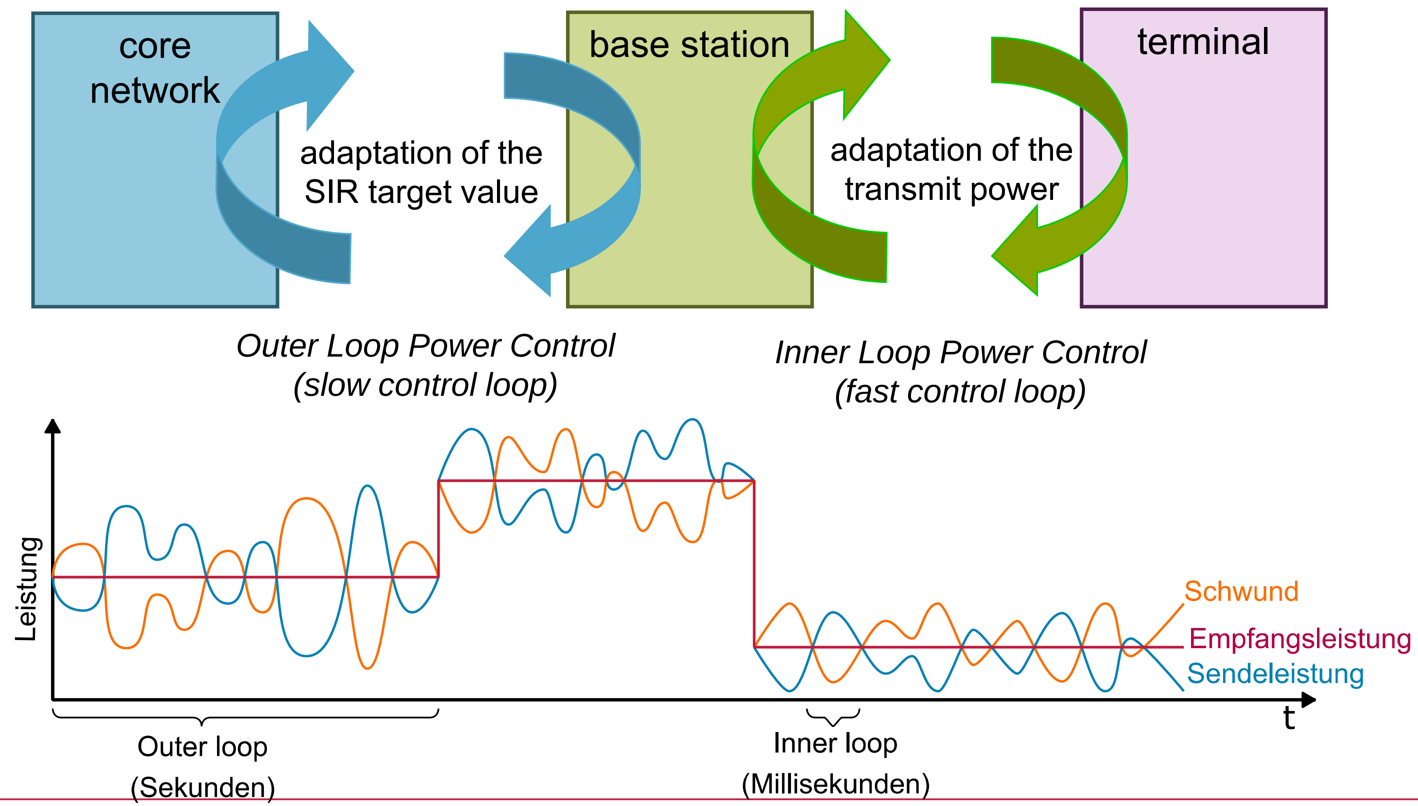
Source: nach C. Lüders, Mobilfunksysteme

5.6 Transmit Power Control

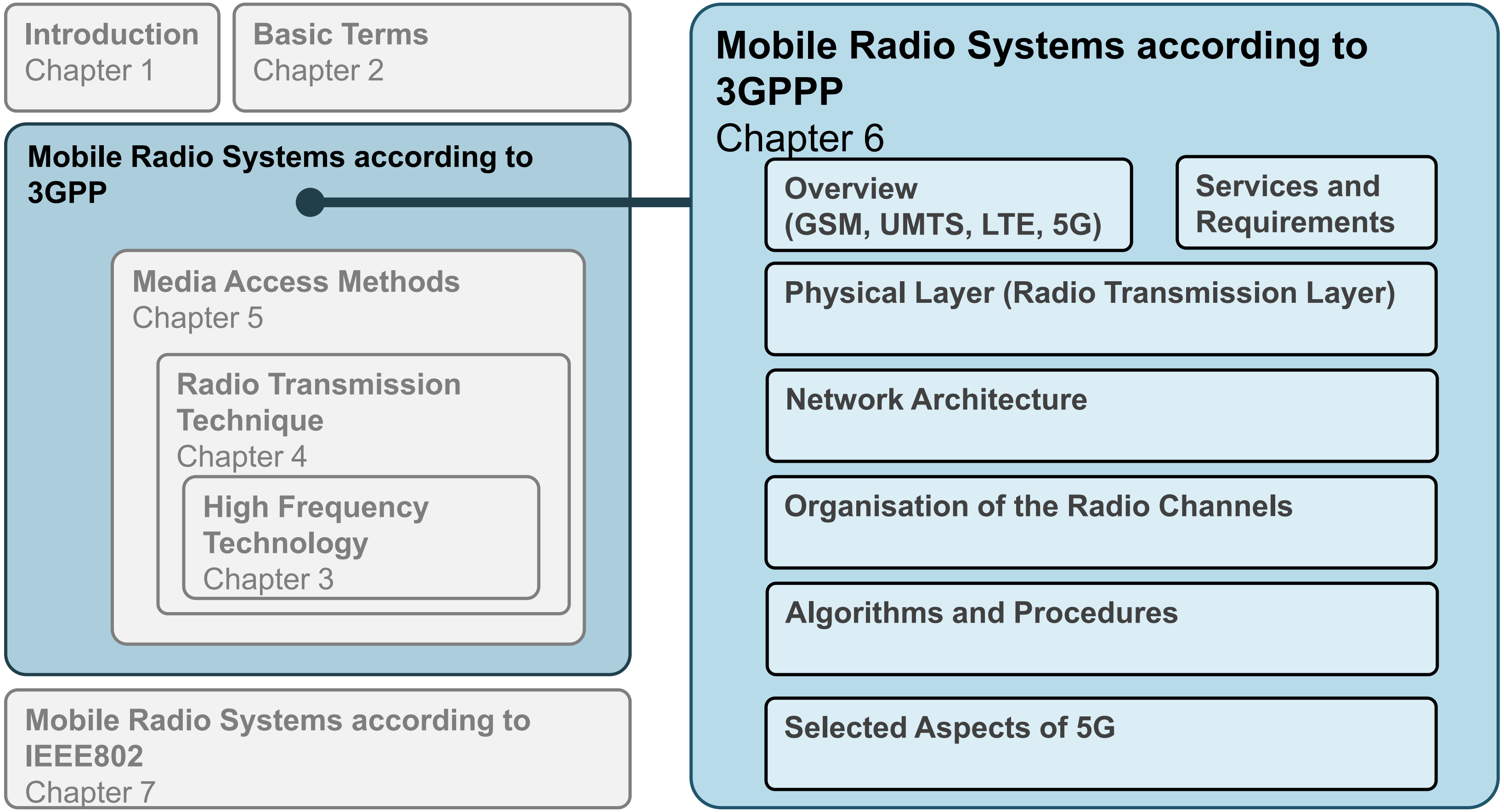
- Mobile radio systems require a fast and precise transmit power control.
- General strategy:
  - Setting of a defined signal-to-noise ratio SIR
  - Target value of the SIR is given by RNC depending on the quality measurements (bit error rate): Outer Loop Power Control
  - Tracking of the transmitting power of the UE and the node B, respectively, according to the adjusted SIR: Inner Loop Power Control
    - Equalisation of the distance-dependent attenuation differences
    - Equalisation of the level fluctuations by fading effects
  - Both kinds of power control are called *Closed Loop Power Control.*



Inner Loop and Outer Loop Power Control



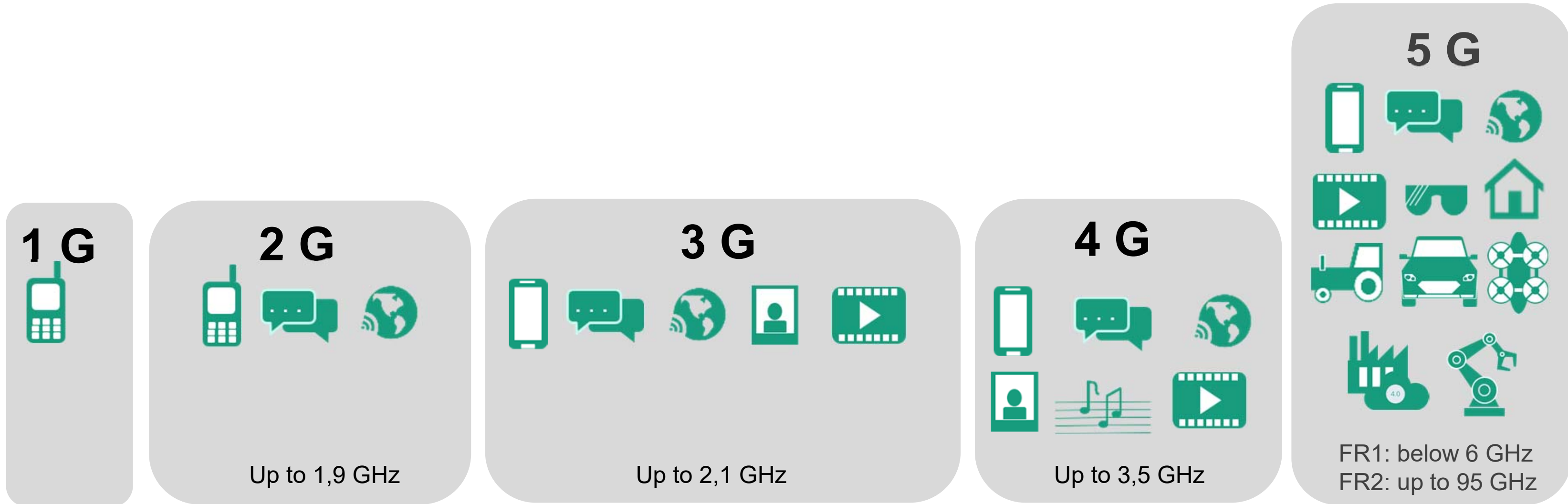
Chapter 6 – Mobile Radio Systems



6 Mobile Radio Systems according to 3GPP
6.1 Overview

- 3GPP classification of the denotations of the radio access networks
  - **GERAN** (**G**SM **E**GDE **R**adio **A**ccess **N**etwork)
    - comprises the radio access networks via the air interfaces according to GSM (including HSCSD, GPRS, EDGE)
  - **UTRAN** (**U**MTS **T**errestrial **R**adio **A**ccess **N**etwork)
    - comprises the radio access networks via the air interfaces according to UMTS (including HSPA, HSPA+)
  - **E-UTRAN** (**E**volved UTRAN)
    - comprises the radio access networks via the air interfaces according to LTE (including LTE-Advanced and LTE-Advanced Pro)
  - **5G-NR** (**5**th **G**eneration **N**ew **R**adio)
    - comprises the radio access networks via the air interfaces according to 5G in the frequency ranges FR1 (< 6 GHz) and FR2 (up to 95 GHz)

Overview of Mobile Communications Generations



1 G	2 G	2 ½ G	3 G	3 ½ G	3 ¾ G	4 G	4 ½ G	5 G
1981	1990	1998	2001	2006	2010	2015	2018	2020
C-Netz NMT AMPS TACS	**GSM**[1] CDMA IS-95A	**GPRS**[2] IS-95B	**EDGE**[3] **UMTS**[4] CDMA 2000	**HSDPA**[5] **HSPA+** 1xEV-D0	**LTE**[6] Rel. 8	**LTE-A**[7] Rel. 10	**LTE-A** **Pro** Rel. 13/14	**LTE / NR**[8] Rel. 15/16/17

Source: Fraunhofer IIS

6.1 Overview

Example of a Standard Document

ETSI TS 136 213 V13.0.0 (2016-05)

LTE;
Evolved Universal Terrestrial Radio Access (E-UTRA);
Physical layer procedures
(3GPP TS 36.213 version 13.0.0 Release 13)

A GLOBAL INITIATIVE

If a serving cell is not configured for a UE as a LAA Scell, and if CSI-RS is configured in the serving cell then the UE shall assume downlink CSI-RS EPRE is constant across the downlink system bandwidth and constant across all subframes for each CSI-RS resource.

If a serving cell is configured for a UE as a LAA Scell, the UE may assume that EPRE of CSI-RS in subframe n2 is same as EPRE of CSI-RS in earlier subframe n1, if all OFDM symbols of subframe n1 and all subframes between subframe n1 and subframe n2, are occupied.

The cell-specific ratio ρ_B / ρ_A is given by Table 5.2-1 according to cell-specific parameter P_B signalled by higher layers and the number of configured eNodeB cell specific antenna ports.

Table 5.2-1: The cell-specific ratio ρ_B / ρ_A for 1, 2, or 4 cell specific antenna ports

P_B	ρ_B / ρ_A	
	One Antenna Port	Two and Four Antenna Ports
0	1	5/4
1	4/5	1
2	3/5	3/4
3	2/5	1/2

For PMCH with 16QAM, 64QAM, or 256QAM, the UE may assume that the ratio of PMCH EPRE to MBSFN RS EPRE is equal to 0 dB.

Table 5.2-2: OFDM symbol indices within a slot of a non-MBSFN subframe where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_A or ρ_B

Number of antenna ports	OFDM symbol indices within a slot where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_A		OFDM symbol indices within a slot where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_B	
	Normal cyclic prefix	Extended cyclic prefix	Normal cyclic prefix	Extended cyclic prefix
One or two	1, 2, 3, 5, 6	1, 2, 4, 5	0, 4	0, 3
Four	2, 3, 5, 6	2, 4, 5	0, 1, 4	0, 1, 3

Table 5.2-3: OFDM symbol indices within a slot of an MBSFN subframe where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_A or ρ_B

Number of antenna ports	OFDM symbol indices within a slot where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_A				OFDM symbol indices within a slot where the ratio of the corresponding PDSCH EPRE to the cell-specific RS EPRE is denoted by ρ_B			
	Normal cyclic prefix		Extended cyclic prefix		Normal cyclic prefix		Extended cyclic prefix	
	n_s mod 2 = 0	n_s mod 2 = 1	n_s mod 2 = 0	n_s mod 2 = 1	n_s mod 2 = 0	n_s mod 2 = 1	n_s mod 2 = 0	n_s mod 2 = 1
One or two	1, 2, 3, 4, 5, 6	0, 1, 2, 3, 4, 5, 6	1, 2, 3, 4, 5	0, 1, 2, 3, 4, 5	0	-	0	-
Four	2, 3, 4, 5, 6	0, 1, 2, 3, 4, 5, 6	2, 4, 3, 5	0, 1, 2, 3, 4, 5	0, 1	-	0, 1	-

5.2.1 eNodeB Relative Narrowband TX Power (RNTP) restrictions

The determination of reported Relative Narrowband TX Power indication $RNTP(n_{PRB})$ is defined as follows:

$$RNTP(n_{PRB}) = \begin{cases} 0 & \text{if} \quad \frac{E_A(n_{PRB})}{E_{\max\_nom}^{(p)}} \le RNTP_{threshold} \\ 1 & \text{if} \quad \text{no promise about the upper limit of } \frac{E_A(n_{PRB})}{E_{\max\_nom}^{(p)}} \text{ is made} \end{cases}$$

Structure of Chapter 6

- In the following sections, the systems defined according to 3GPP are not explained by generations, but by functionalities and features, respectively.
- The advantage of this is that functionalities and features, which are equal or similar to several generations, do not have to be explained repeatedly.
- Moreover, this makes the representation and the recognition of developments easier (see e. g. network architecture).

GSM

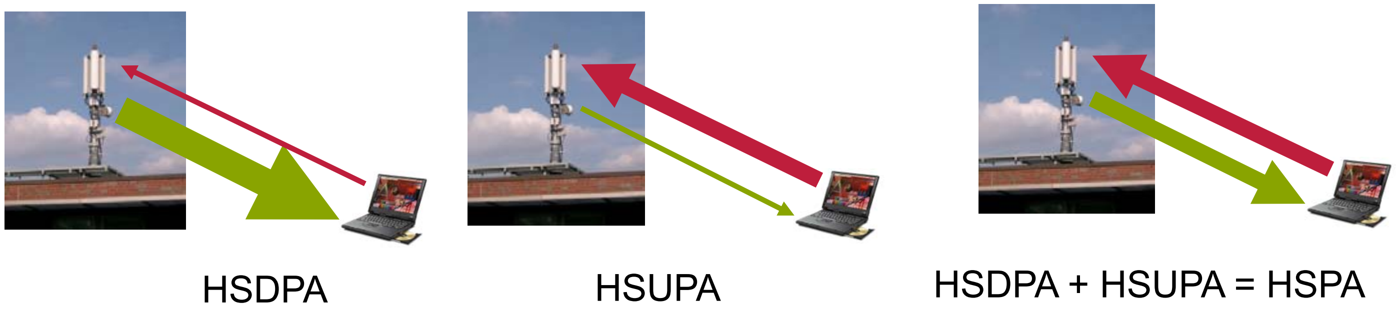
- **General Standard of Mobile Communication (GSM)**; introduction in the year 1991
  - conceived as mobile continuation of ISDN with the main item voice transmission
  - circuit switch, max. data rate 9.6 kbit/s
- **High-Speed Circuit Switched Data (HSCSD)**; introduction in the year 1997
  - circuit-switched data transmission
  - max. data rate 57.6 kbit/s
  - billing according to connection time
- **General Packet Radio Service (GPRS)**; introduction in 1998
  - packet switch
  - max. data rate approx. 160 kbit/s
  - billing according to data volume
- **Enhanced Data Rates for GSM Evolution (EDGE)**, introduction approx. in 2001
  - increase of the data rate by the factor 3 while retaining the carrier separation
  - max. data rate approx. 480 Kbit/s

UMTS

- **Universal Mobile Telecommunication System (UMTS)** (introduction in 2001) is characterised by a very large variation of services with different requirements for the transmission quality
  - data rate from 4.75 kbit/s to 2 Mbit/s
    - depends on the service (voice < 12.2 kbit/s, video telephony > 64 kbit/s)
    - data rates can be variied according to the traffic load and the receive conditions (rate adaption)
  - demanded bit error rate ranges from error-free transmission (e-commerce) to 3% FER (Frame Erasure Rate) in case of voice
  - the bandwidth of the tolerable delay ranges from no delay (voice) up to a delay time of a few minutes (e-mail)
  - symmetric traffic (voice) up to extremely asymmetric traffic (video-on-demand)
  - sequential transmission is inevitable (voice, internet radio) up to completely unimportant (web browsing)

HSPA (High Speed Packet Access)

- Comparable to HSCSD, GPRS or EDGE for GSM, the further development of UMTS High Speed Packet Access (HSPA) exists which allows an increase of the data rates:
  - High Speed Downlink Packet Access (HSDPA)
  - High Speed Uplink Packet Access (HSUPA)
- Increase of the data rate in DL up to 14.4 Mbit/s (theoretical) and 5.6 Mbit/s in Uplink



- **HSPA+**
  - Further increase of the data rates
    - DL : 42 Mbit/s
    - UL: 11 Mbit/s

LTE

- Motivation for the development of **Longterm Evolution (LTE)**; introduction in 2010

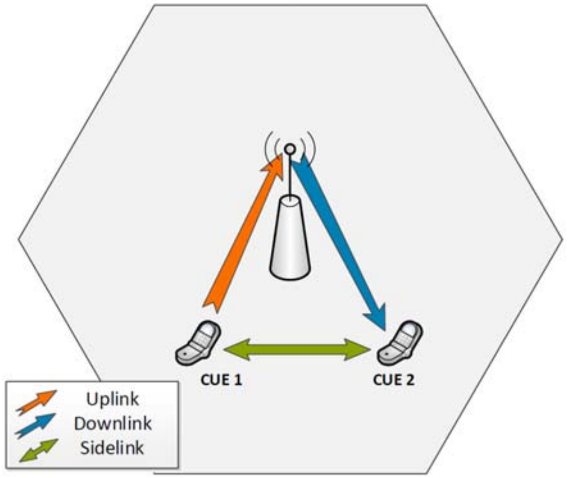
  - Performance
    - Higher data rates
    - More efficient use of the frequency spectrum
    - Lower latency

  - Variability
    - Voice services
    - Real-time services (real-time gaming)
    - Internet
    - Video/TV applications

  - Costs
    - Less operational costs
    - Less energy consumption

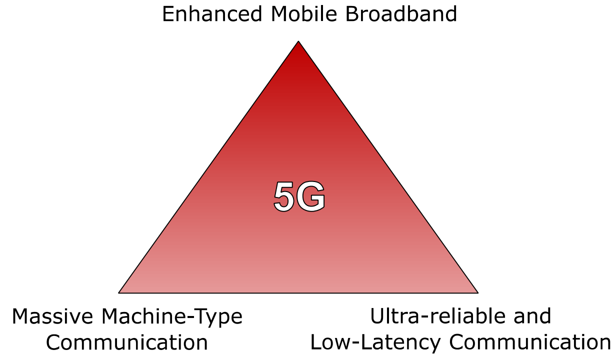
LTE-A / LTE-A Pro

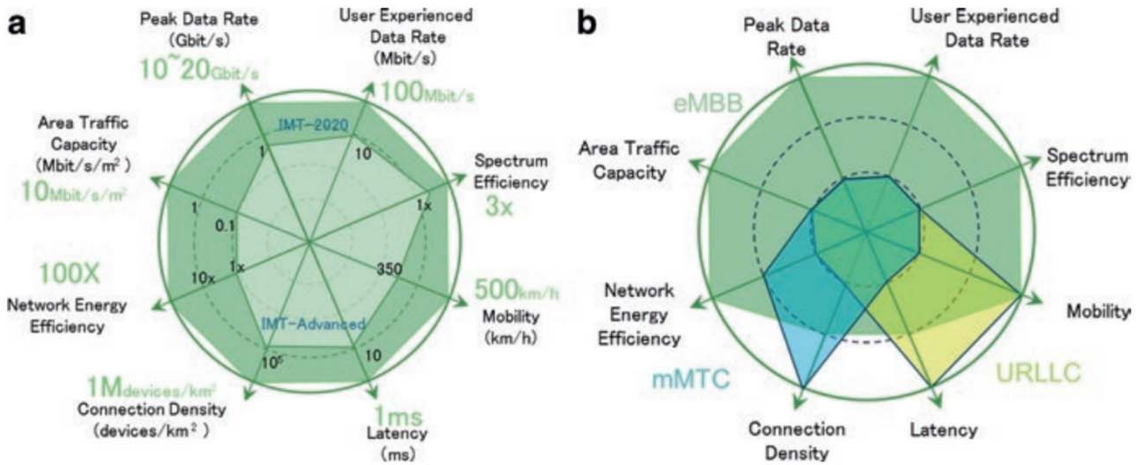
- LTE starting from Release 10 is referred to as LTE Advanced **(LTE-A)**
  - LTE Advanced meets the **IMT (International Mobile Telecommunications) Advanced** requirements of the ITU (International Telecommunication Union):
    - Spectral efficiency of 15 bit/s/Hz in the downlink and 6.75 bit/s Hz in the uplink
  - The objective is to obtain peak data rates of 1 Gbit/s for low mobility and 100 Mbit/s for high mobility
    - Starting from Release 13, it is referred to as **LTE-Advanced Pro**
    - Essential enhancements in Rel. 13 are i. a.:
      - device-to-device communication including functionalities for BOS services (authorities and organisations with safety issues) and vehicle-to-X-communication (C-V2X, cellular vehicle-to-X)
      - use of unlicensed bands in the 5 GHz range
      - better integration using WLAN
      - reduction of latency



5G

- In view of different indicators, the requirements of 5G (IMT 2020) are many times higher than with IMT-Advanced (LTE-A)
- Classification of the services into three groups:
  - Enhanced Mobile Broadband (eMBB)
  - Massive Machine-Type Communication (mMTC)
  - Ultra-reliable and Low-Latency Communication (URLLC)





Source: W.Lei et al. 5G System Design: An End to End Perspective, Springer 2020

Examples of Indicators with 5G

Source: www.vdi-wissensforum.de

eMBB

10 000 x more traffic

100 Mbit/s „everywhere“

Higher Data Rates

> 10 Gbit/s

Source: www.elektrotechnik.vogel.de

URLCC

10-100 x more terminals

5G

< 1ms latency

Internet of Things

Real-Time Services

10 years battery life

very high reliability

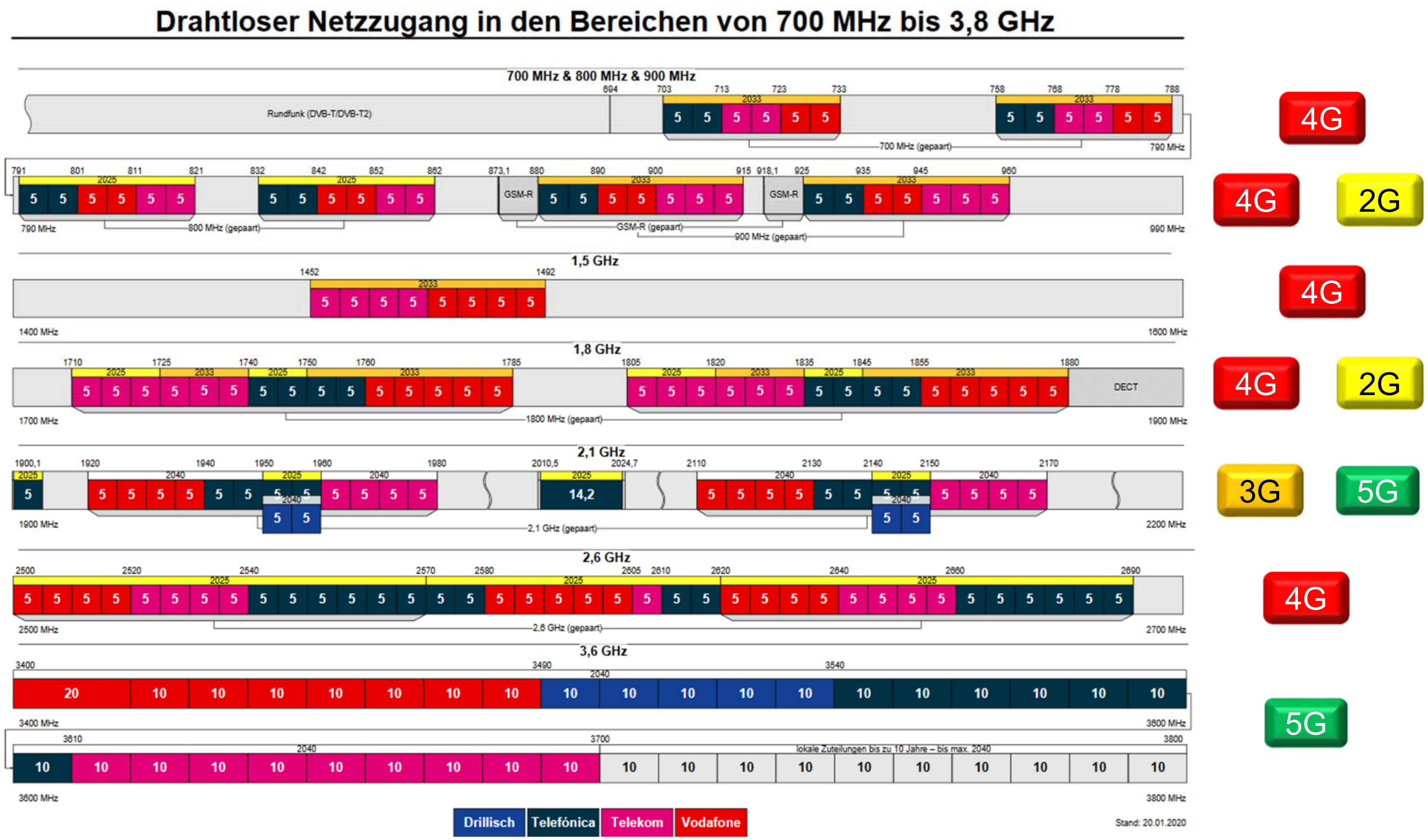
mMTC

6.3 Physical Layer (Radio Transmission Layer)

- With the transition from 4G to 5G, with the introduction of a new generation, there is not a basically new radio transmission method for the first time!
- Essential innovations are in the core network behind the radio link and the software!

1G	analogue transmission
2G	initially digital transmission; TDMA/FDMA (GSM)
3G	WCDMA (UMTS)
4G	**OFDM** (LTE)
5G	**OFDM** with some modifications (5G NR)

Spectrum Usage in Germany (as of Auction 2019)



Source: Bundesnetzagentur

Further 5G Frequency Ranges in Germany

Local campus networks at 3.7 GHz to 3.8 GHz

Unlicensed bands at 5 GHz (comp. WLAN)

Millimeter wave (24.25 GHz to 27.5 GHz)

Selected LTE Frequency Bands in Europe

Band	Mode	Frequency range [MHz]
1	FDD	1920-1980 (UL), 2110-2170 (DL)
3	FDD	1710-1785 (UL), 1805-1880 (DL)
7	FDD	2500-2570 (UL), 2620-2690 (DL)
8	FDD	880-915 (UL), 925-960 (DL)
20	FDD	832-862 (UL), 791-821 (DL)
28	FDD	703-733 (UL), 758-803 (DL)
32	FDD	1452-1492 (DL) only with carrier aggregation
33	TDD	1900-1920
34	TDD	2010-2025
38	TDD	2570-2620
40	TDD	2300-2400
41	TDD	3400-3600
42	TDD	3600-3800

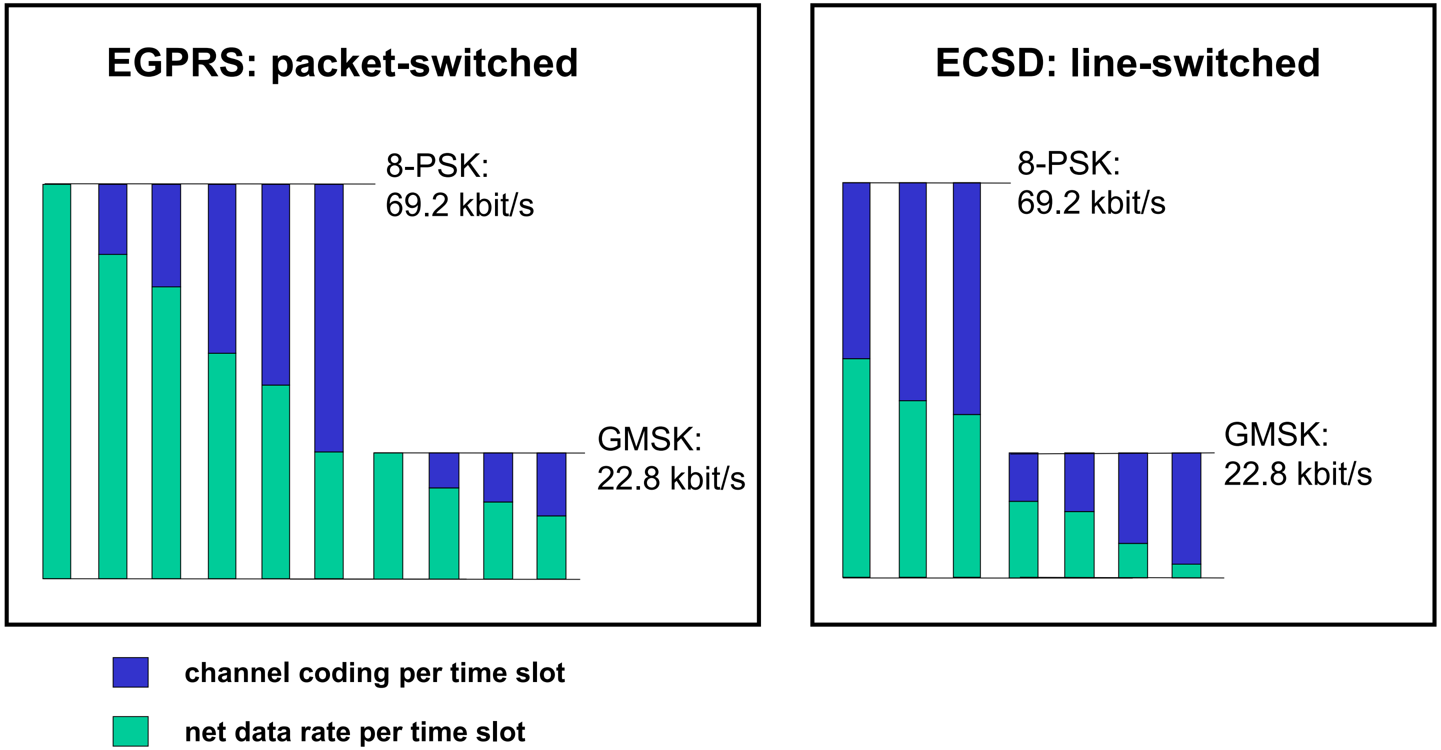
GSM

- Use of a TDMA/FDMA method **(see folio 253)**
  - Carrier separation of 200 kHz
  - 1 TDMA frame has 8 time slots
  - GMSK modulation
  - Circuit switch
    - max. data rate 9.6 kbit/sec
- **HSCSD**
  - Bundling of up to 4 time slots at 4.4 kbit/s (57.6 kbit/s) each
- **GPRS**
  - Packet switch
  - Up to 8 users share a time slot
  - Bundling of up to 8 time slots at 22.8 kbit/s each
  - Max. data rate 160 kbit/s (in a part of the time slots, signaling information is transmitted)
  - Convolutional Coding
  - Adaptation of the error protection depends on the propagation conditions

EDGE

- Enhanced Data Rates for GSM Evolution (EDGE)
  - Application of 8-PSK modulation instead of GMSK
  - Increase in data rate by the factor 3 (22.8 kbit/s/slot -> 69.2 kbit/s/slot)
    - while maintaining the carrier separation of 200 kHz
    - less interference resistance
    - higher requirements for the linearity of the power amplifier
    - bundling of up to 8 time slots => maximum data rate of 480 kbit/s
  - Adaptation of the error protection depends on the propagation conditions similar to GPRS => adaptive selection of the modulation and coding methods

Net Data Rate and Coding Schemes using EDGE

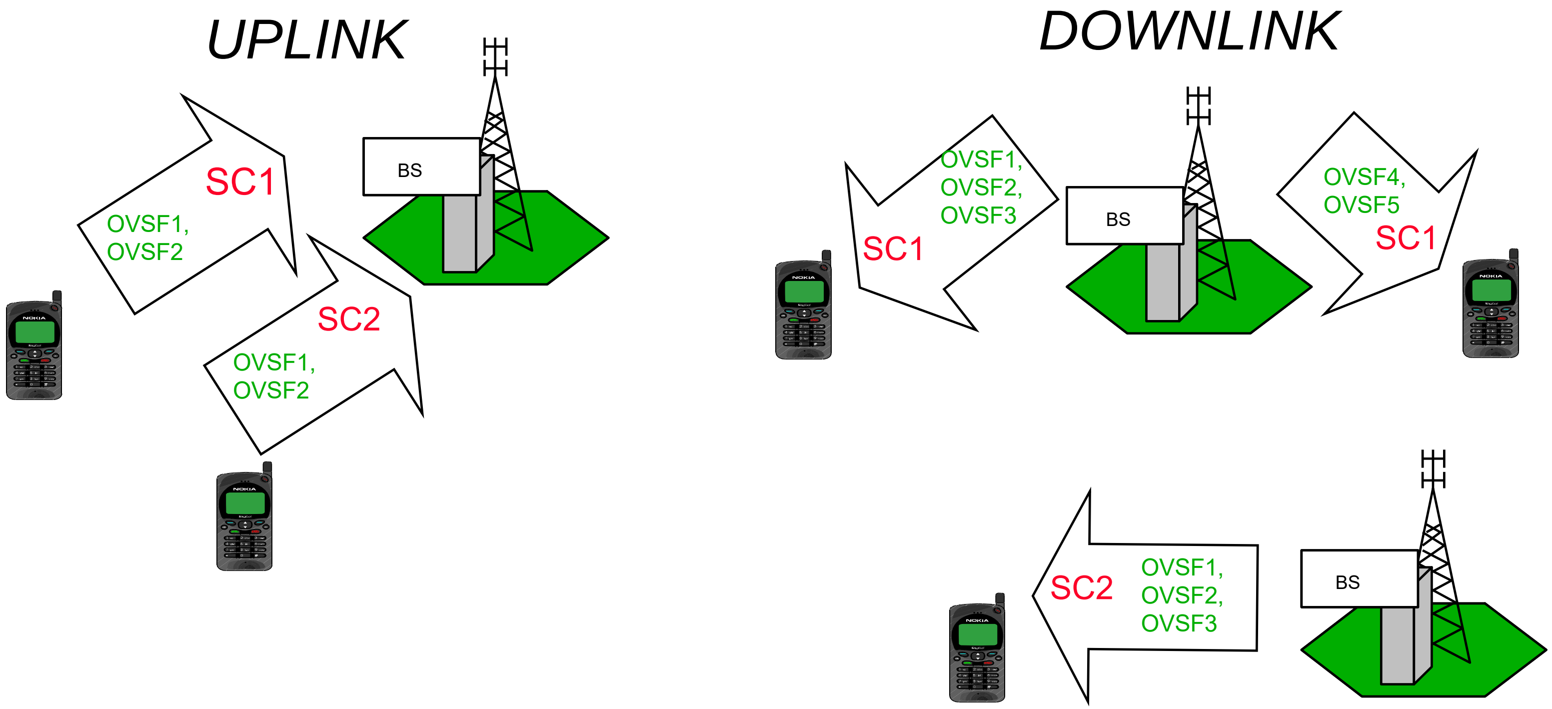


UMTS

- Application of code-multiplex methods (Wideband CDMA), FDD*
  - First version: UMTS Release 99
  - Channel bandwidth 5 MHz, (3.84 MHz – channel bandwidth actually used)
  - QPSK
  - Maximum data rate 2 Mbit/s (theoretical) and 384 kbit/s (practical), respectively
  - All users of a radio cell use the same frequency at the same point in time
  - Frequency re-use factor of 1 (all radio cells can use the same frequency)
  - Separation of the signals of different users as well as of the signals of different cells via codes
    - **OVSF codes (see folio 239)**
      - Connection-specific for the uplink as well as for the downlink
      - For control data in the UL, a spreading factor of 256 is basically used.
      - One UE can operate up to 6 connections at the same time.
        - Identification by orthogonal codes and phase relation, respectively
    - **Scrambling codes (see folio 218)**
      - Cell-specific code in the downlink (512 different codes exist)
      - UE-specific code in the uplink

* The also existing UMTS-TDD variant is not considered here

OVSF and Scrambling Codes in UL and DL



UMTS – Further Development to HSPA and HSPA+

- **HSPA**
  - Increase in the data rate in DL up to 14.4 Mbit/s (theoretical) is achieved by four measures:
  - Adaptive modulation and coding incl. application of higher-value modulation methods (16QAM)
  - Optimisation of the repetition of the erroneous packets
  - Fast scheduling of the packets by
    - execution at the base station
    - application of short frame durations
  - Channel Sharing

UMTS – Further Development to HSPA and HSPA+

- **HSPA+**
  - Further increase in the data rates to 84 Mbit/s (DL) and 23 Mbit/s (UL), respectively, at the air interface:
    - Modulation:
      - 64QAM in DL (increase by 50% to 21 Mbit/s)
      - 16QAM in UL (increase by 100% to 11.2 Mbit/s)
    - 2x2 MIMO antenna technology (further theoretical doubling of the data rate)
    - Dual-cell technique (application of 2 5-MHz blocks [carrier aggregation])
      - 84.4 Mbits in DL (from Rel. 8)
      - 23 Mbit/s in UL (from Rel. 9)

- Further characteristics:
  - Reduction of latencies
  - Direct IP connection of the base stations
  - Lower power consumption

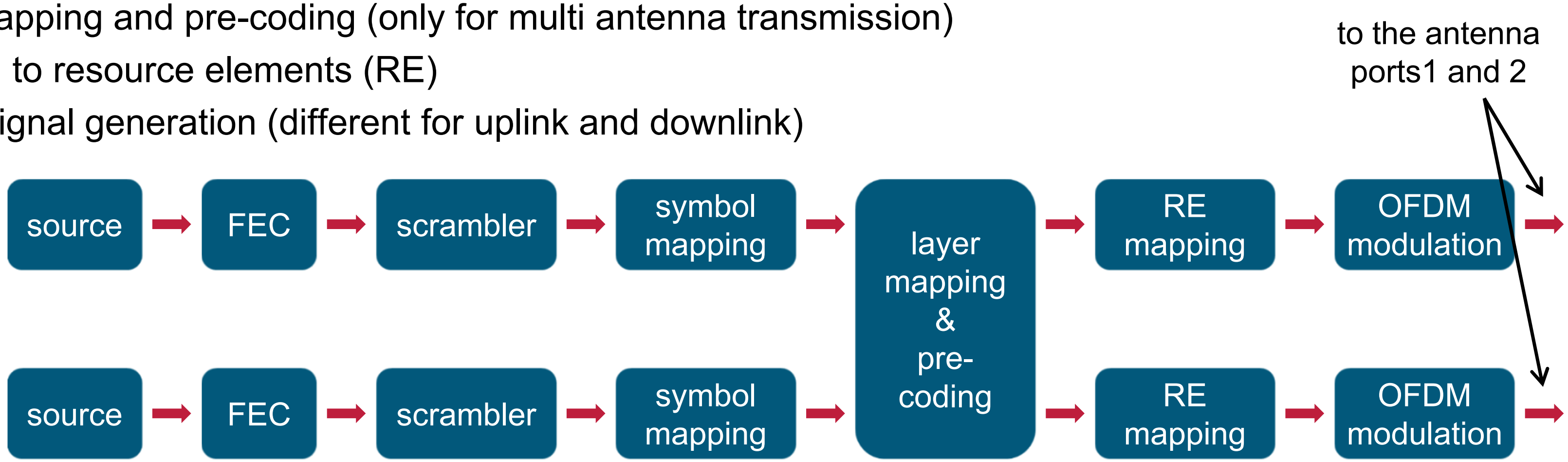
LTE

- Performance of base station (eNodeB) and terminal (UE) varies significantly. Uplink and downlink are adapted to the respective characteristics of eNodeB and UE:
  - In the **Downlink**, **OFDM** is used
  - In the **Uplink**, **Single-Carrier Frequency Division Multiplexing** (SC-FDMA) is applied
- Specified bandwidths: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz
- Multiple access technologies in uplink and downlink: OFDMA/TDMA
- Multi antenna configurations (MIMO) are supported
- Adaptive modulation and channel coding
  - QPSK, 16-QAM und 64-QAM*
- Duplex method: FDD and TDD (in contrast to UMTS, with LTE both modes are very similar)

* only in DL

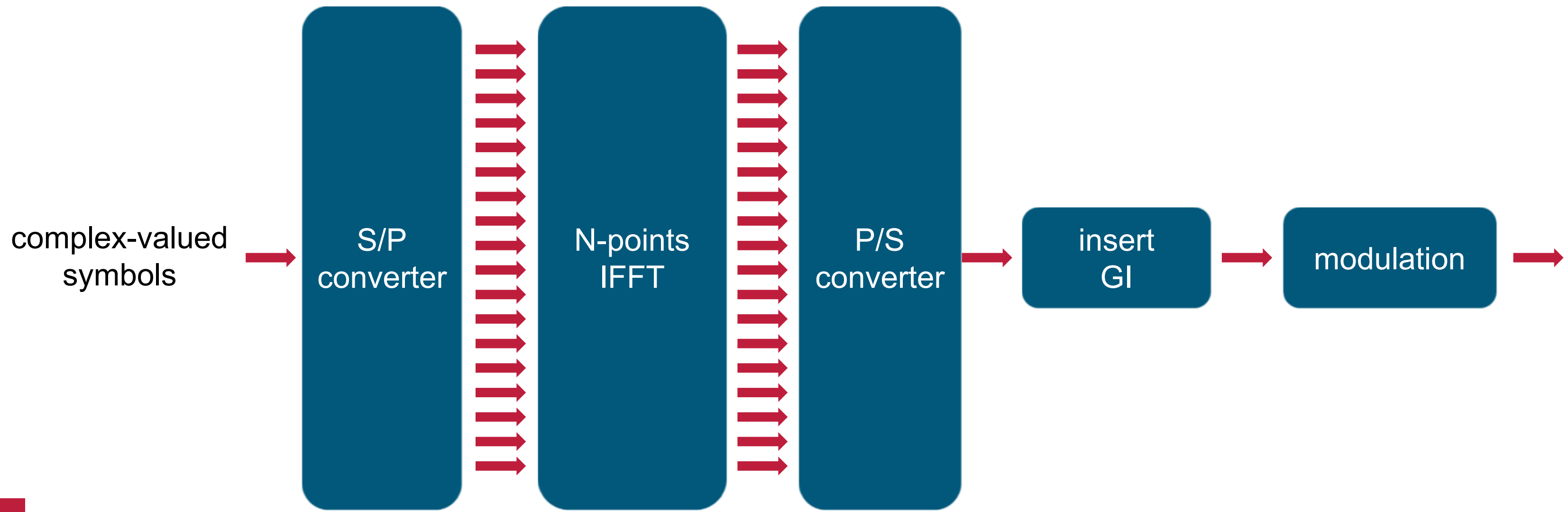
Signal Generation at the Physical Layer

- The signal generation at the physical layer (in UL/DL) comprises the following steps:
  - Adding of the error correction (Forward Error Correction (FEC))
    - Convolutional code for control information
    - Turbo code for user data
  - Scrambling (corresponds to multiplication by PN sequence)
  - Symbol mapping (modulation of bit groups to complex-valued symbols)
  - Layer mapping and pre-coding (only for multi antenna transmission)
  - Mapping to resource elements (RE)
  - OFDM signal generation (different for uplink and downlink)



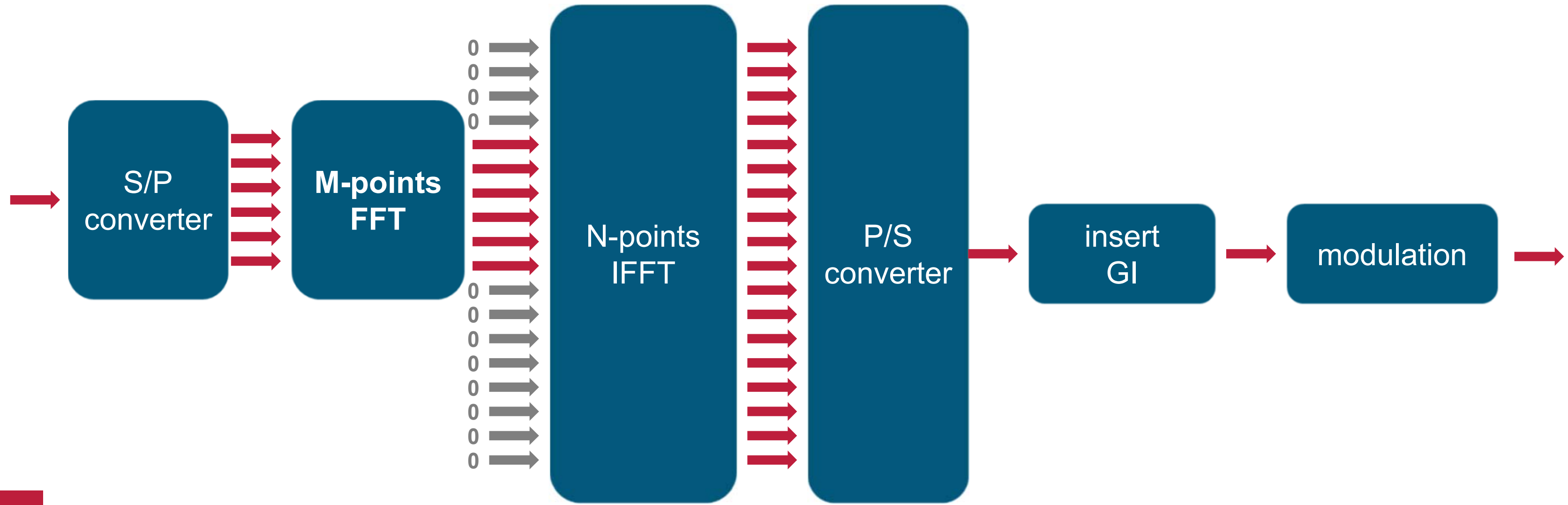
Signal Generation in the Downlink – OFDM

- Reasons for the selection of OFDM for LTE downlink:
  - Excellent suitability for frequency-selective radio channels
  - Flexible usage of the available frequency spectrum (frequency-selective scheduling)
  - Easier support of MIMO technologies (subcarriers are not frequency-selective)
  - Efficient implementation options (FFT/IFFT)
  - Better performance for Broadcast services (SFN)



Signal Generation in the Uplink – SC-FDMA

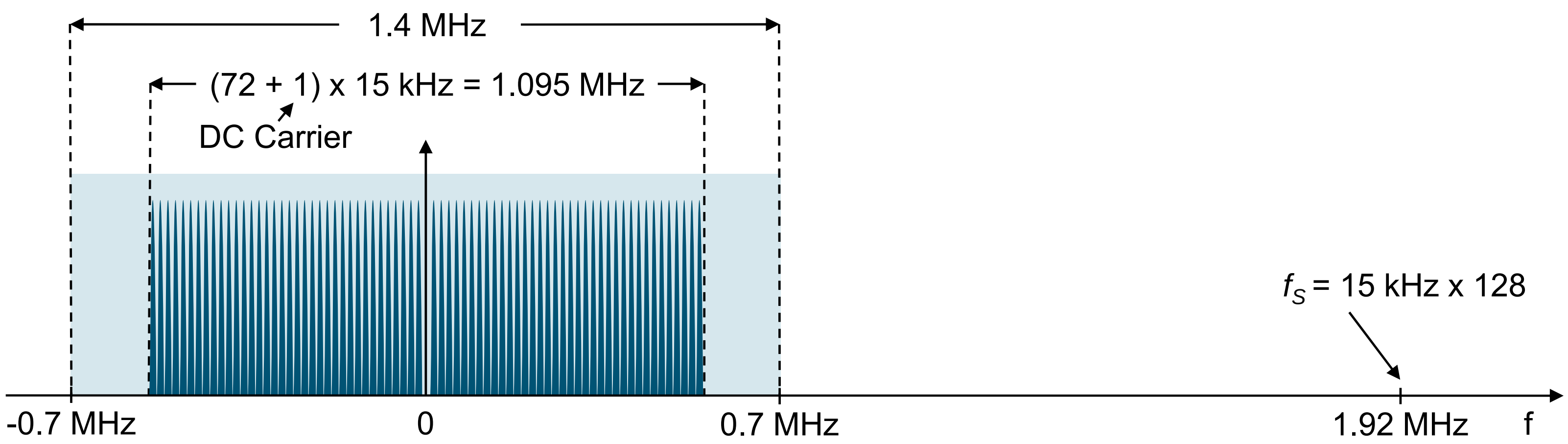
- The principle of SC-FDMA is very similar to the OFDM principle
- The only difference to OFDM consists in the additional M-points FFT block
- The technique is also referred to as **DFT-Spread OFDM** or **DFT-Precoded OFDM**
- Advantages of the method:
  - Better PAPR characteristics (extension of battery life, increase in cell range)
  - Equalisation in the frequency domain (efficient implementation)



Overview of Essential OFDM Parameters with LTE (1)

Bandwidth	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
subcarrier separation	15 kHz					
FFT length	128	256	512	1024	1536	2048
sampling rate	1.92 MHz	3.84 MHz	7.68 MHz	15.36 MHz	23.04 MHz	30.72 MHz
number of subcarriers	72	180	300	600	900	1200
number of PRB	6	15	25	50	75	100

Illustration of the parameters using the example of 1.4 MHz bandwidth:I



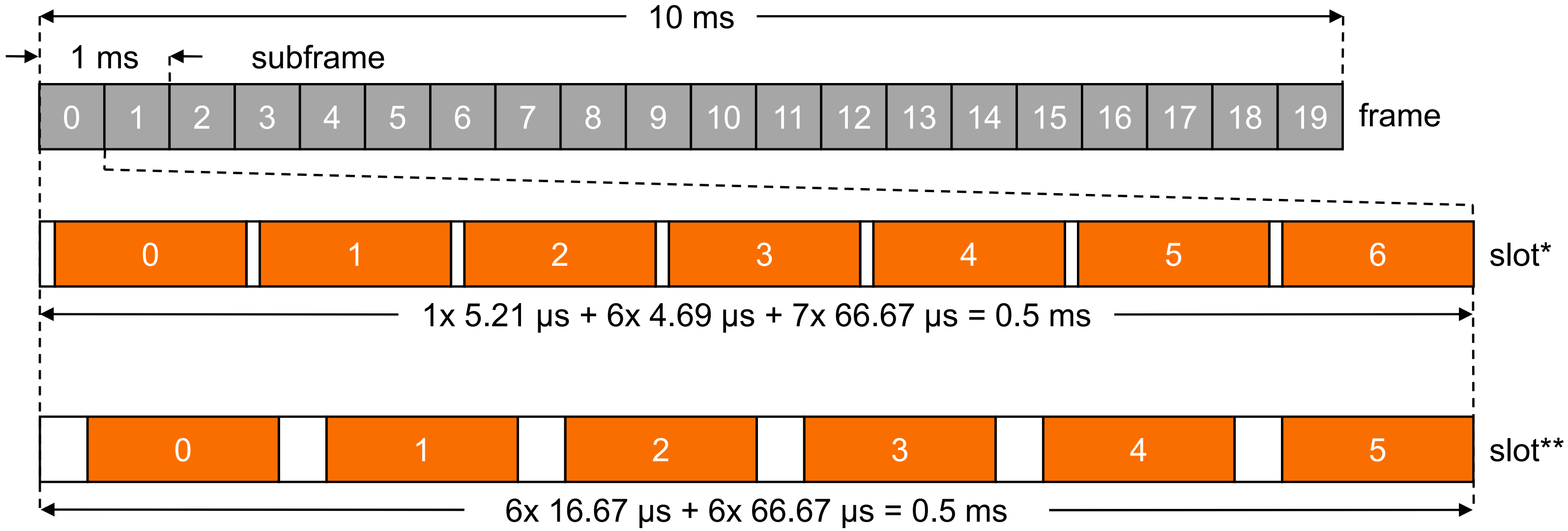
Overview of Essential OFDM Parameters with LTE (2)

- Duration of the OFDM core symbol (66.67 µs) is independent of the selected bandwidth
- Two GI (Guard interval) lengths for different use cases are specified:
  - **Short GI**: primarily for **Unicast operation**
  - **Long GI**: for **Broadcast transmission** or for **cells with large cell radii**
- On the next slide, the frame structure (frame, etc.) with LTE is discussed

frame duration		10 ms
subframe duration		1 ms
slot duration		0.5 ms
OFDM symbols per slot	short GI	**7**
	long GI	6
FFT duration (=1/Δ*f*)		**66.67 µs**
duration of the Guard interval	short GI	5.21 µs (1x); **4.69 µs** (6x)
	long GI	16.67 µs
OFDM symbol duration	short GI	71.88 µs (1x); **71.36 µs** (6x)
	long GI	83.34 µs

LTE Frame Structure in Uplink and Downlink

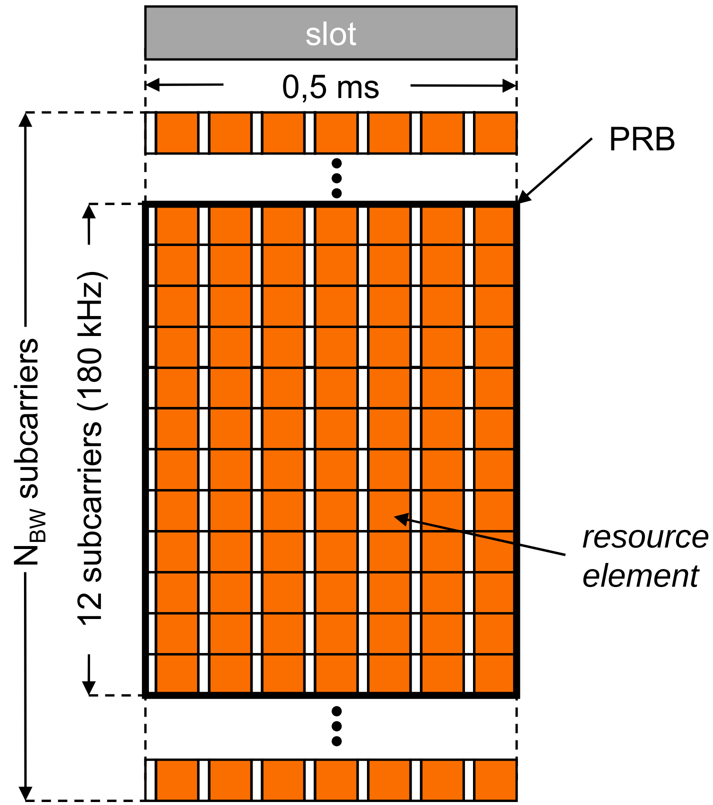
- Frame structure of LTE is identical in UL and DL
- The data stream is divided into **frames** of a duration of 10 ms each
- A frame consists of 10 **subframes** (1 ms each)
- A subframe is divided into 2 **slots** (0.5 ms each)
- A slot contains 7 or 6 OFDM symbols each (dependent on the length of the GI)



* with short GI, ** with long GI

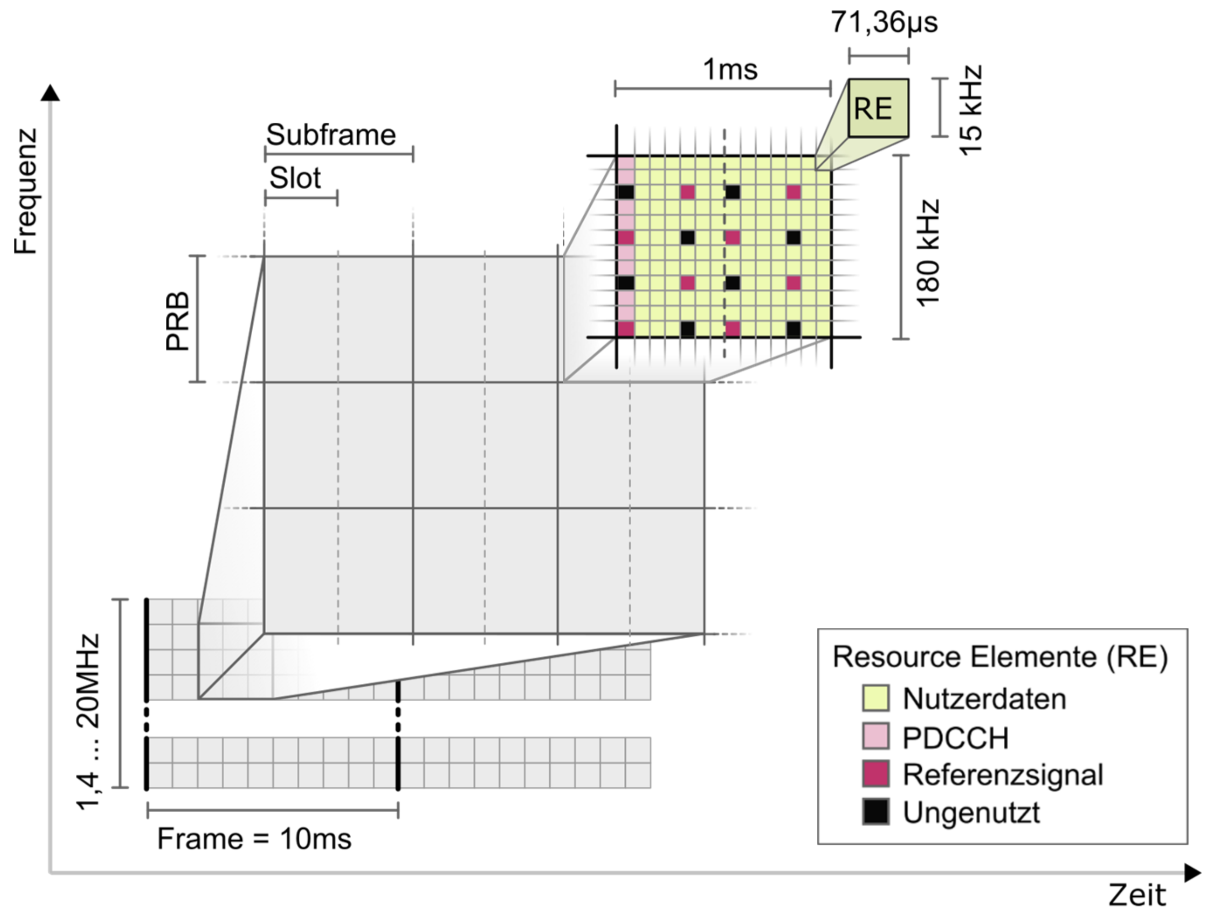
Definition of the Ressource Block (1)

- Allocation of the data to single users takes place in **Physical Resource Blocks (PRB)**
- A PRB consists of **12 subcarriers** (complies with 12 x 15 kHz = 180 kHz) and **6 or 7 OFDM symbols** (complies with a *slot* duration of 0.5 ms)
- PRBs are the smallest units that are distributed by the scheduler to the respective UEs
- Depending on the bandwidth, the number of subcarriers N_{BW} per channel varies and thus the number of PRBs



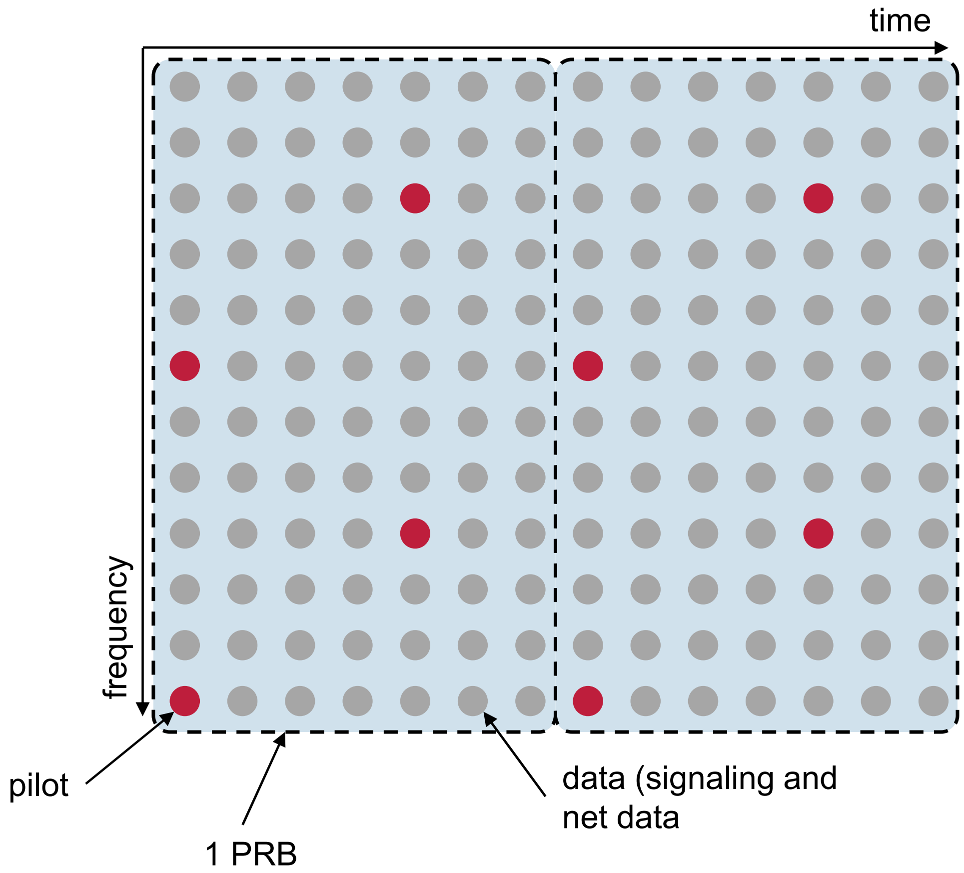
Bandwidth in MHz	1.4	3	5	10	15	20
N_{BW}	72	180	300	600	900	1200
PRBs	6	15	25	50	75	100

Definition of the Resource Block (2)



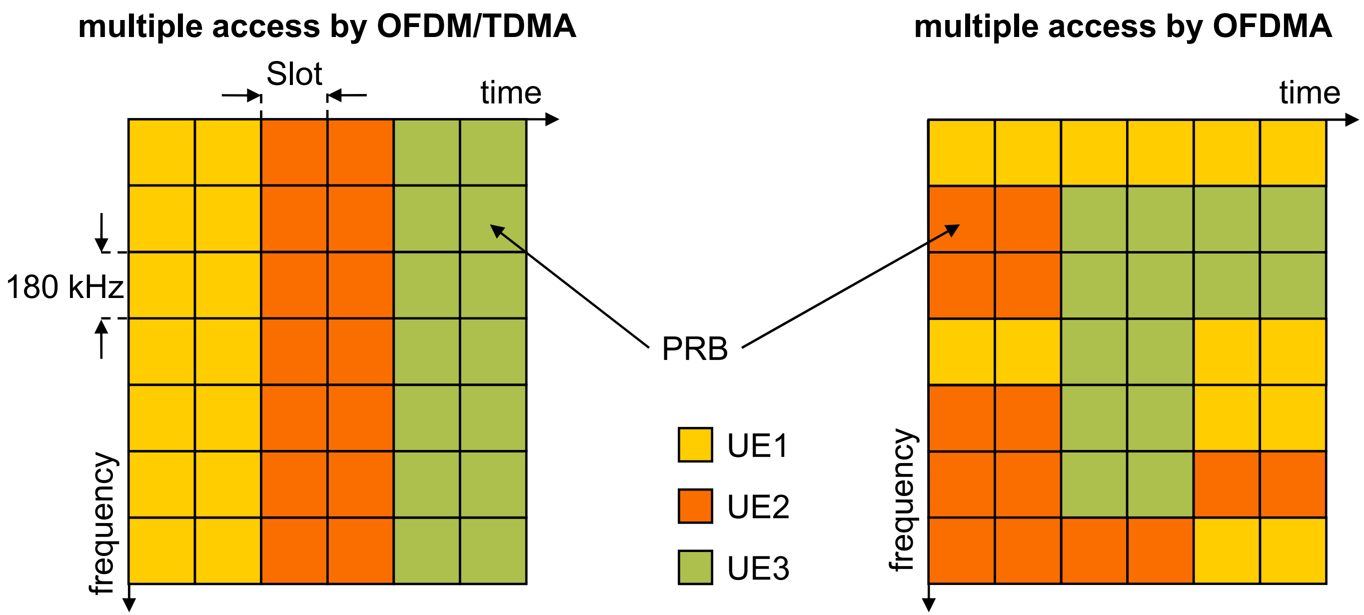
Reference signals (Pilots) with LTE in Downlink

- LTE uses scattered pilots
- Absolute position in the time grid / frequency grid depends on the cell
- Pilots in DL are sent as Broadcast signal (are received by all MS in the cell)
- MS uses estimation for
  - coherent demodulation
  - feedback to base station (adaptive modulation)
- With MIMO configurations, pilots are orthogonal to each other



Orthogonal Frequency Division Multiple Access (OFDMA)

- OFDMA describes an OFDM-related multiple access method
- Available ressources can be assigned to single UEs in **frequency as well as in time direction**
- OFDMA allows a very flexible distribution of the ressources to different users
- Resource allocation takes place in eNodeB (different scheduling approaches possible)



Scheduling Algorithms

- In LTE mobile radio networks, various scheduling algorithms exist
- Algorithms are a „company secret“ of the vendor and the operator, respectively
- Example of three selected algorithms with 4 users:

SINR	**High**	**Low**	Normal	Normal
Data demand	Normal	Normal	**High**	**Low**

Scheduling algorithm	Description	Resource allocation
Round Robin	same amount of resources for all users	
Maximum Throughput	maximizes data rates at the base station	
Proportional Fair	SINR adapted resource allocation	

- The deployed scheduler determines the individual user experience

LTE Data Rate

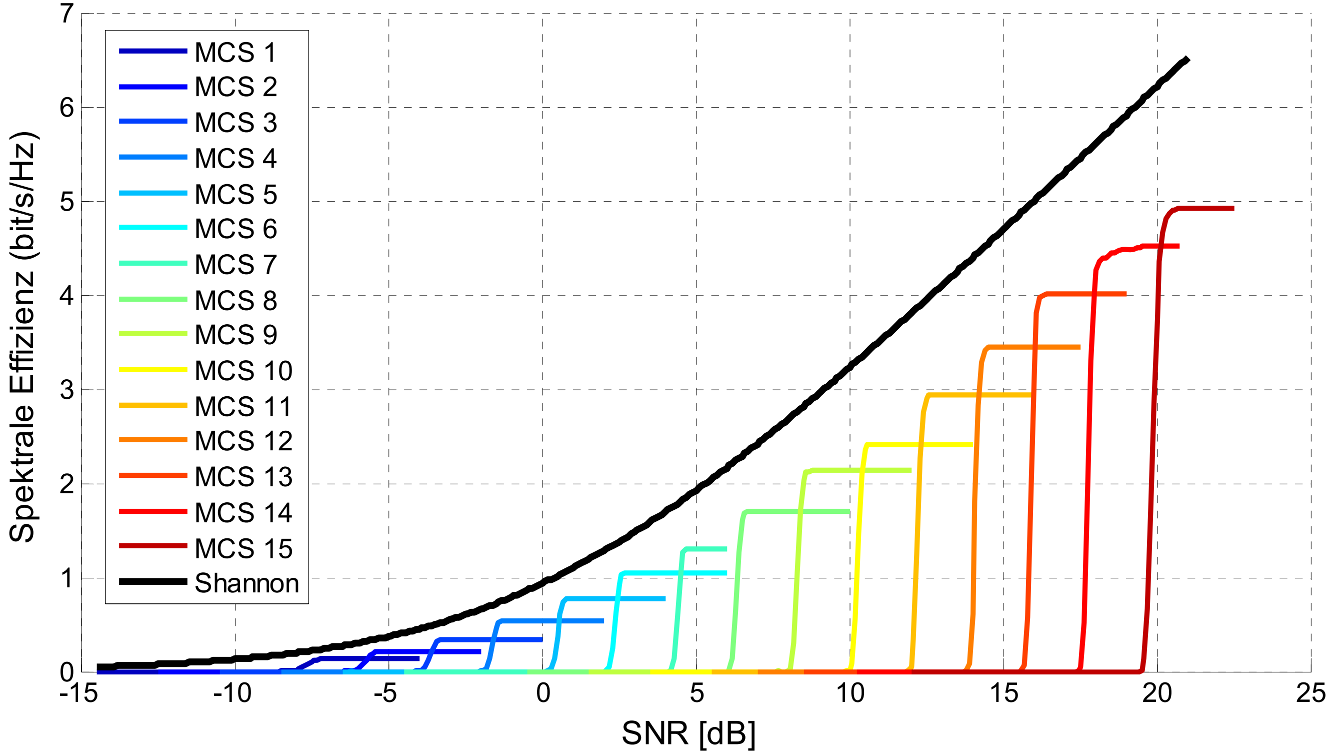
MCS	Modulation	Bit per resource	Code rate x 1024	Data rate per RB [kbit/s]
1	QPSK	2	78	25.6
2	QPSK	2	120	39.4
3	QPSK	2	193	63.3
4	QPSK	2	308	101.0
5	QPSK	2	449	147.3
6	QPSK	2	602	197.5
7	QPSK	2	378	248.1
8	16-QAM	4	490	321.6
9	16-QAM	4	616	404.3
10	16-QAM	4	466	458.7
11	64-QAM	6	567	558.1
12	64-QAM	6	666	655.6
13	64-QAM	6	772	759.9
14	64-QAM	6	873	859.4
15	64-QAM	6	948	933.2

Which Data Rates are possible for MCS1

- Sample calculation for MCS 1
  - Data rate per RB (normal Guard interval) =
    12 subcarriers x 7 time slots x 2 bit/resource (QPSK) x 78/1024 (code rate) x
    1 resource block/0.5 ms = 25.6 kbit/s
  - Data rate per RB (long Guard interval) =
    12 subcarriers x 6 time slots x 2 bit/resource (QPSK) x 78/1024 (code rate) x
    1 resource block/0.5 ms = 21.9 kbit/s
- Overhead by signaling not yet considered
- For the long Guard interval, lower data rates result from higher SFN gain
- Adaptive allocation of the MCS on the basis of the connection quality

Adaptive Throughput Mapping

- Which MCS can be applied depends on the SINR conditions of the user
- The MCS is dynamically adapted to the channel (Adaptive Throughput Mapping)



Bandwidth-Dependent Data Rate at MCS 15 (SISO)

- Assumption: Reduction of the data rate by 20% due to overhead → 746.5 kbit/s per RB

Band width [MHz]	Mode	Number of resource blocks	Data rate DL [Mbit/s]
1.4	FDD	6	4.5
3	FDD	15	11.2
5	FDD	25	18.6
10	FDD	50	37.3
15	FDD	75	56.0
20	FDD	100	74.6

LTE-A (LTE-Advanced)

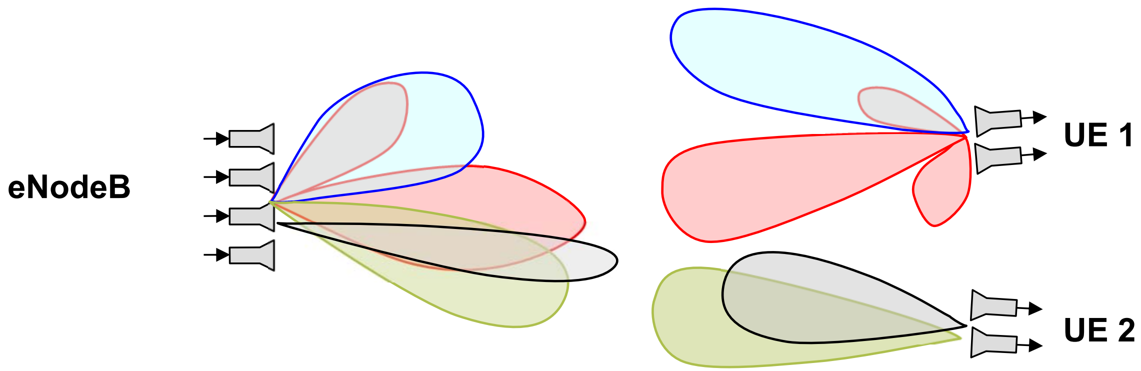
- LTE from Release 10 is referred to as LTE Advanced (LTE-A)
- The aim is to achieve peak data rates of 1 Gbit/s for low mobility and 100 Mbit/s for high mobility

	IMT-Advanced requirement	LTE Rel. 8	LTE Rel. 10
bandwidth	min. 40 MHz	up to 20 MHz	up to 100 MHz
spectral efficiency (peak) downlink	15 bit/s/Hz	16 bit/s/Hz	16 bit/s/Hz (4x4 MIMO) 30 bit/s/Hz (8x8 MIMO)
spectral efficiency (peak) uplink	6.75 bit/s/Hz	4 bit/s/Hz	8.1bit/s/Hz (2x2 MIMO) 16.1bit/s/Hz (4x4 MIMO)
latency (signaling data)	< 100 ms	50 ms	50 ms
latency (net data)	< 10 ms	4.9 ms	4.9 ms

- Inter alia, the aim is to be achieved by
  - carrier aggregation
  - 8x8 MIMO in downlink

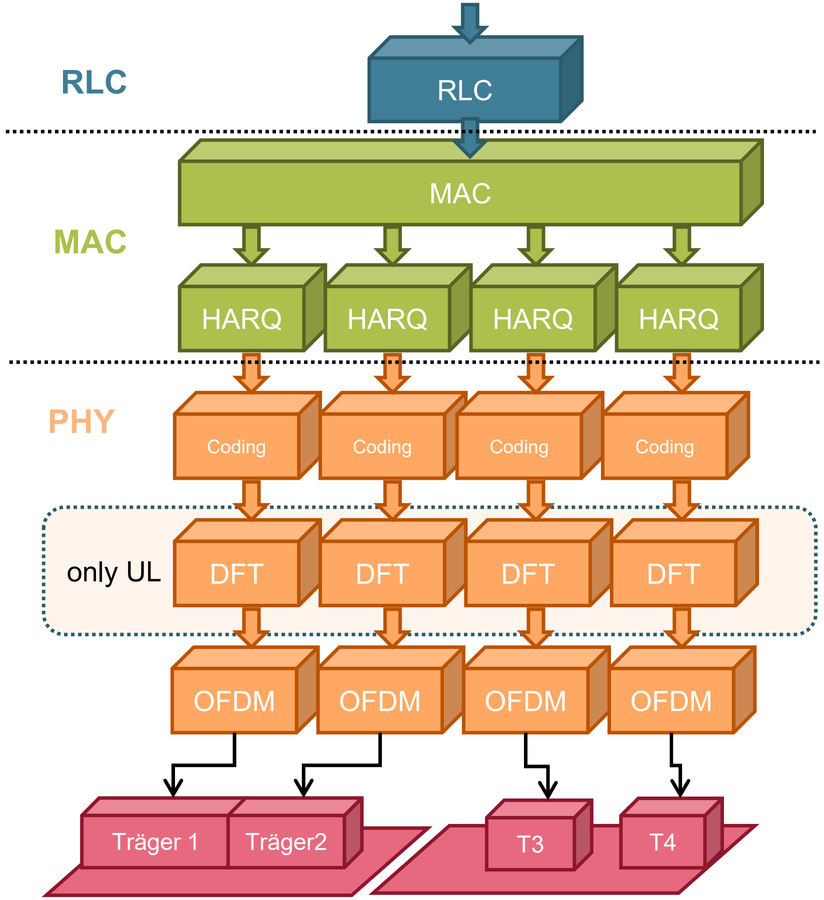
Extension of MIMO

- Downlink
  - Transition from 4x4 MIMO to 8x8 MIMO
  - Additional reference signals for the transmission of channel state information (CSI- Channel State Information)
  - User-specific demodulation of the reference signals
  - Application of Multi User Beamforming (e.g. 4x2 MIMO)
- Uplink
  - Transition from 2x2 MIMO to 4x4 MIMO



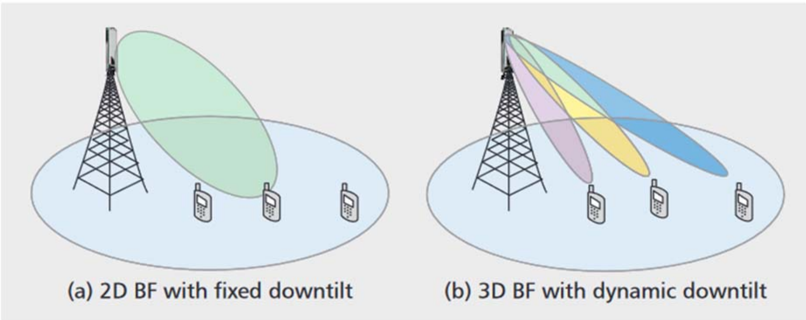
Carrier Aggregation

- For a single connection, the required bandwidth (e.g. 100 MHz) does no longer have to be available at a contiguous frequency band:
  - Aggregation of various carriers of different bandwidths from multiple spectrum ranges
  - Better utilisation of fragmented spectrum
  - Backward compatibility with Release 8/9
  - For each carrier, a separate connection on PHY level exists



LTE-Advanced Pro

- Essential extensions in Rel. 13, i. a.:
  - Improvement with carrier aggregation (bundling of up to 32 channels)
    - max. 25 Gbit/s (theoretical) at 256 QAM in DL
    - max. 14 Gbit/s (theoretical) at 64 QAM in UL
  - Use of unlicenced bands in the 5 GHz range
  - LTE Cellular V2X
  - 3D – (full-dimensional) – MIMO



source: IEEE Wireless Communications, June 2014

5G NR

- 5G New Radio (5G NR) is based on LTE
- Essential modifications:
  - Extension of the frequency bands to FR1 (450-6000 MHz) and FR2 (24,25-52,6 GHz)
  - Bandwidths
    - FR1: 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 MHz
    - FR2: 50, 100, 200, 400 MHz
  - ODFM is applied in downlink and uplink (no SC-FDMA anymore!)
    - Numerology:
      - Variable subcarrier spacing (SCS – subcarrier spacing) of 2^{μ} x 15 kHz (μ=0,1,2,3,4)
      - can be selected in dependence on the Doppler frequency
      - Longer subcarrier separations lead to shorter OFDM symbol durations => shorter slot durations => favourable to reduce the latency, which is important for URLLC

Supported Numerologies/Definition of Resource Blocks

Source: W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020

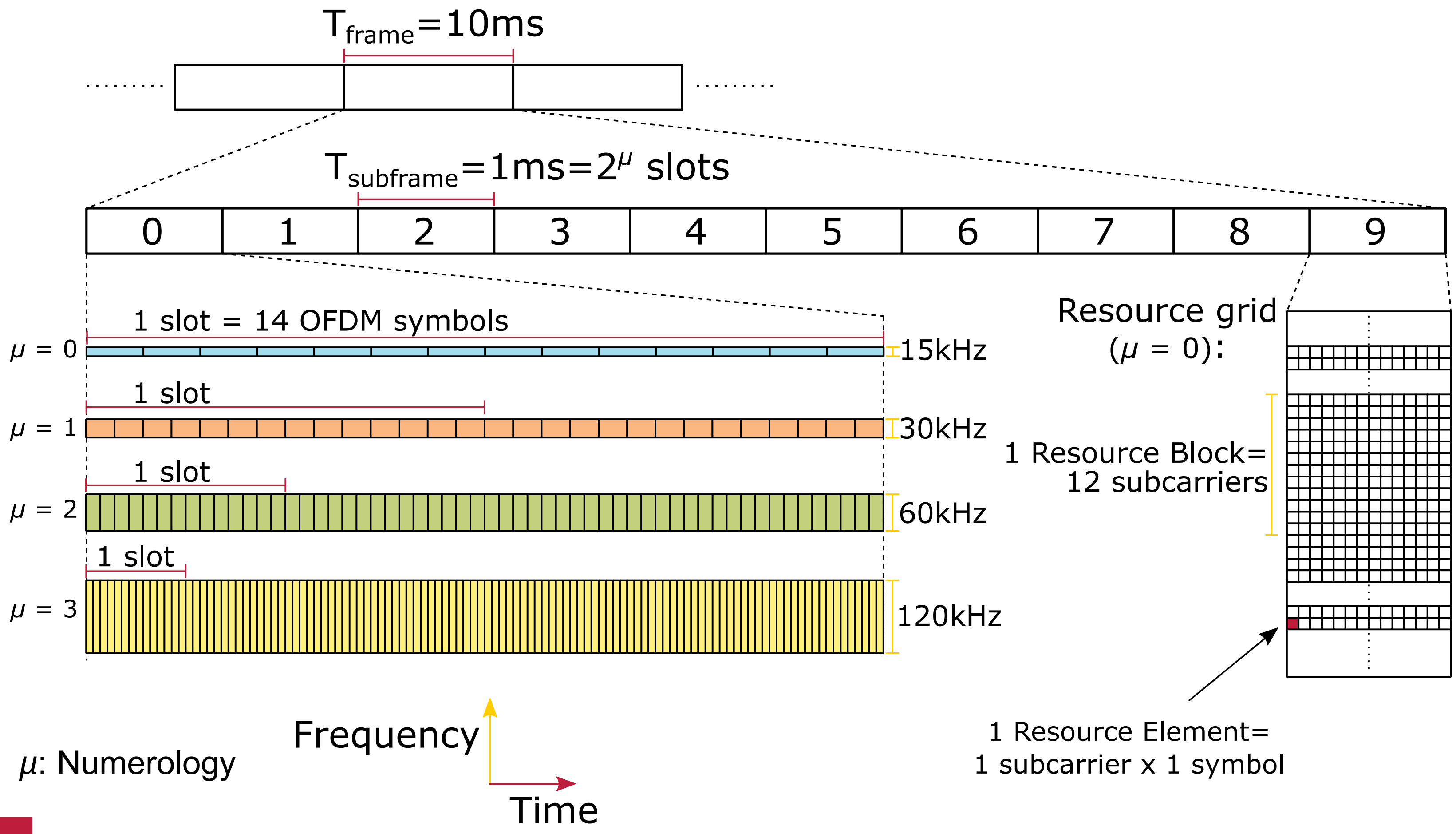
	SCS	Cyclic prefix			Applicable frequency range			
			Length of CP within one subframe		FR1			
μ	$\Delta f = 2^{\mu} \cdot 15$ [kHz]	Type	$l = 0$ or $7 \cdot 2^{\mu}$ (normal CP)	others	Sub 1 GHz	1–3 GHz	3–6 GHz	FR2
0	15	Normal	$144 * \Delta + 16 * \Delta$	$144 * \Delta$	√	√	√	–
1	30	Normal	$144 * \Delta/2 + 16 * \Delta$	$144 * \Delta/2$	√	√	√	–
2	60	Normal	$144 * \Delta/4 + 16 * \Delta$	$144 * \Delta/4$	–	√	√	√
2	60	Extended	$512 * \Delta$		–	√	√	√
3	120	Normal	$144 * \Delta/8 + 16 * \Delta$	$144 * \Delta/8$	–	–	–	√
4[a]	240	Normal	$144 * \Delta/16 + 16 * \Delta$	$144 * \Delta/16$				

Note: Δ is the oversampling factor over 2048

[a]240 KHz is defined in the numerology, but not used for FR1 and FR2 currently in Rel-15

	LTE	5G NR
Bandwidth of a Resource Block (RB)	180 kHz (12x15 kHz)	variable (12 x 2^{μ} x 15 kHz)
Number of OFDM symbols per RB	6-7	no restriction;

Ultra-Reliable and Low-Latency Communication (URLLC)



μ: Numerology

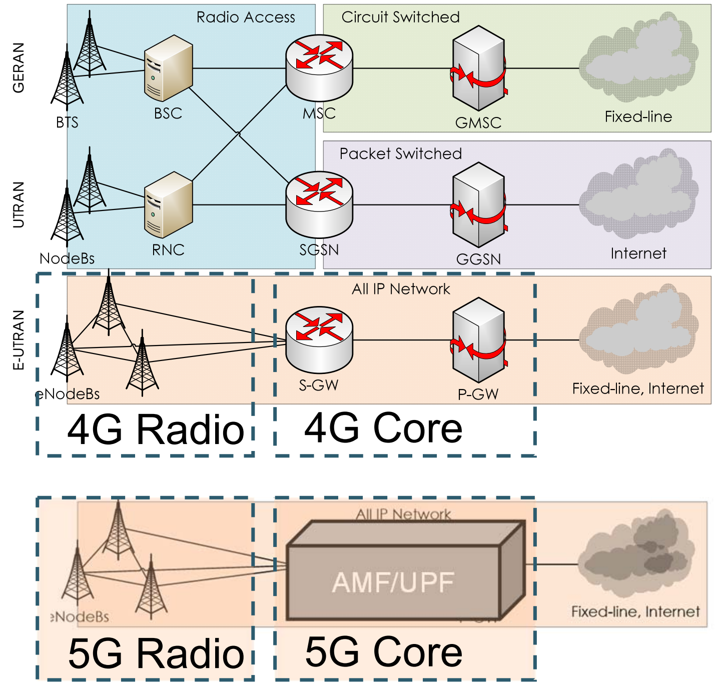
5G Multi-Layer Approach

Layer	5G Use case	Application	Frequency Range
Super Data Layer	eMBB	Special application using ultra-high data rates	Beyond 6 GHz (at least 800 MHz contiguous bandwidth)
Coverage and Capacity Layer	eMBB, URLLC, mMTC	Extensive; no deep indoor coverage	2-6 GHz (100 MHz contiguous bandwidth)
Over-Sailing Layer	eMBB, URLLC, mMTC	Extensive deep indoor coverage	Below 2 GHz (up to 20 MHz bandwidth)

Source: based on W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020

6.4 Network Architecture

- With the network architecture, during the development of 2 over 3G and 4G towards 5G an evolution can be noticed:
  - GERAN (2G):
    - Strongly hierarchical circuit-switched network with GSM
    - Introduction of packet switching with GPRS
  - UTRAN (3G, UMTS)
    - Modifications in the radio access network (Radio Access)
    - First IP components with HSPA+
  - E-UTRAN (4G, LTE)
    - Transition to all-IP networks
  - 5G:
    - Further development of the core network to make shorter latency times possible
    - Introduction of Networks Slicing, Multi Access Edge Computing



GSM Network Achitecture

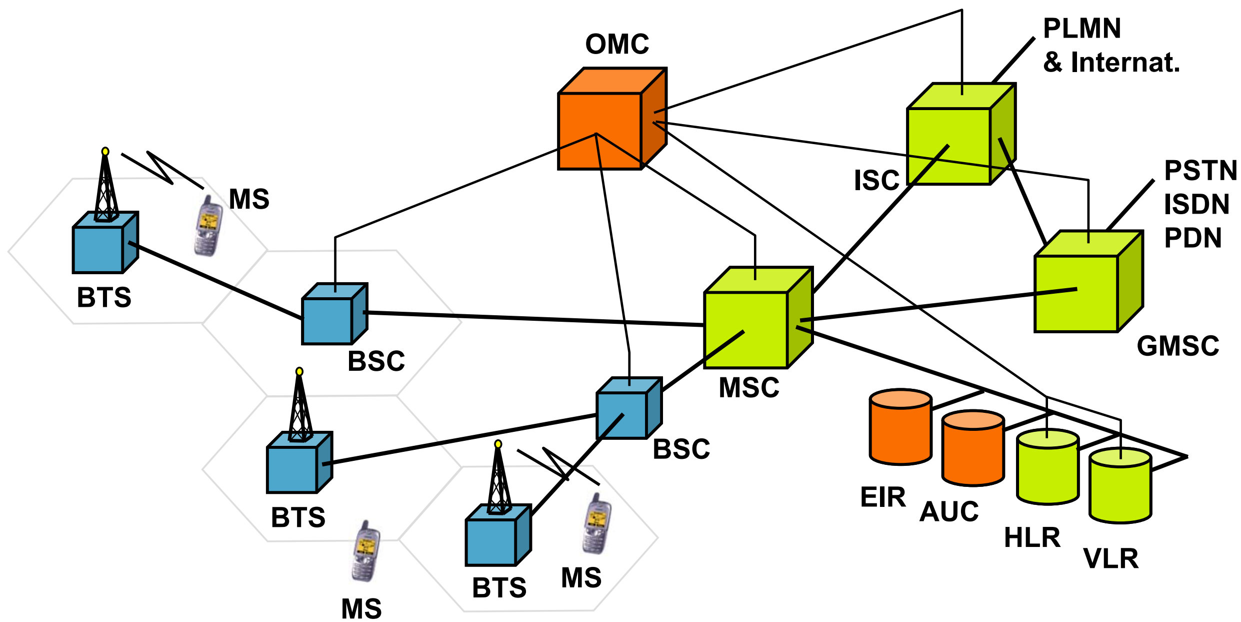
- The overall system is divided into 3 subsystems
  - Radio Sub-System - RSS
    - Mobile Station (MS)
    - Base Station Sub-System (BSS)
  - Switching subsystem (Network and Switching Sub-System - NSS)
  - Subsystem for operation and maintenance (Operation Sub-System - OSS)

- Access Network: network consisting of the components of the BSS

- Core Network: network consisting of the components of the NSS

- Transport Network: network consisting of the connections between the network elements from BS upward

Essential Components of the GSM Network Architecture



BSS Base Station Sub-System
NSS Network and Switching Sub-System
OSS Operation Sub-System

MS Mobile Station
BTS Base Transceiving Station
BSC Base Station Controller
MSC Mobile Switching Center
GMSC Gateway MSC
ISC International Switching Center

HLR Home Location Register
VLR Visitor Location Register
EIR Equipment Identity Register
AUC Authentication Center
OMC Operation and Maintenance Center

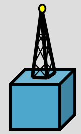
Souce: according to J. Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

Mobile Stations (MS)

MS

- Mobile stations are those devices used by mobile subscribers for service access.
- Two essential components:
  - device (mobile equipment)
  - Subcriber Identity Module (SIM)
    - includes subscriber information
    - Radio network information (e. g. latest location area, list of preferred networks abroad)
- Main task of the MS:
  - Receiving and transmitting of network and control data
  - Measurements of receive levels and bit error rates

Base Station Sub-System (BSS)



Base Station (BS), Base Transceiver Station (BTS)

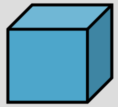
- Radio coverage of a specific area
- Main task:
  - Transmitting and receiving of net and signalling information
  - Measurements of the reception quality
  - Complete signal processing (exception: speech decoding)
- Transmitting power: some watt up to maximal 100 W
- Sector cells: 1 base station covers up to 3 sector cells

BS antenna system

Base station

BSC and TRAU

BSC



Base Station Controller (BSC)

- controls 10 to 100 base stations
- Traffic aggregation and dispersion
- Radio channel selection with call set-up
- Decision on handover and transmitting power control
- Connection between BS and BSC via leased lines or microwave links in line or ring configuration

Transcoding and Rate Adaption Unit (TRAU)

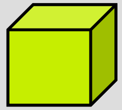
- Conversion of the GSM speech signal (13 kbit/s) to ISDN signal (64 kbit/s)
- Adaptation of data rates for data services

Base Station Controller

Radio link to BSC

6.4 Network Architecture
Network and Switching Sub-System (NSS)

MSC



Mobile Switching Centre

- ISDN switching centre with additional functions to ensure mobility
- Main task:
  - Directed set-up of a call between 2 or several subscribers

- Gateway MSC (GMSC):
  - Transition between GSM network and another network (analogue telephone network, ISDN, another mobile radio network, data network)

- Signalling between different network elements in NSS is effected via the signalling system No. 7 (SS#7)

HLR and VLR

Home Location Register (HLR)

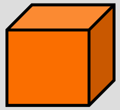
- Data base containing subscriber data
  - Identification number (mobile ISDN multiple subscriber number)
  - Services subscribed by the user
  - Identification number of the currently responsible MSC (important for roaming)
  - Maintenance of the parameters for additional services
  - Not under control by an MSC

Visitor Location Register (VLR)

- Normally assigned to an MSC
- Copy of the data from the HLR of those subscribers, for which the MSC linked with the VLR is currently responsible

Operation Sub-System

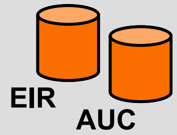
OMC



Operation and Maintenance Centre (OMC)

- Generally separated for base station and switching sub-systems
- Operation and maintenance work regarding the network
  - Detection, localisation and possibly correction of errors in the network components
  - Configuration of the network elements (frequency plans, transmitting power, handover parameters)
  - Software management (updates of software versions for the network elements)
  - Collection of data for the network performance (traffic load, blocking rates, quality of the received signal, ...)
  - Subscriber service (accounting, administration, billing)

Operation Sub-System



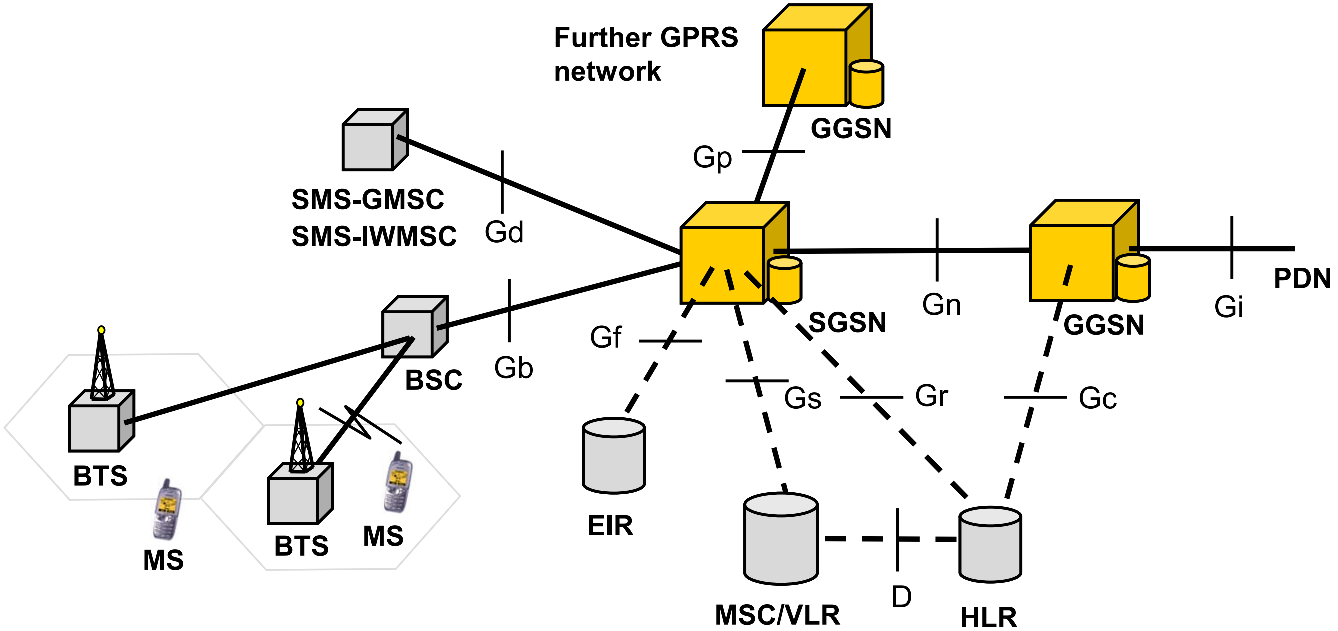
Authentication Centre (AuC)

- Storage of the personal network access key for every subscriber
- Check of the network access authorisation

Equipment Identification Register (EIR)

- Management of the registration numbers of the mobile stations
- Identification as well as blocking of obsolete and stolen mobile stations, respectively

GPRS System Architecture



SGSN Serving GPRS Support Node
GGSN Gateway GPRS Support Node

Source: according to J. Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

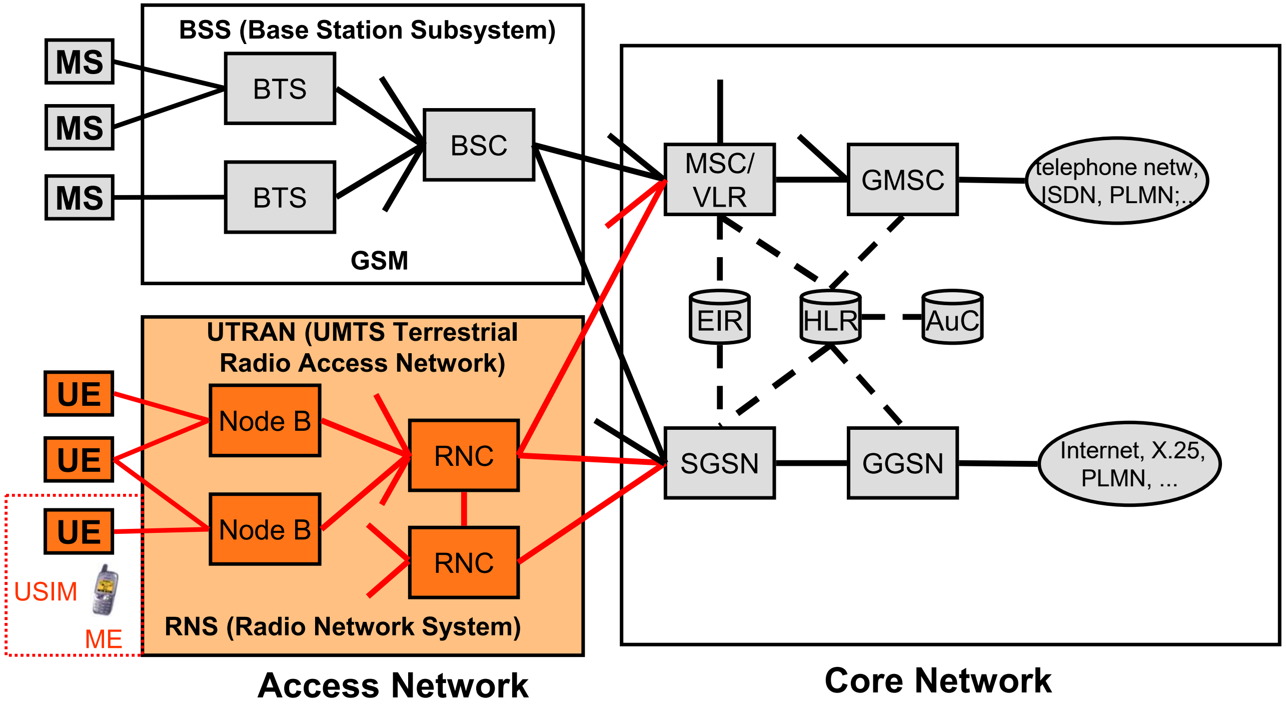
GPRS Network Elements

Serving GPRS Support Node (SGSN)

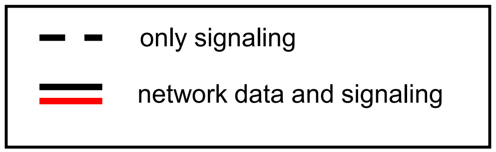
- Responsible for the delivery of the data packets from and to the mobile stations
  - Routing of packets
  - Functions for attaching and detaching of mobile stations
  - Management of the logical connections
  - Authentification
  - Storage of location information and user-specific information in the location register
  - Billing

- **Gateway GPRS Support Node (GGSN)**
  - Interface to the supported external data networks PDN (Packet Data Network)
    - Convertion of the GPRS packet coming from the SGSN into the protocol of the PDN
    - In the opposite direction, analysis of the PDP (Packet Data Protocol) address and conversion to the GSM address

UMTS



RNC:	Radio Network Controller
UE:	User Equipment
ME:	Mobile Equipment
USIM:	UMTS Subscriber Identity Module



Source: according to C. Lüders, Mobilfunksysteme

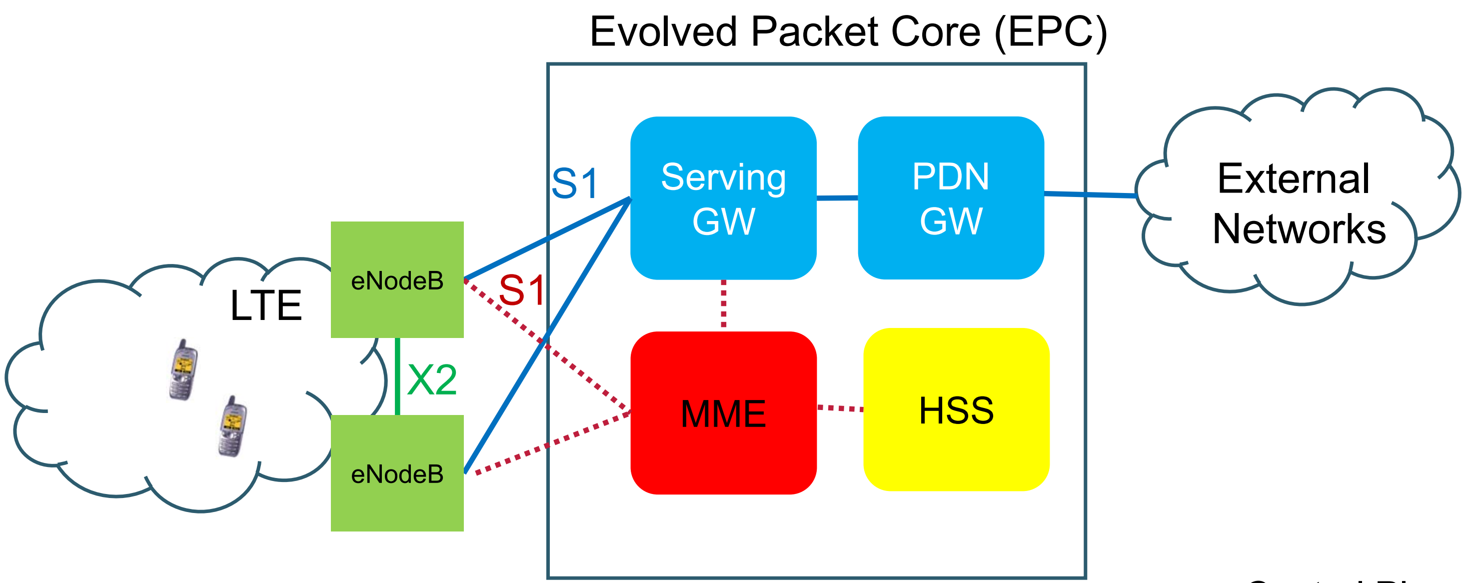
UMTS – Network Elements

- **User Equipment (UE)**
  - UMTS mobile station consisting of the terminal and the UMTS Subscriber Identity Module (USIM)

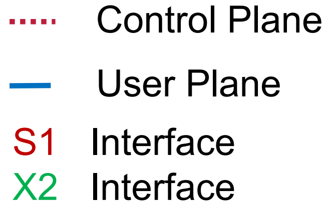
- **Node-B**
  - corresponds approximately to the GSM base station
  - Radio coverage of one or several cells
  - Operation in FDD mode, TDD mode or in both

- **Radio Network Controller (RNC)**
  - Control of several Node-Bs
  - corresponds approximately to BSC in GSM
  - RNCs are linked together (important for soft handover)

LTE



GW: Gateway
PDN: Packet Data Network
MME: Mobility Management Entity
HSS: Home Subscriber Server



Source: according to www.3gpp.org

LTE – Network Elements

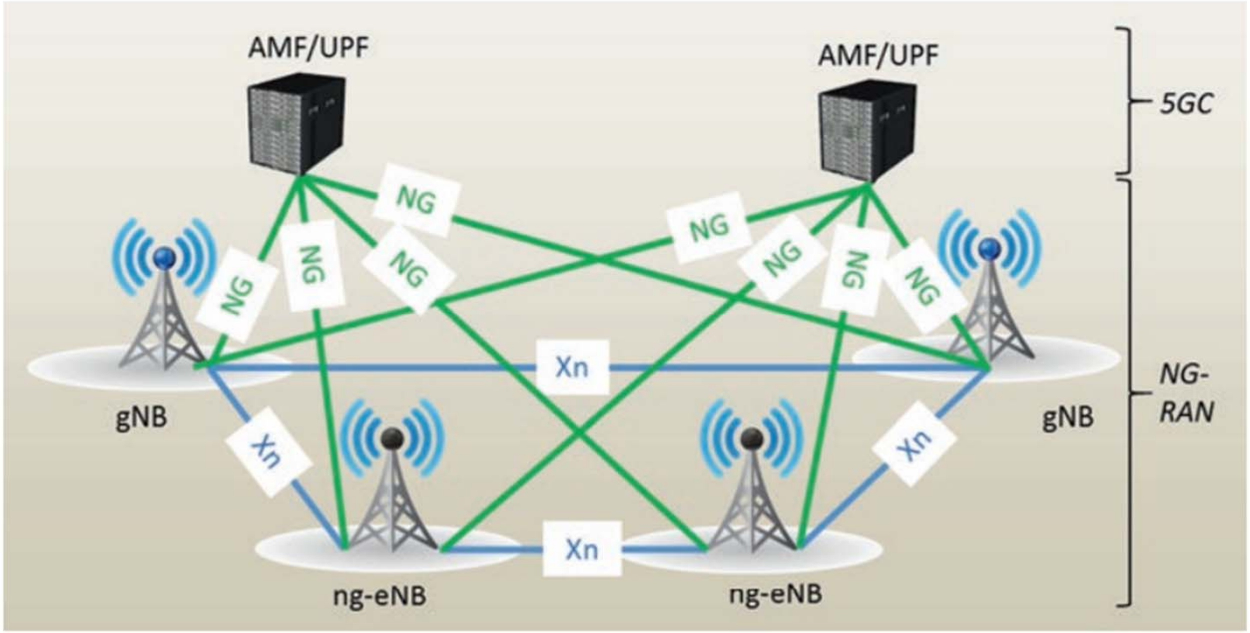
- **eNodeB:**
  - LTE base station (operation in TDD or FDD)
  - Tasks comparable to GSM or UMTS base station
  - Additional tasks that, with GSM/UMTS, have been undertaken by BSC and RNC, respectively.
- **Core network elements of the user plane**
  - **Serving Gateway (S-GW)**
    - Transport of the IP data between UE and external networks
    - Interface between radio access network and core network
    - Routing of incoming and outgoing IP packets
    - Anchor point for handover
  - **Packet Data Network Gateway (PDN-GW)**
    - Connection between EPC and external IP networks
    - Routing of packets from and to external networks
    - Management of IP addresses, billing
  - S-GW and PDN-GW are logically separated entities, however, in practice they are often integrated into a network element

LTE – Network Elements

- **Core network elements of the control plane**
  - **Mobility Management Entity (MME)**
    - Undertakes signalling relevant for mobility and security
    - Tracking and paging for UEs in idle mode
  - **Home Subscriber Server (HSS)**
    - Includes information about users and the subscribed services
    - Functions for mobility management, call and session set-up
    - Authentication of users and access points
    - Based on HLR and AuC (comp. GSM)

5G Network Architecture

Source: W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020



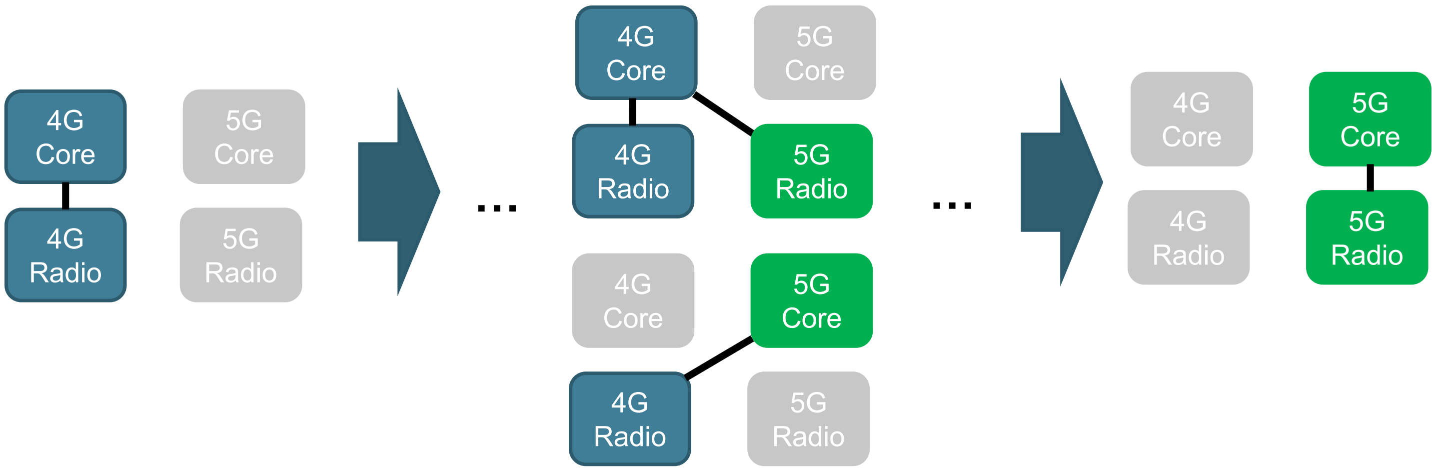
gNB:	5G base station
ng-eNB:	4G base station
Xn interface:	links base stations to one another (comp. X2 at LTE)
NG interface:	links base stations with AMF/UPF (Access and Mobility Management Function/ User Plane Function)

5G Network Elements

- **NG-RAN**
  - **gNB:** 5G base station
  - **Ng-eNB:** 4G base station
  - Tasks:
    - Radio resource management
    - Radio admission control
    - Scheduling
    - Measurements, configuration
    - etc.
- **Access and Mobility Management Function (AMF)**
  - Functions of the control plane such as authentication, mobility management, SMF selection etc.
- **User Plane Function (UPF)**
  - Functions of the user plane such as packet routing and forwarding, QoS handling etc.
- **Session Management Function (SMF)**
  - Functions for the session management, e. g. UE IP address allocation

Migration Strategies 4G->5G

- 5G base stations (5G radio) can be operated at a 4G Core (Non Standalone – NSA) as well as at a 5G Core (Standalone).
- Vice versa, 4G base stations can also be operated at a 5G Core.
- This allows numerous migration paths:



Network Slicing

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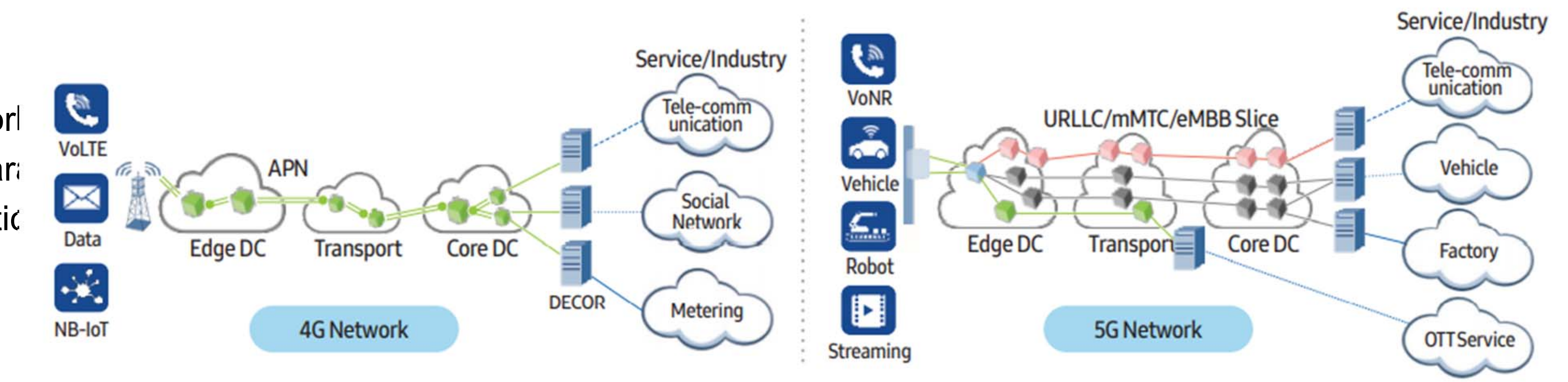
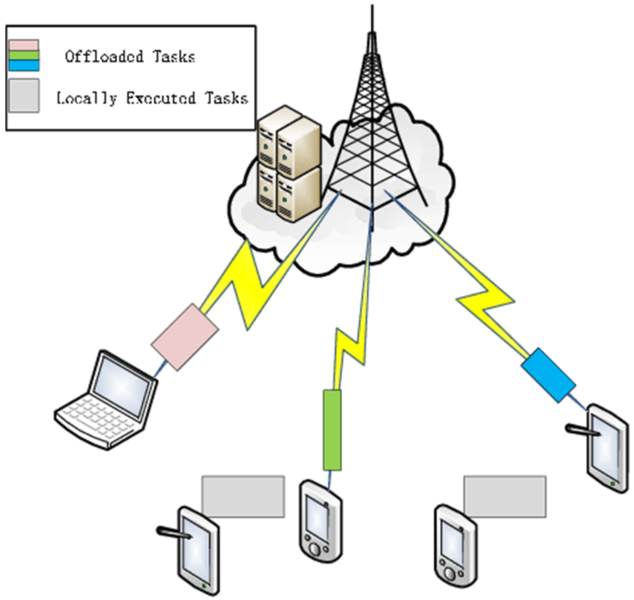


Source: Samsung, Techncial White Paper Network Slicing, April 2020

Multi Access Edge Computing (MEC)

- Multi Access Edge Computing (sometimes also referred to as Mobile Edge Computing)
  - Services and ressources are provided and made possible near the base station (i.e. on the edge of the network):
    - high bandwidths
    - small latency times
    - realisation of real-time services (e. g. autonomous driving, augmented reality)



Source: www.ip-insider.de

6.5 Organisation of the Radio Channels

- In a mobile radio system, the physical layer in the OSI reference model includes complex functions at the user-network interface (radio interface), such as

  - signalling
  - broadcast of general system information
  - synchronisation
  - channel allocation
  - paging
  - net data transmission

- These different functions have different requirements and have to be modelled over a limited number of resources available.

Description of the Radio Channel is divided into 3 Layers

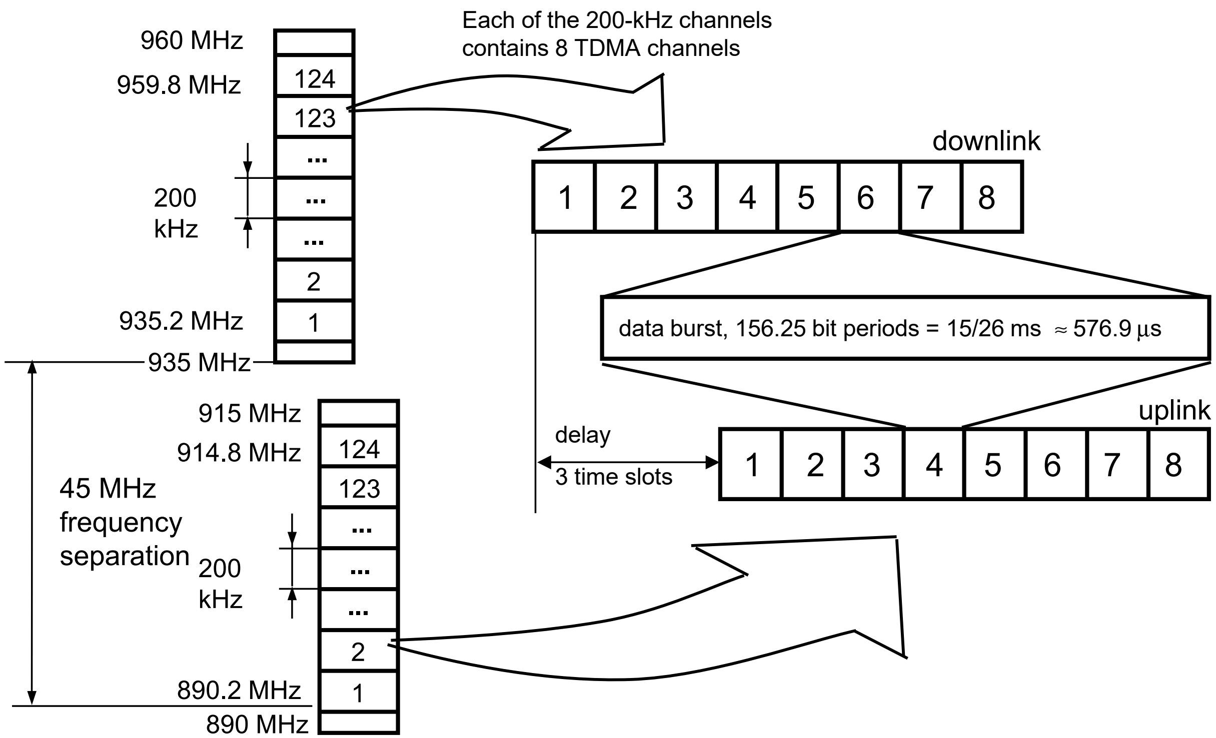
- Physical channel
  - Identification by stating the physical resource, e. g.
    - frequency and time slot (GSM)
    - spreading code, frequency (UMTS)
    - resource element (LTE, 5G)

- Transport channel
  - Characterisation of the radio channel in terms of the format for the transmission of the information (e. g. channel coding, interleaving, burst type)

- Logical channel
  - Identification by the type of information (e. g. net data, control data) transmitted and by the tasks observed by the logical channel, respectively

- In the following, the principle is first explained by means of the radio channels in GSM

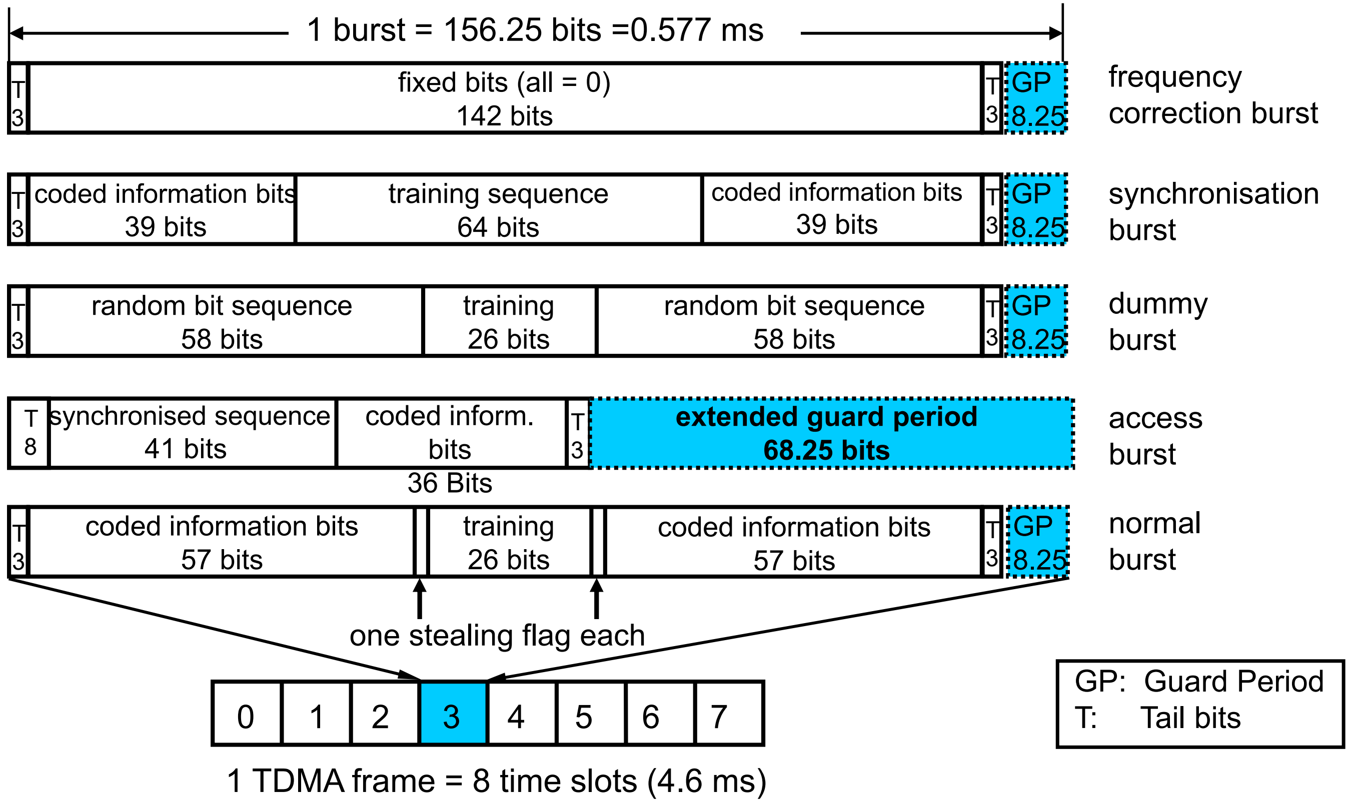
Physical Channels in GSM



- In each time slot of a TDMA frame, data bursts of a bit period time of 156.25 are transmitted.

Transport Channels in GSM

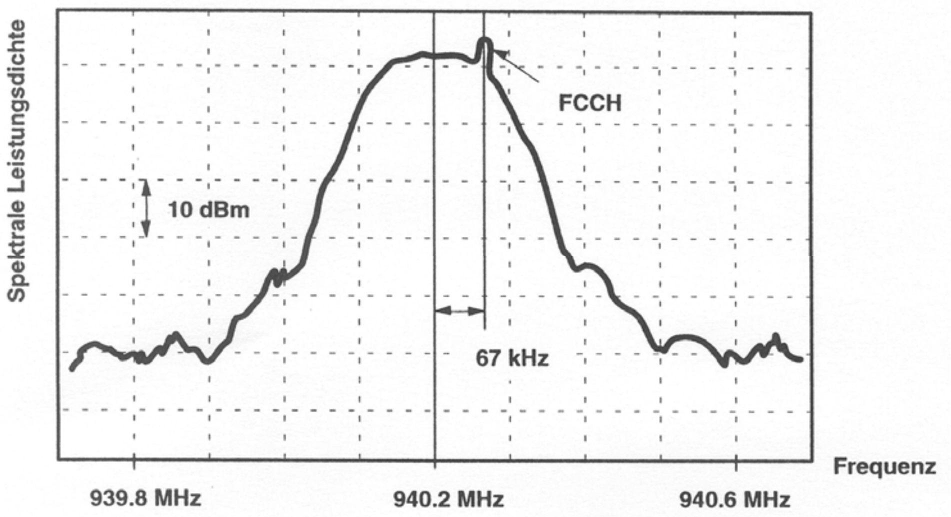
- Bursts of the TDMA Method



Frequency Correction Burst

- Frequency synchronisation of a mobile station

- FB complies with the transmission of an unmodulated carrier with a frequency shift of 67 kHz above the nominal carrier center frequency.



Typical spectrum of a BCCH carrier

Source: according to J. Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

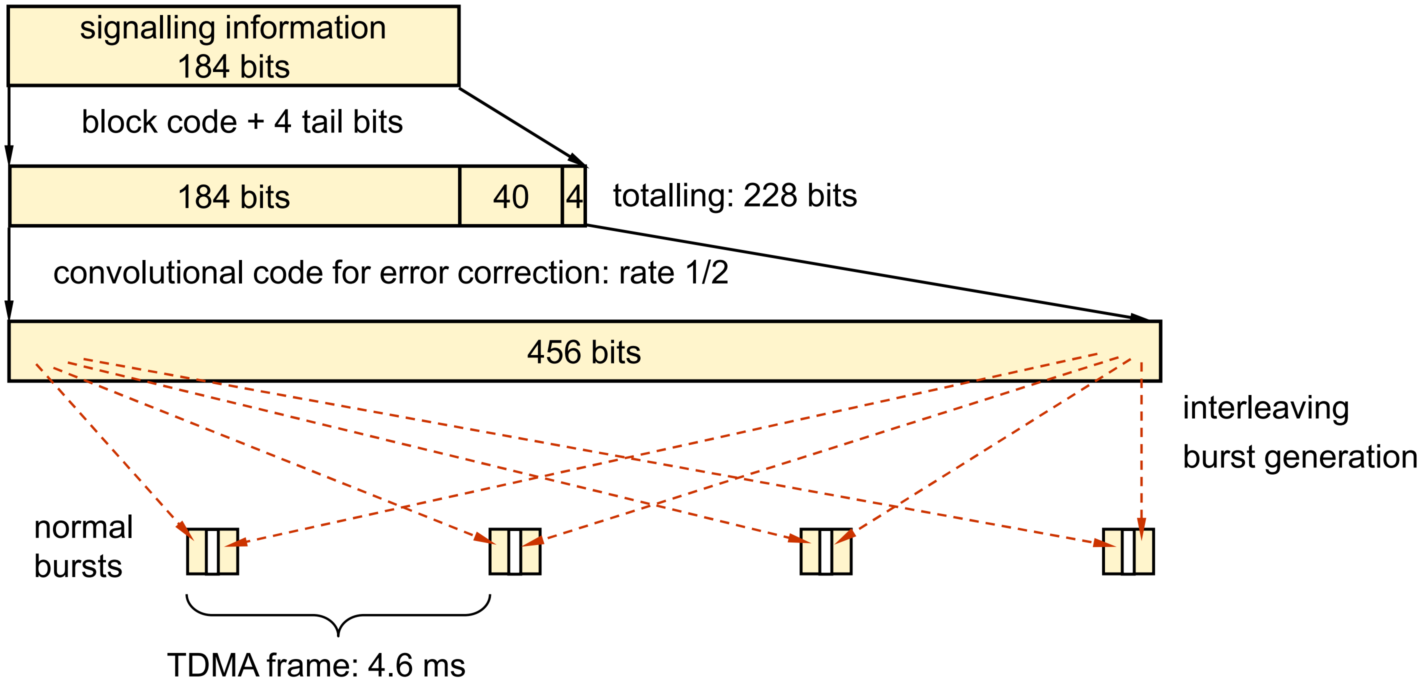
Bursts

- Synchronisation burst
  - With this burst, information required for the synchronisation of the mobile station with the BS is transmitted.

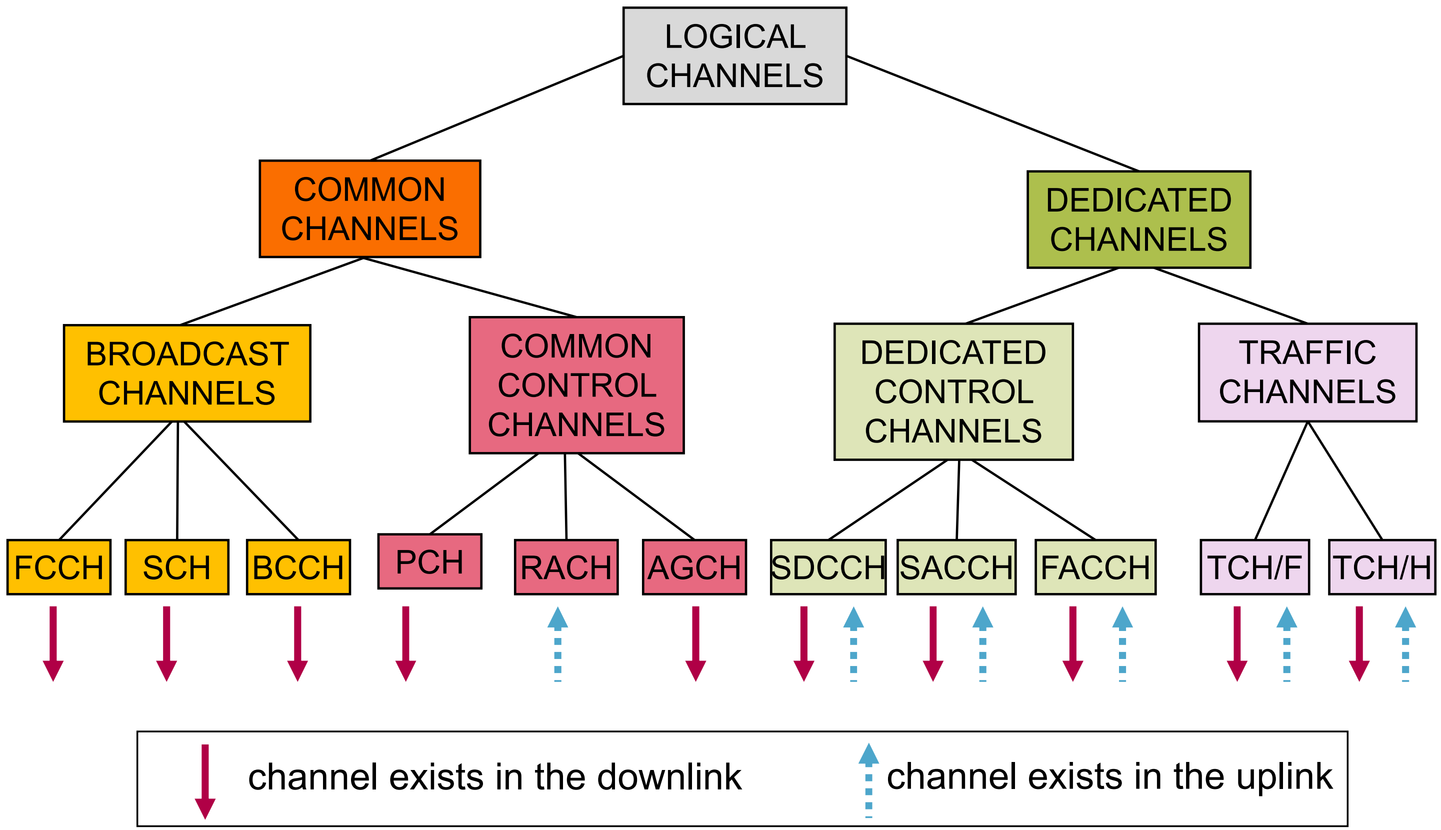
- Dummy burst
  - is emitted by the BS on the BCCH frequency carrier if no bursts have to be sent
  - allows power measurements of the mobile station

- Access burst
  - is applied to random access
  - Longer guard period to reduce the probability of collisions

Main Transport Format with Signalling (e. g. BCCH)



Logical Channels



Classification of Logical Channels

- Dedicated channels assigned exclusively to a user and channels shared by several mobile stations of a radio cell (common channels) are distinguished.
- Traffic channels
  - Traffic Channel (TCH)
    - Traffic channels are used for transmission of user data streams (voice, fax, data)
    - No transmission of signalling information
    - Partitioning into
      - TCH/F: one full-rate traffic channel
      - TCH/H: two half-rate traffic channels

Signalling Channels

- Signalling channels
  - Control and management of the mobile radio network
    - Subdivision of the signalling channels into 3 groups
  - Broadcast channels (unidirectional BSS->MS)
    - BCCH (Broadcast Common Control Channel)
      - must be available in every radio cell
      - For every cell, one frequency carrier is defined as BCCH carrier
      - BCCH on time slot 0 of the BCCH carrier
      - Cell and network indicator
      - Channel configuration
      - Parameters for cell selection and call set-up
      - Frequency numbers of the BCCH carriers of the adjacent cells

Signalling Channels

- FCCH (Frequency Correction Channel)
  - transmits information for the frequency synchronisation of the mobile station
- SCH (Synchronisation Channel)
  - Information for identification of the BS as well as of data for the frame organisation

- Common Control Channels CCCH (bi-direktional)
  - PCH (Paging Channel) BSS->MS
    - is used by the BS to reach an MS in case of an incoming call
  - RACH (Random Access Channel) MS->BSS
    - for the request for a signalling channel by the MS (call initiation or reaction to PCH)

Signalling Channels

- AGCH (Access Grant Channel) BSS->MS
  - Allocation of an SDCCH or TCH, e. g. to open a call or to transmit an SMS message
  - Response of the BS to RACH

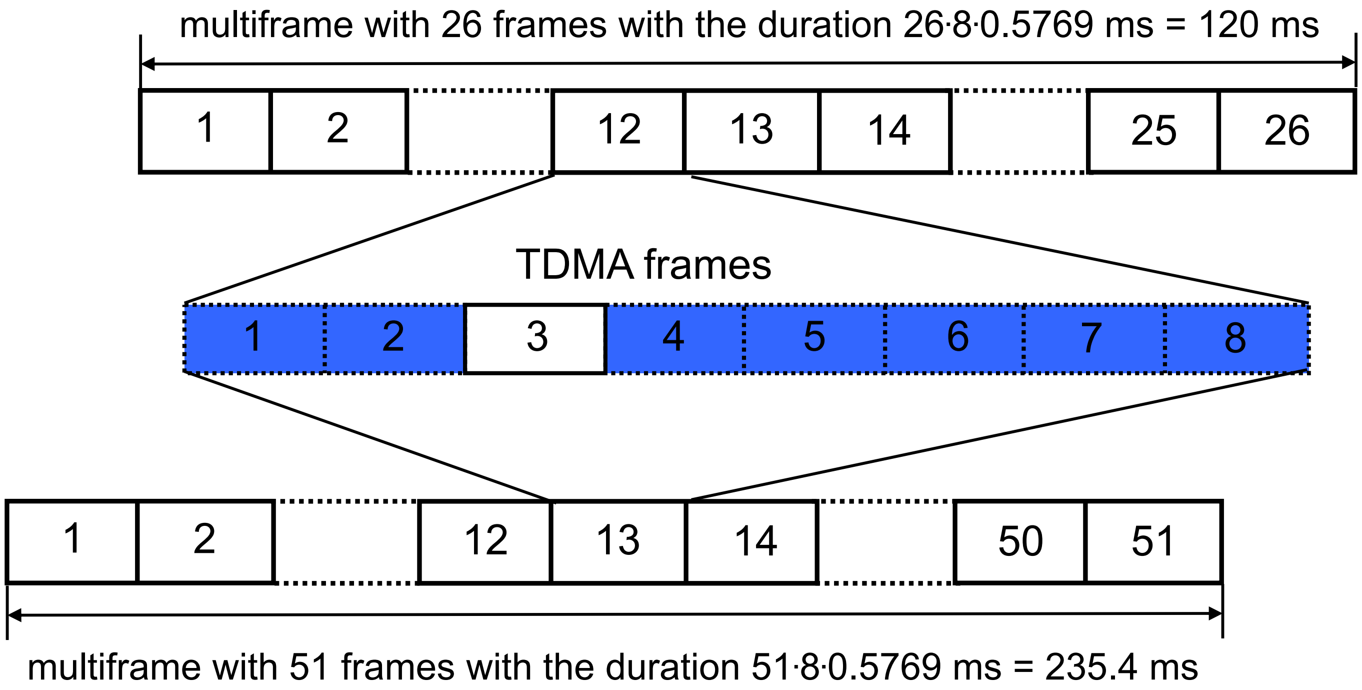
- Dedicated Control Channel (bi-directional, MS<->BSS)
  - SDCCH (Stand-alone Dedicated Control Channel)
    - Call set-up
    - Authentication, signalling, allocation of the TCH
    - Transmission of SMS (in case MS is in the idle mode)

Signalling Channels

- SACCH (Slow Associated Control Channel)
  - always coupled with an SDCCH or TCH
  - Synchronisation, transmit power control
  - Channel measurement (measurement report)
  - Measurement report is transmitted continuously

- FACCH (Fast Associated Control Channel)
  - Usage instead of SACCH, to interchange information over a much shorter period as it would be possible with SACCH
  - Application with handover, usage instead of TCH (stealing mode)

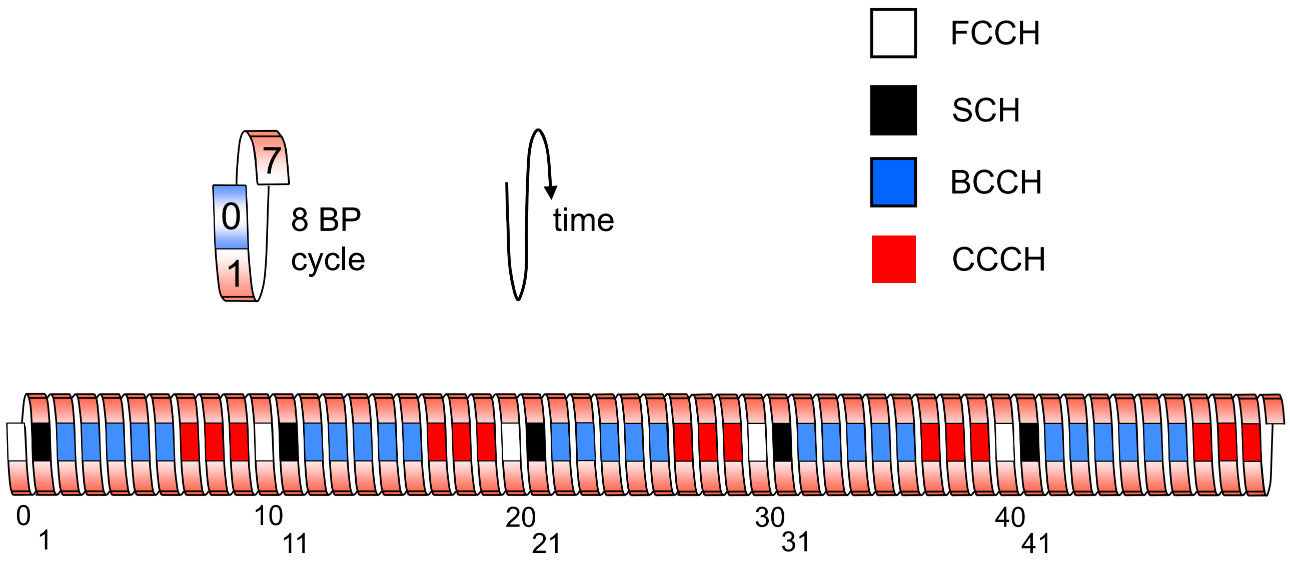
Mapping of Logical Channels on Physical Channels



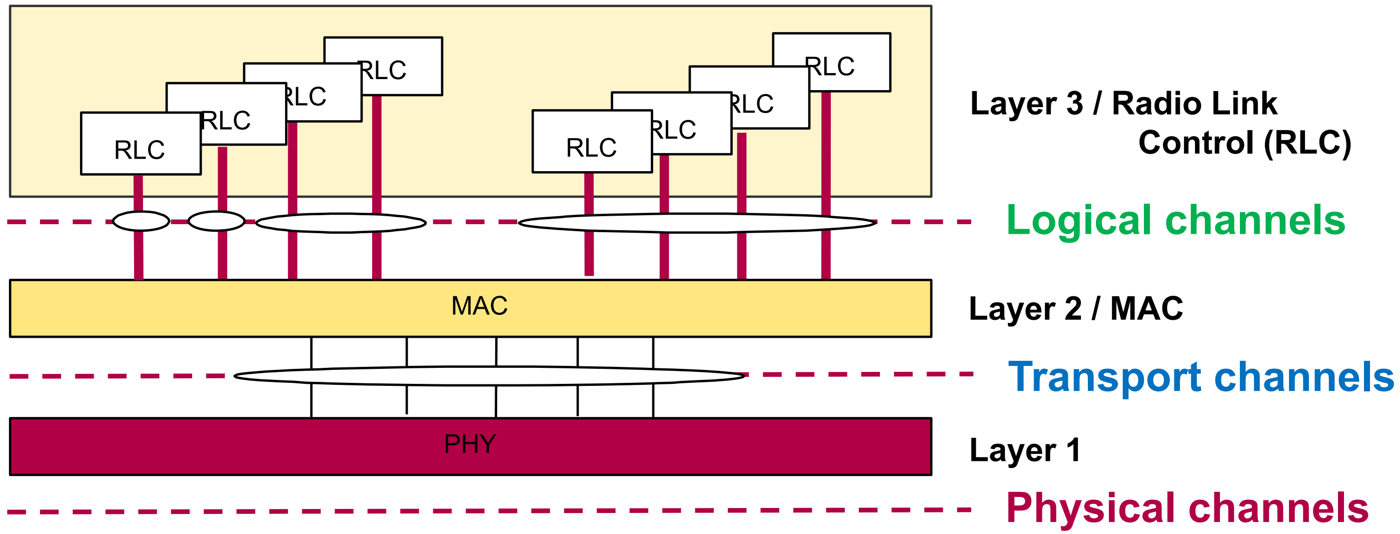
GSM frame structures

Source: according to J. Eberspächer, H.-J. Vögel, GSM Global System for Mobile Communication

Example of the Channel Organisation in the 51-Multiframe



Radio Channels in UMTS



Examples of mapping logical channels -> Transport channel -> Physical channel:

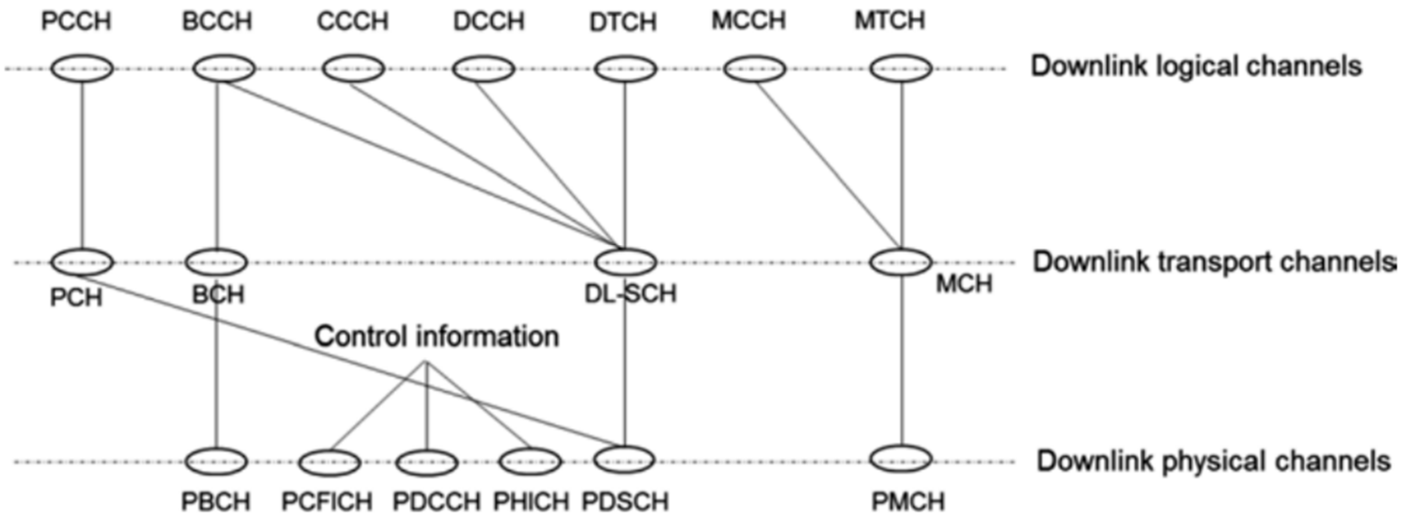
Paging Control Channel (PCCH) -> Paging Channel (PCH) -> Secondary Common Control Physical Channel (SCCPCH)

Dedicated Traffic Channel (DTCH) -> Dedicted Channel (DCH) -> Dedicated Physical Data Channel (DPDCH)
-> Downlink Shared Channel (DSCH) -> Physical Downlink Shared Channel (PDSCH)
-> Forward Access Channel (FACH) -> SCCPCH

Radio Channels in LTE

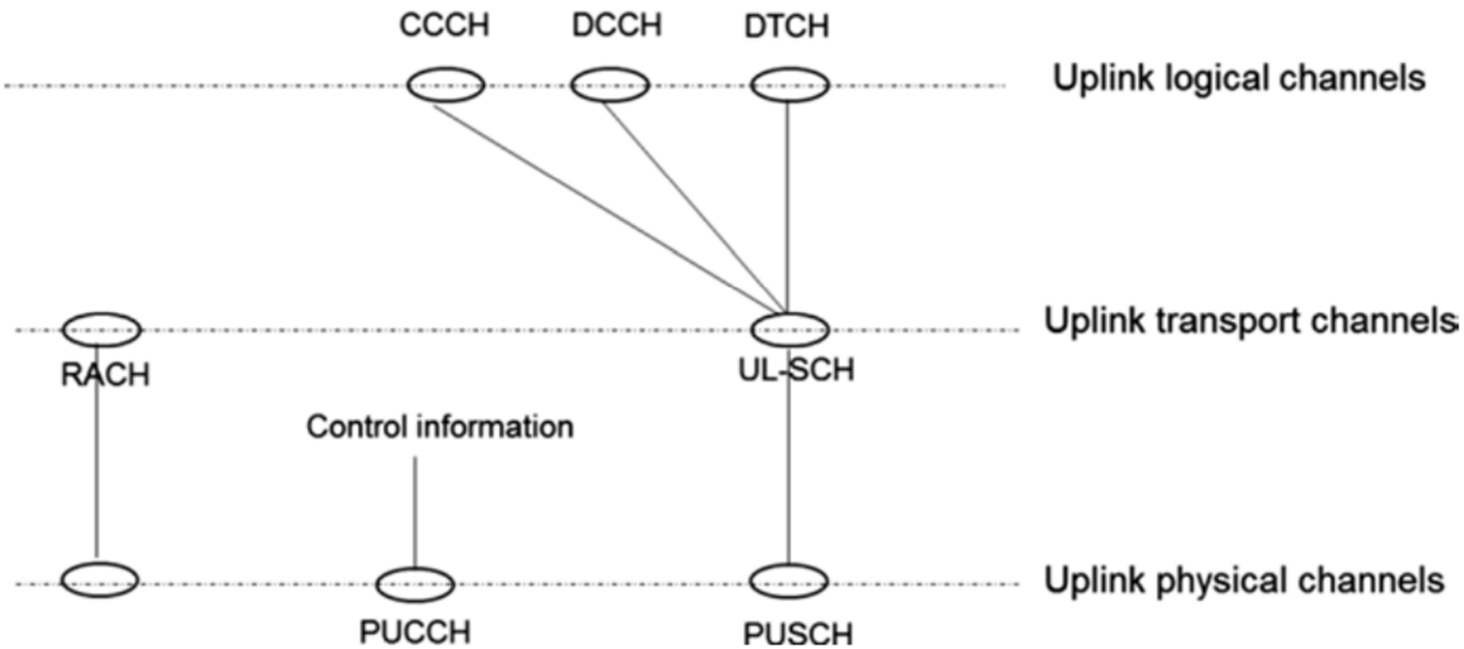
- Physical channel:
  - Number of ressource elements transmitting information from the higher layers (including logical channels and transport channels) **(see slide 283).**
  - The following physical channels are defined in downlink:
    - Physical Downlink Shared Channel, PDSCH
    - Physical Broadcast Channel, PBCH
    - Physical Multicast Channel, PMCH
    - Physical Control Format Indicator Channel, PCFICH
    - Physical Downlink Control Channel, PDCCH
    - Physical Hybrid ARQ Indicator Channel, PHICH
  - The following physical channels are defined in uplink:
    - Physical Uplink Shared Channel, PUSCH
    - Physical Uplink Control Channel, PUCCH
    - Physical Random Access Channel, PRACH

Allocation of Channels in DL



Source: W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020

Allocation of Channels in UL



Source: W. Lei et al. 5G System Design: An End to End Perspective, Springer 2020

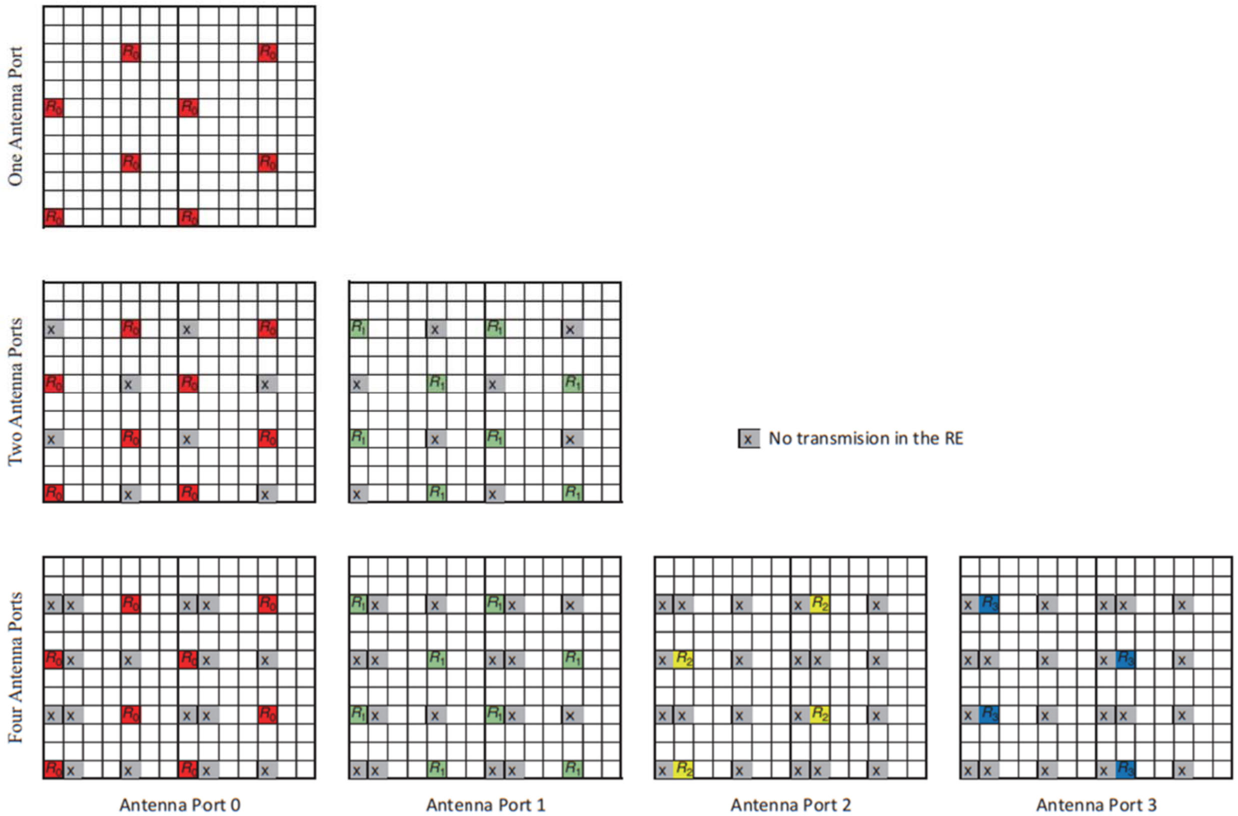
Reference Signals

- For channel estimation, reference signals (pilot signals) are transmitted by the receiver.
- Every reference signal is linked to an antenna port.
- The following reference signals exist in downlink:
  - **Primary and Secondary Synchronisation Signals (PSS, SSS):**
    - Cell search and detection of the physical cell ID (PCI)
    - In LTE, there are 502 different PCIs
  - **Cell-specific Reference Signal (CRS):**
    - Channel Estimation for the demodulation of PBCH, PDCCH/PCFICH/PHICH and PDSCH in transmission modes 1-6
    - Measurement of the channel state information
  - **UE-specific Reference Signal (DM-RS)**
    - Demodulation of PSDCH in certain transmission modes 7-10
    - Only available in „scheduled PRB“

* Transmission Modes: denotes different transmission modes as for instance SISO (TM1), Transmit Diversity (TM2), …, Multi-User MIMO (TM5), …, Beamforming (TM7)

CRS depending on the Number of Antennas

Source: W. Lei et al. 5G System Des



Reference Signals

- **CSI Reference Signal (CSI-RS)**, from release 10**:**
  - Determination of the Channel State Information (CSI) in transmission mode 9 and 10
- **Discovery Reference Signal (DRS)**, from release 12:
  - Is for the fast and efficient determination of small cells
- **Further reference signals for broadcast and multicast**

- The following reference signals exist in uplink:
  - **Uplink Demodulation Reference Signal (DM-RS):**
    - Channel estimation by the base station
  - **Sounding Reference Signal (SRS)**
    - Uplink measurements for link adaption, scheduling, power control, etc.

Essential Differences with 5G NR compared to LTE

- Basically, the structure of logical, transport and physical channels remains with various enhancements

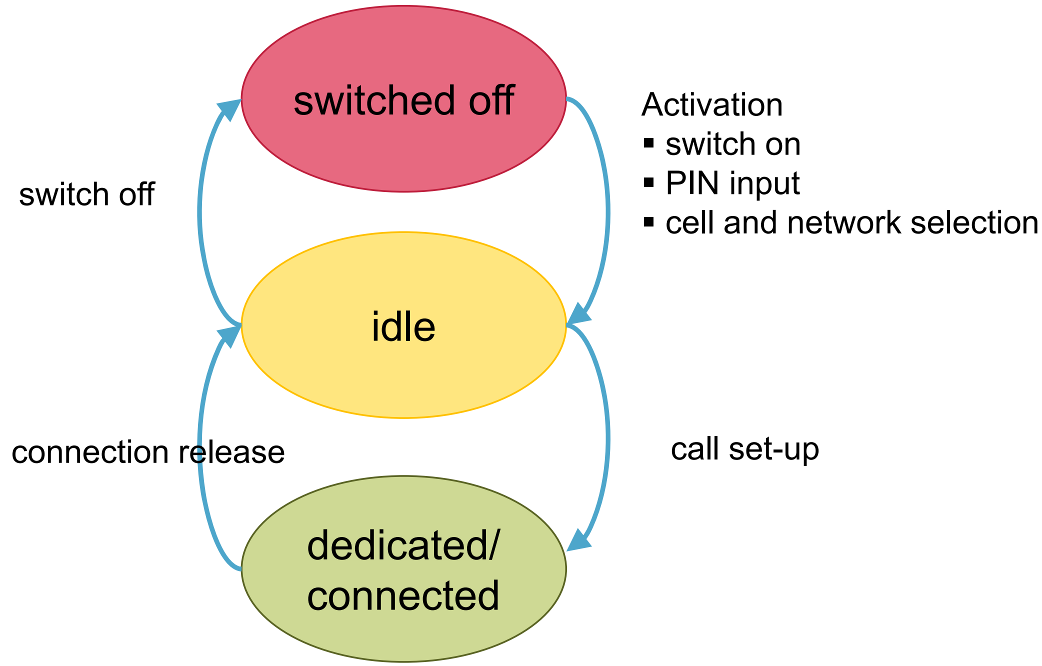
- With the reference signals there is no more CRS (always-on!) to reduce interference
  - CRS – functionality is distributed to other reference signals
  - New reference signals:
    - **Phase Tracking Reference Signal (PT-RS)**
      - For the reduction of phase noise (particularly relevant for FR2)
    - **Quai Co-Location (QCL)**
      - Essential in the context of Cooperative Multipoint Transmission (CoMP)

6.6 Procedures and Algorithms

- In this section, some selected procedures and algorithms are introduced exemplarily.
- Here, the focus is on basic procedures that are each explained by taking the example of GSM and/or LTE:
  - Log-in of the mobile station
  - Cell search
  - Call set-up
  - Measurements
  - Handover
  - Power control

Log-in of the Mobile Station

- Three states of the mobile station exist
- In the idle mode, the network knows the location area of the MS not on the cell layer but only on the Location Area (GSM) and Tracking Area (LTE), respectively
- In the dedicated/connected mode, the network knows the location of the MS on the cell layer



Activities of the Mobile Station

Activities of the mobil station in the idle mode

- Monitoring of the paging channel
- Cell reselection
- Location Area Update/Tracking Area Update

Activities of the mobile station in the dedicated mode

- Channel measurement
- Handover
- Power control
- Control of the transmission time

Activation of the Mobile Station

- Enabling the mobile station, the cell and network search starts.

- Cell selection mechanism (GSM)
  1. Determination of the receive level of several carriers and sorting according to their strength
  2. Check of the BCCH carrier by means of the peak caused by the frequency correction burst
  3. Frame synchronisation
  4. Decoding of the BCCH information
  5. Check of the receive level that has to be greater than a given access threshold (RX_LEV > RX_LEV_ACCESSMIN)
  6. Check of the priority of the cell

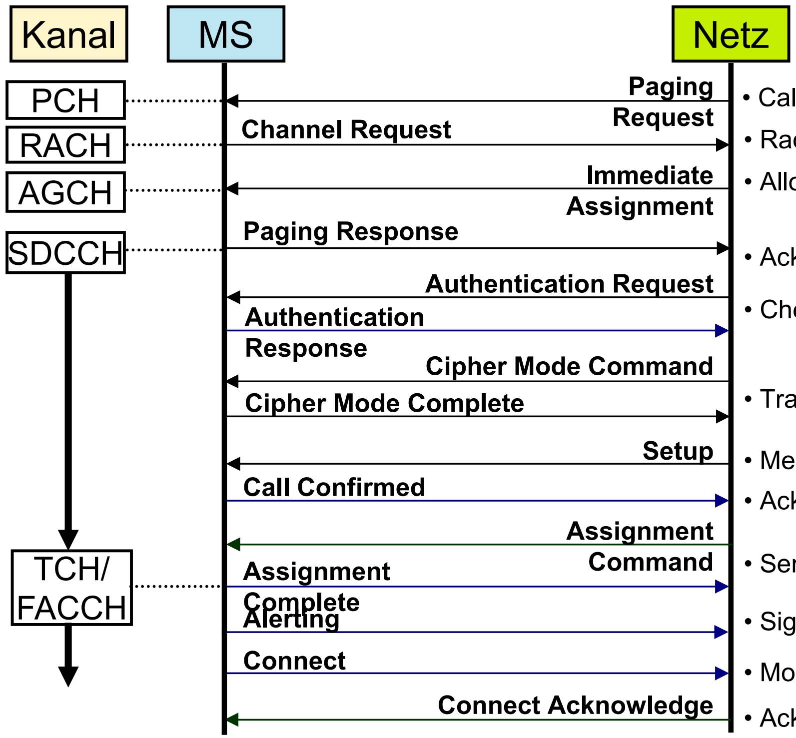
Activities of the Mobile Station in the Idle Mode

- Monitoring of the paging channel
  - Incoming call
  - Transmission of the paging messages from all cells of the location area
  - MS has to monitor PCH periodically
- Cell Reselection
  - Check of the receive level of the current cell and the adjacent cell
  - When changing the location area, additional planning parameter CELL_RESELECT_HYSTERESIS to avoid ping-pong effects
- Location update
  - Comparison of the Location Area Codes (LAC) stored on the SIM Card with the LAC in the BCCH
  - Execution of the location update procedure in case of deviation

Call Set-Up

- Basically, two cases have to be distinguished:
  - Mobile Originated Call (MOC)
    - The call is initiated by the mobile station.
  - Mobile Terminated Call (MTC)
    - The mobile user is called.
    - In this case, the location area of the mobile user has to be determined first.
      - Request at the HLR
      - Determination of the VLR
      - Determination of the location area
      - Paging in the entire location area

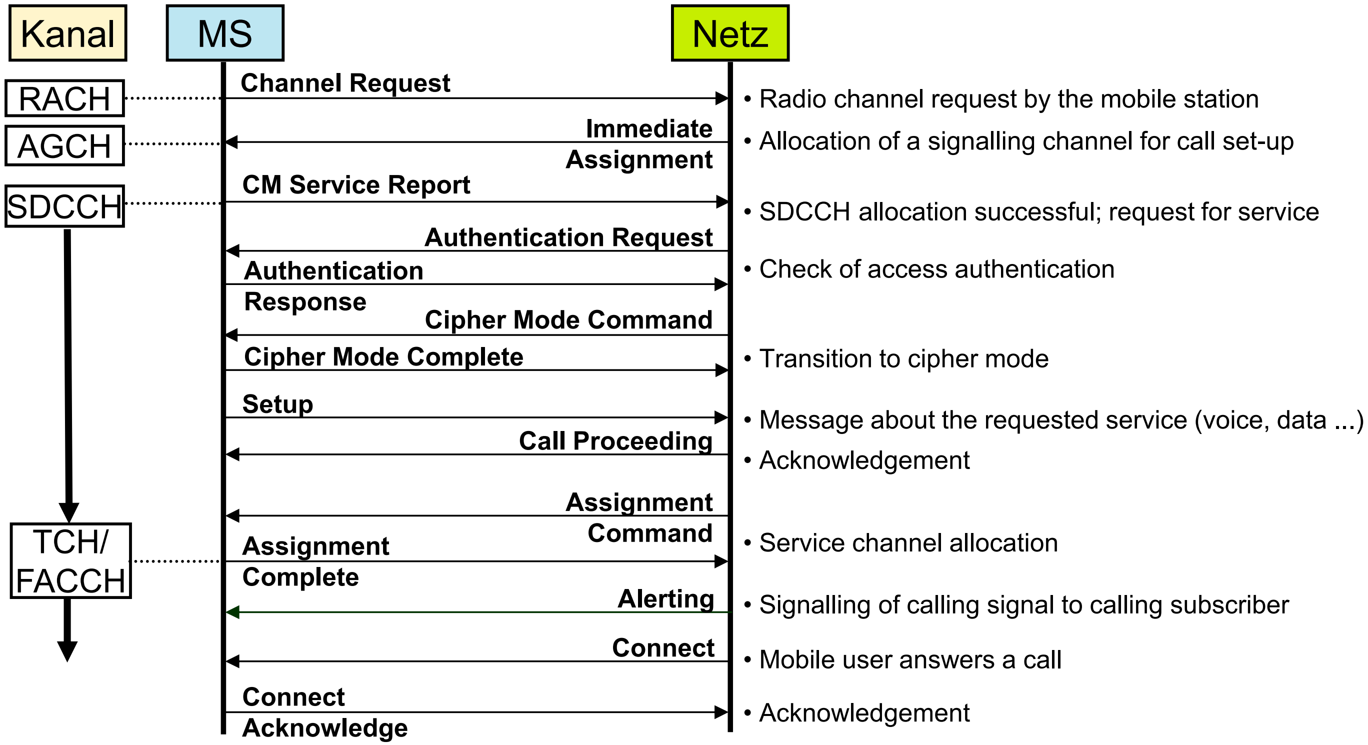
Set-Up of the Radio Link with MTC



- Call request
- Radio channel request by the mobile station
- Allocation of a signalling channel for call set-up
- Acknowledgement: mobile user was found
- Check of access authentication
- Transition to cipher mode
- Message about the requested service (voice, data ...)
- Acknowledgement
- Service channel allocation
- Signalling of calling signal to calling subscriber
- Mobile user answers a call
- Acknowledgement

Source: according to C. Lüders, Mobilfunksysteme

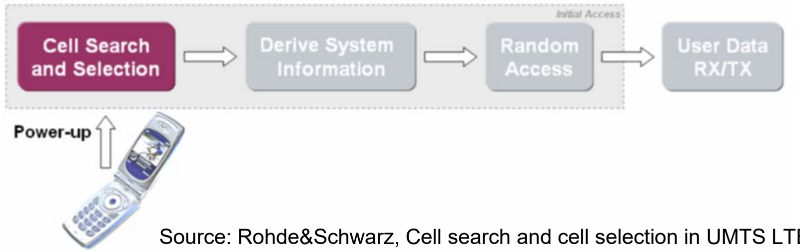
Set-Up of the Radio Link with MOC



Source: according to C. Lüders, Mobilfunksysteme

Cell Search with LTE

- Until an LTE terminal can communicate with the LTE network, the following steps are required:
  - Step 1: LTE cell search
  - Step 2: Receipt and decoding of the cell-system information

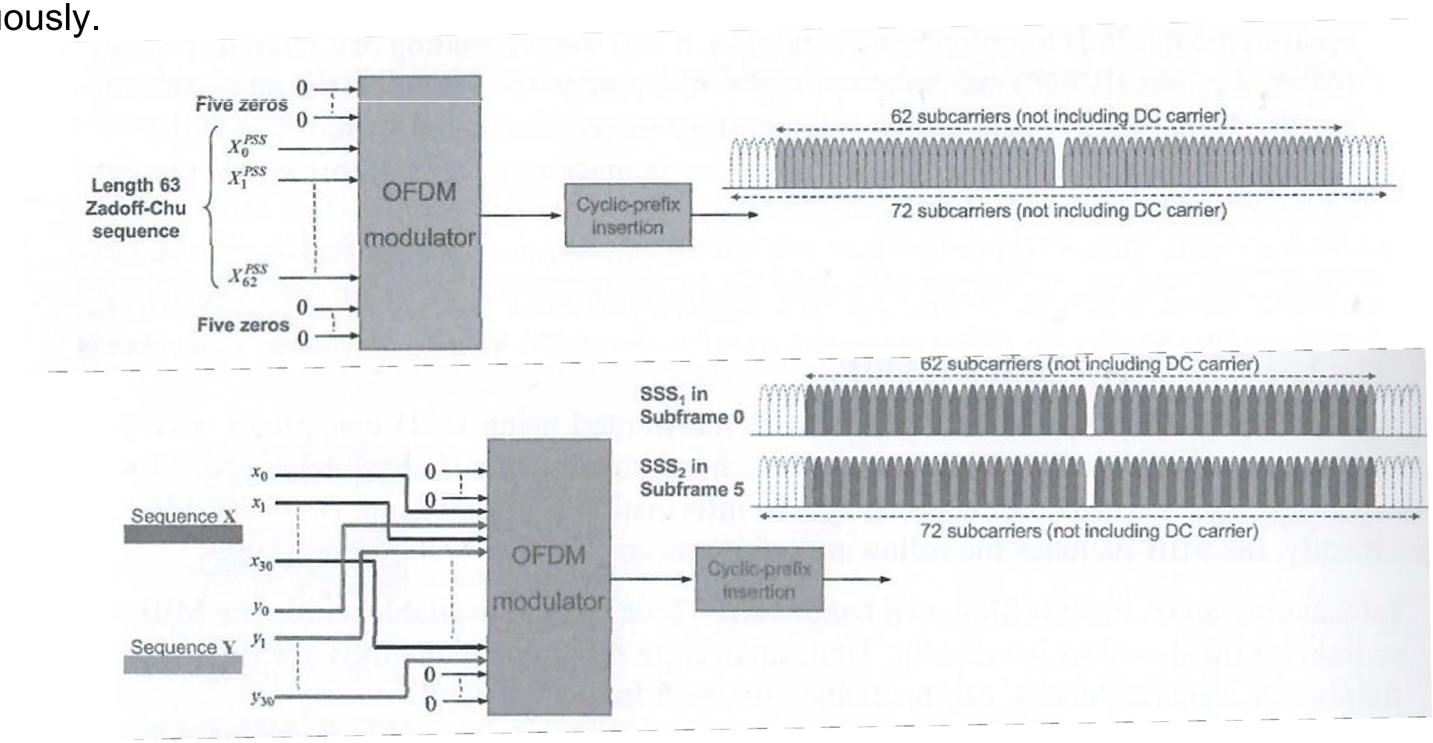


Source: Rohde&Schwarz, Cell search and cell selection in UMTS LTE Application Note

- Cell search is the procedure with which the mobile station carries out the time (Symbol/Slot/Frame) and frequency synchronisation and determines the Physical Layer Cell Identity (PCI).
- For this, on every downlink carrier two synchronisation signals are sent required for the frame synchronisation as well as for the determination of the PCI:
  - Primary Synchronisation Signal (PSS):
    - 3 different Zadoff-Chu sequences of the length 63
  - Secondary Synchronisation Signal (SSS)
    - 168 different sequences that are determined from the interleaving of two m-sequences of the length 31

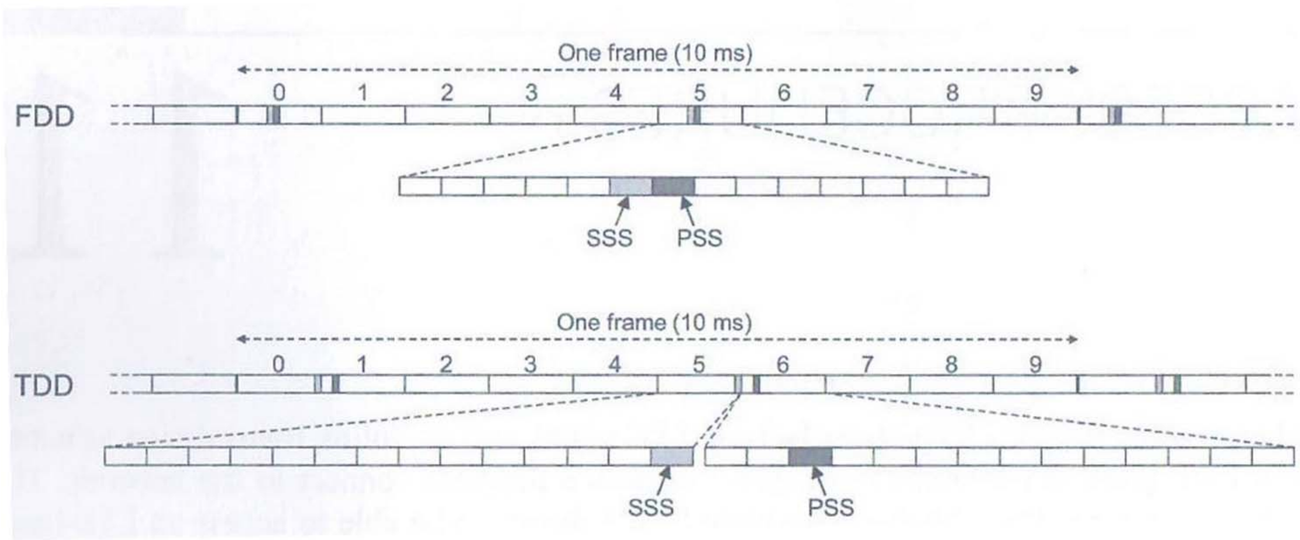
Generation of PSS and SSS Sequences

- By combination of the 3 PSS and 168 SSS, there are 504 different PCIs all in all, which locally mark the radio cell unambiguously.



Source: E. Dahlman et al., LTE-Advanced Pro and the Road to 5G, Wiley

Position of PSS and SSS Sequences in the Time Domain



Source: E. Dahlman et al., LTE-Advanced Pro and the Road to 5G, Wiley

Decoding of the Cell-System Information

- Further system information about the radio cell is transferred via two mechanisms and two different transport channels:
  - Limited information is transferred via the Master Information Block (MIB) via the BCH, i.a.
    - Information about the bandwidth
    - Information for decoding of the SIBs

MIB Physical Layer Information	**SIB Type 1** Access restrictions, SIB scheduling information	**SIB Type 2** Common and shared channel information
SIB Type 3 Cell re-selection information	**SIB Type 4** Cell re-selection information, intra-frequency neighbor information	**SIB Type 5** Cell re-selection information, intra-frequency neighbor information
SIB Type 6 Cell re-selection information for UTRA	**SIB Type 7** Cell re-selection information for GERAN	**SIB Type 8** Cell re-selection information for CDMA2000
SIB Type 9 Home eNB identifier (HNBID)	**SIB Type 10** ETWS[1] primary notification	**SIB Type 11** ETWS[1] secondary notification

[1] ETWS = Earthquake and Tsunami Warning System

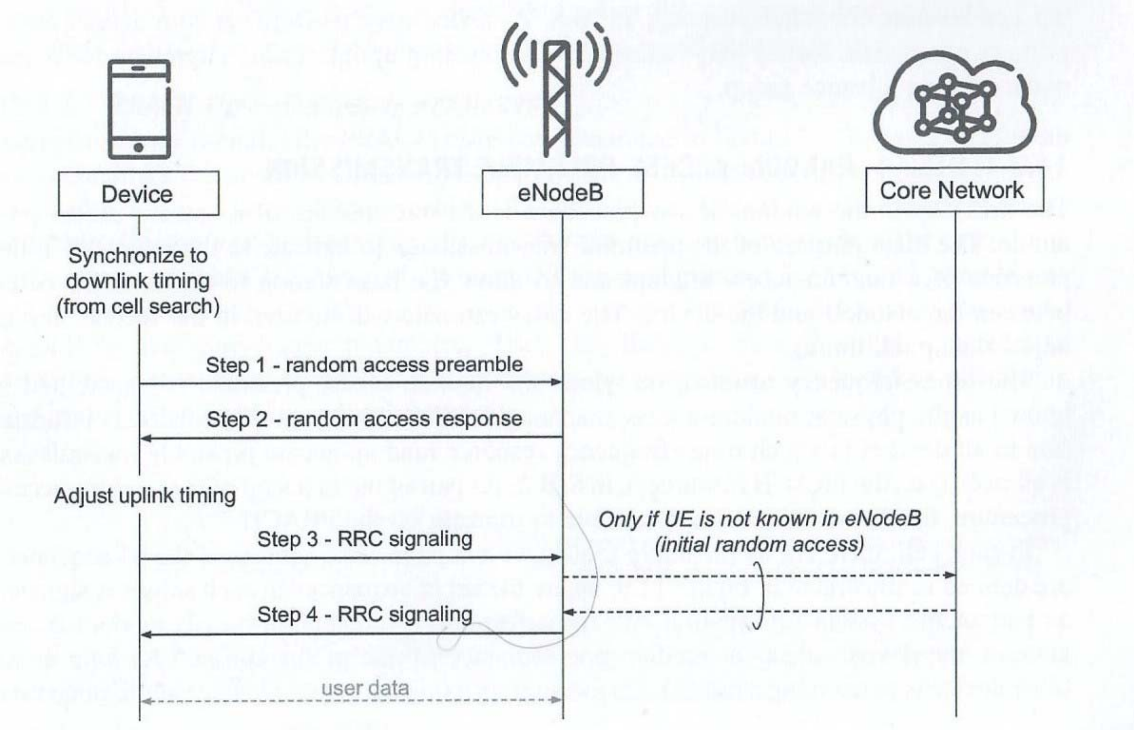
Source: Rohde & Schwarz, Cell search and cell selection in UMTS LTE Application Note

- Detailed information is transferred via the System Information Blocks (SIB) in DL-SCH, i.a. the ECGI (E-UTRAN Cell Global Identifier)

- In both cases, the logical channel BCCH is applied that can be transferred via the BCH as well as via the DL-SCH (**see slide 338**)

Setup of the Radio Link Using LTE

- Random Access Procedure



Source: E. Dahlman et al., LTE-Advanced Pro and the Road to 5G, Wiley

Modifications of the Cell Search with 5G NR

- With cell search and log in into the 5G network, two cases are distinguished:
  - 5G NR is operated in the non-standalone mode:
    - Access to the network takes place via an LTE carrier that makes a dual connectivity with a 5G NR carrier possible
    - Initially, access takes place as in the LTE network
    - The mobile station includes the system information about the availability of a 5G carrier
    - If applicable, configuration of the mobile station at a 5G NR carrier frequency
  - 5G NR is operated in the standalone mode:
    - Access takes place direct via the 5G NR carrier
    - Due to the large number of 5G NR carriers, an energy-efficient method for synchronisation is required => decoupling of channel raster and synchronisation raster

Measurements at the Radio Interface (GSM)

- As long as a call set-up exists, measurement reportsare transmitted regularly on the SACCH to the active base station.

- These measurements provide the basis for the algorithms for handover and power control.

- The following parameters are measured:
  - Uplink and downlink of the active channel (TCH and SDCCH, respectively)
  - BCCH carriers of the active cell and the adjacent cells
  - BCCH channels of the adjacent cells are communicated via the BCCH of the MS.

- Characterisation of the channel by three parameters
  - RXLEV: measure for the received power in dBm
  - RXQUAL: measure for the bit error rate (before error correction)
  - TA: Timing Advance

Radio Frequency Channel Numbers at GSM

- ARFCN: absolute radio frequency channel number
- Dependency between ARFCN and the frequency

System	Range of values for ARFCN n	UL frequency $F_{UL}(n)$	DL frequency $F_{DL}(n)$
GSM 900	$1 \leq n \leq 124$	$890+0.2n$	$F_{UL}(n)+45$
E-GSM 900	$0 \leq n \leq 124$ $975 \leq n \leq 1023$	$890+0.2n$ $890+0.2(n-1024)$	$F_{UL}(n)+45$
GSM 1800	$512 \leq n \leq 885$	$1710.2+0.2(n-512)$	$F_{UL}(n)+95$
GSM-R	$955 \leq n \leq 974$	$876.2+0.2(n-955)$	$F_{UL}(n)+45$
GSM 1900	$512 \leq n \leq 810$	$1850.2+0.2(n-512)$	$F_{UL}(n)+80$

6.6 Procedures and Algorithms

GSM Ranges of Values

Range of values for the received power

Range of values for the received power

RXLEV	received field strength/dBm
0	P < -110
1	-110 < P < -109
2	- 109 < P < -108
	....
60	- 51 < P < -50
61	- 50 < P < -49
62	- 49 < P < -48
63	P > -48

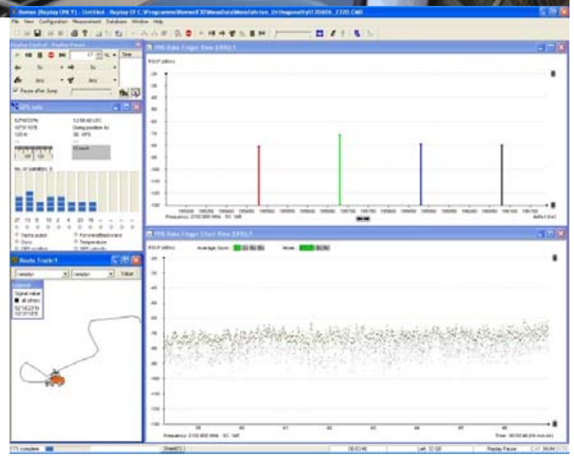
Range of values for the bit error rate

RXQUAL	bit error rate %
0	BER $\leq$ 0.2
1	0.2 < BER $\leq$ 0.4
2	0.4 < BER $\leq$ 0.8
3	0.8 < BER $\leq$ 1.6
4	1.6 < BER $\leq$ 3.2
5	3.2 < BER $\leq$ 6.4
6	6.4 < BER $\leq$ 12.8
7	BER > 12.8

Range of values for timing advance: distance/km = 0.55 * TA mit $0 \leq TA \leq 63$

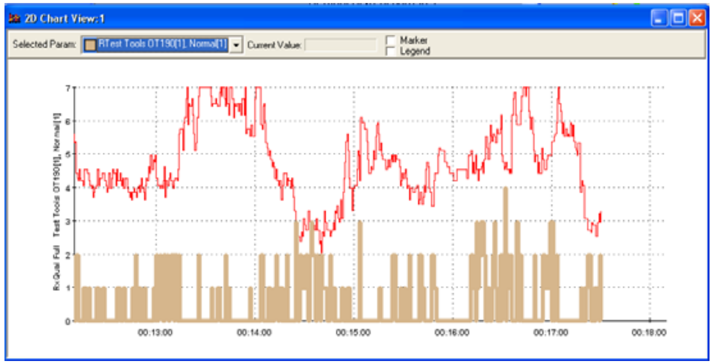
- Determination of the bit error rate using information from the channel estimation and analysing the corrected errors during error correction, respectively

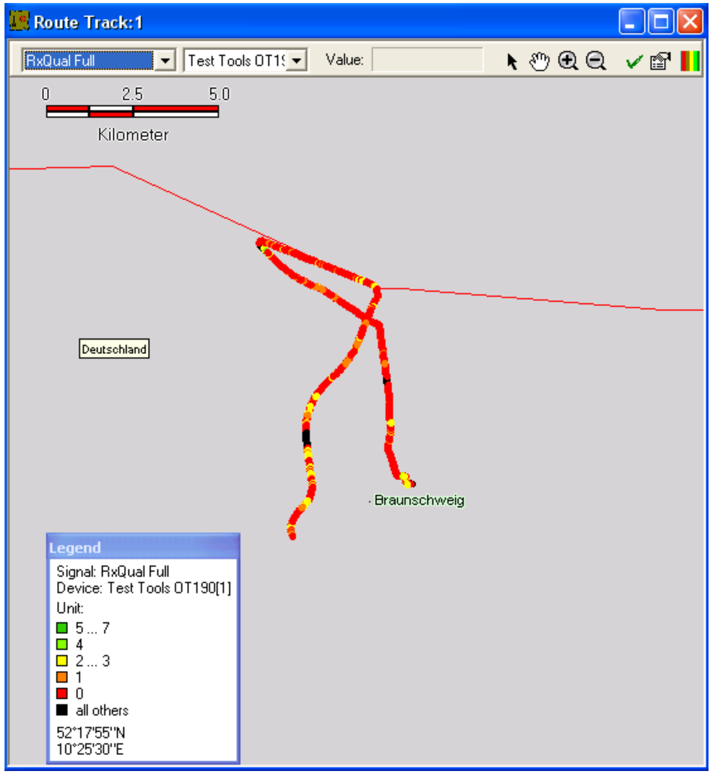
Mobile Coverage Measurement System



Example of Measuring Results

- Graphic representation of the course of RxQual





6.6 Procedures and Algorithms

LTE Measurements

- Measurements by the mobile station:
  - **RSRP** (Reference Signal Received Power): mean received power of a single PRB with a reference signal (calculated via an OFDM symbol without cyclic prefix); averaging over the linear value.
  - **RSSI**: Overall received broadband power including noise and interference. The value is not (etwas fehlt hier) to the base station, but it is the input variable for the calculation of RSRQ.
  - **RSRQ** (Reference Signal Received Power): measure for the reception quality calculated from the quotient from RSRP and RSSI/N, with N corresponding to the number of PRBs used for the measurement of RSSI.

$$RSRQ = RSRP/(RSSI/N)$$

Reported value	Measured quantity	Unit	Reported value	Measured quantity	Unit
RSRP_00	RSRP< -140	dBm	RSRQ_00	RSRQ< -19.5	dB
RSRP_01	-140≤RSRP< -139	dBm	RSRQ_01	-19.5≤RSRQ< -19	dB
RSRP_02	-139≤RSRP< -138	dBm	RSRQ_02	-19≤RSRQ< -18.5	dB
	…			…	
RSRP_97	-44≤RSRP	dBm	RSRQ_34	-3≤RSRQ	dB

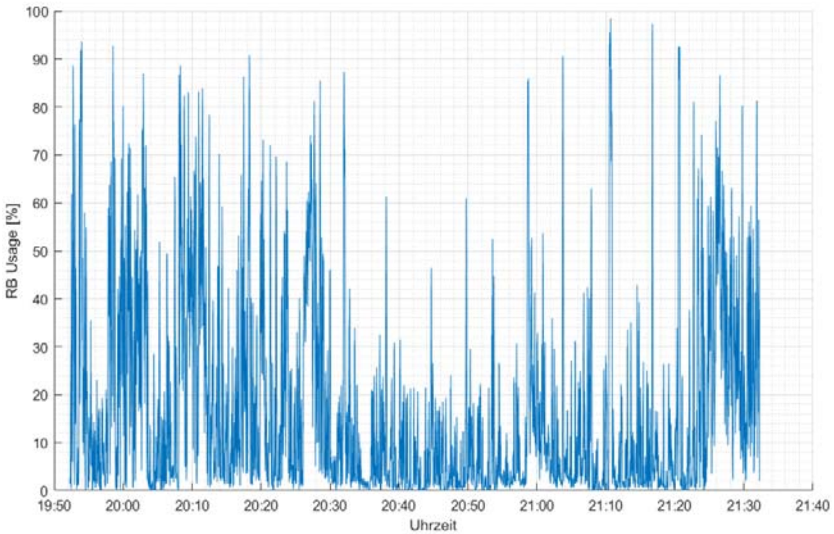
Technische Universität Braunschweig

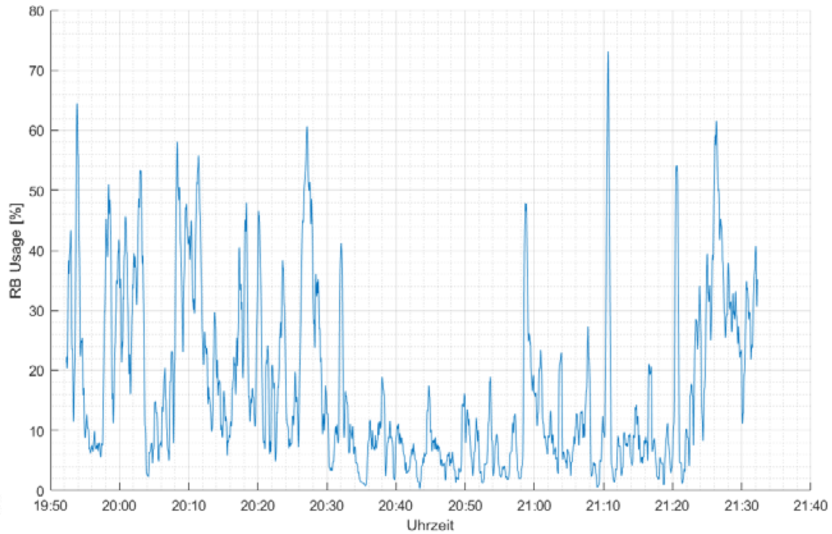
Institut für Nachrichtentechnik

Example of LTE Measurements (1)

Use of resources of a network operator during an event in the Volkswagen Event Hall

Absolute	Averaged (30 seconds)

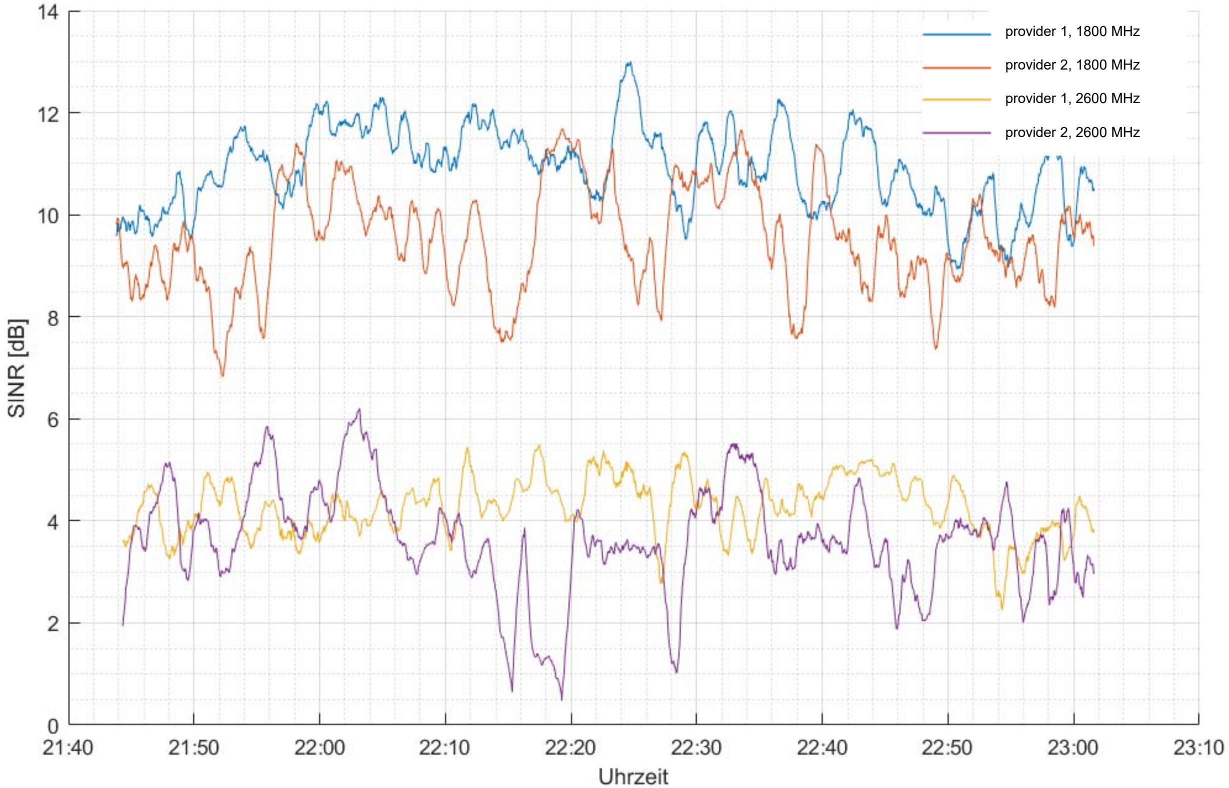




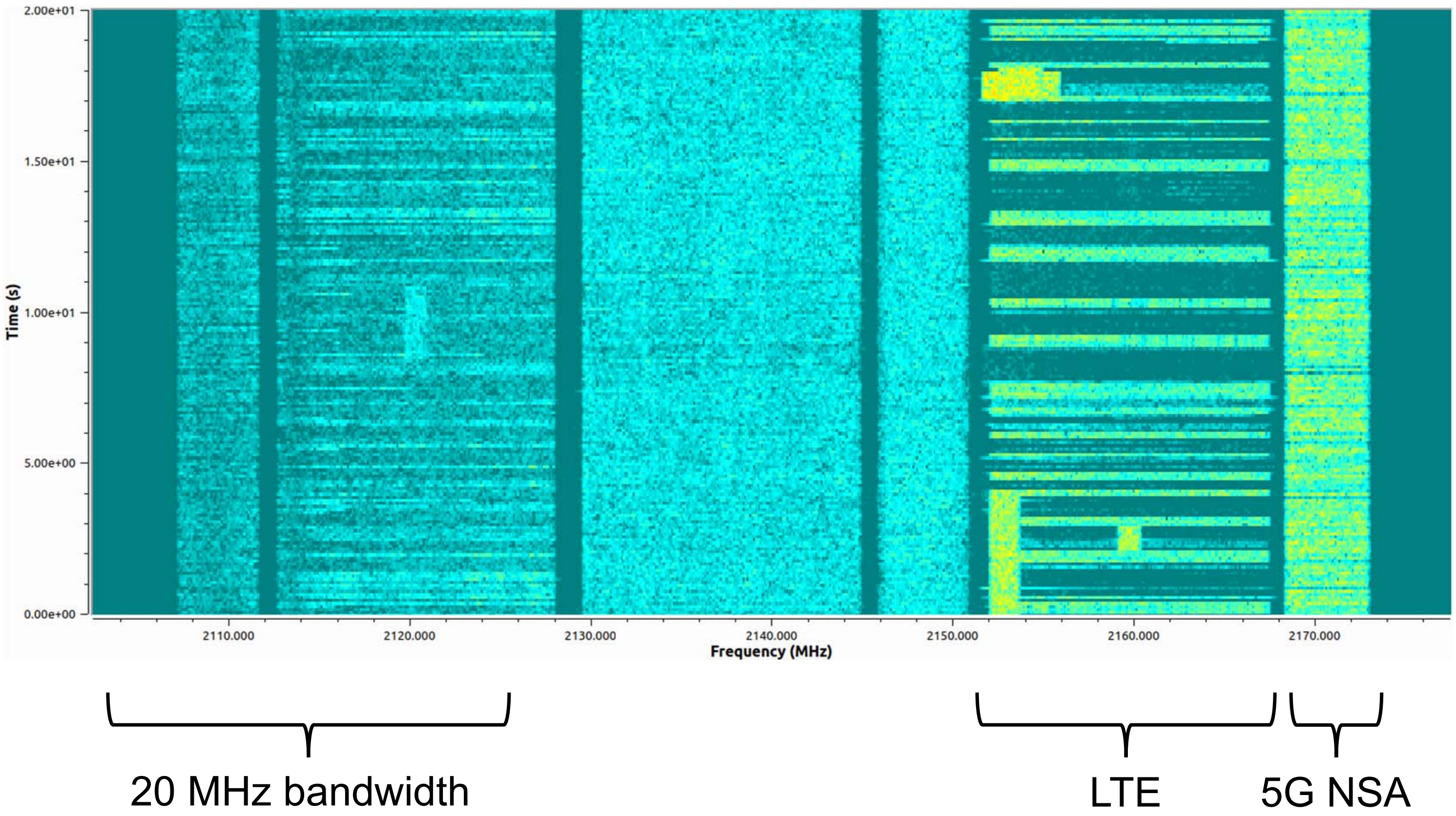
By analysing the signaling traffic, the measurement setup allows to determine the workload of the mobile radio cell in the downlink. The illustrations show the use of ressources in percent in a high temporal resolution (left) and averaged over a period of 30 seconds (right).

Example of LTE Measurements (2)

SINR comparison over provider and frequency

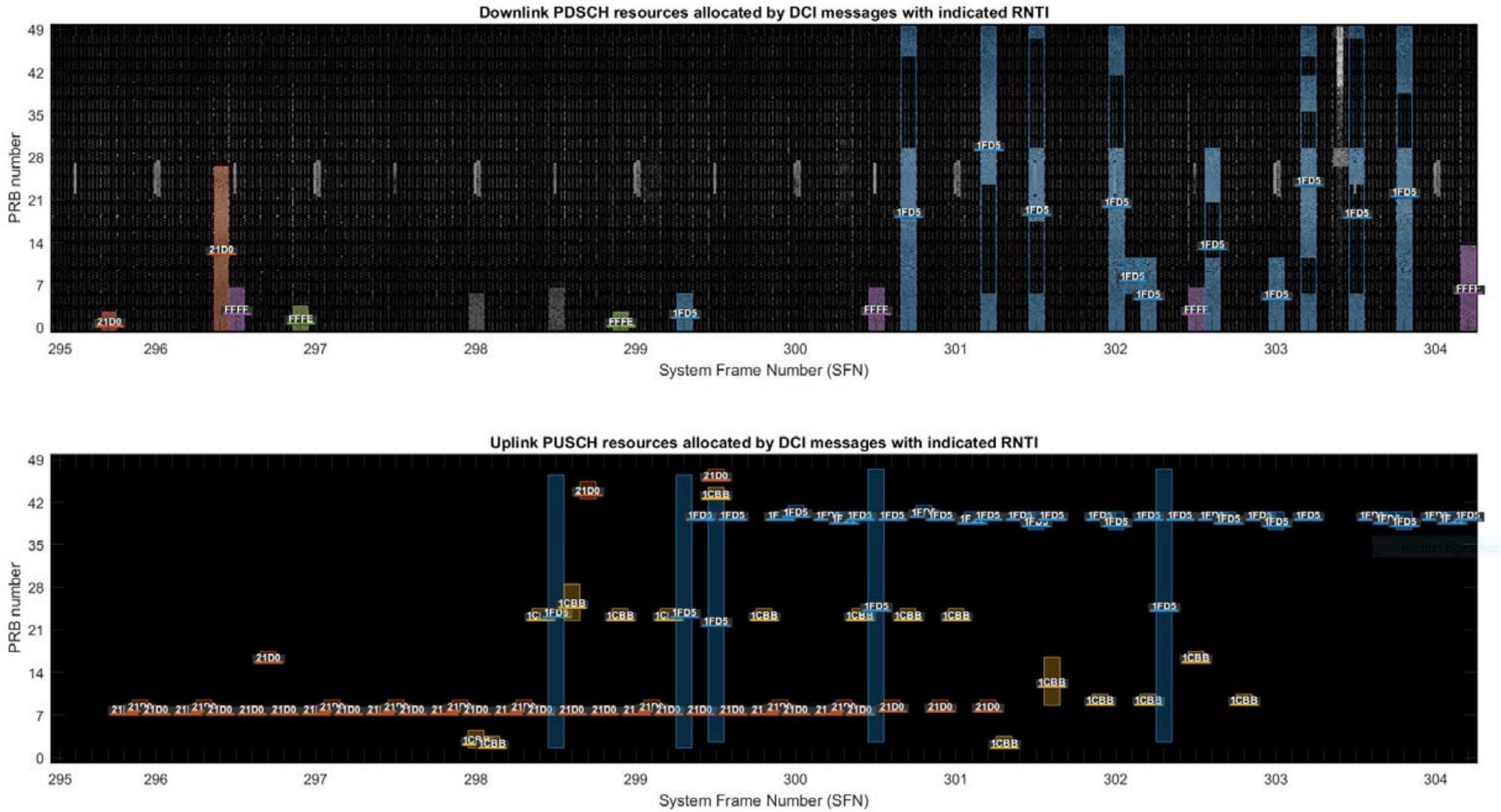


Spectrum Analysis of the 2.1 GHz Band

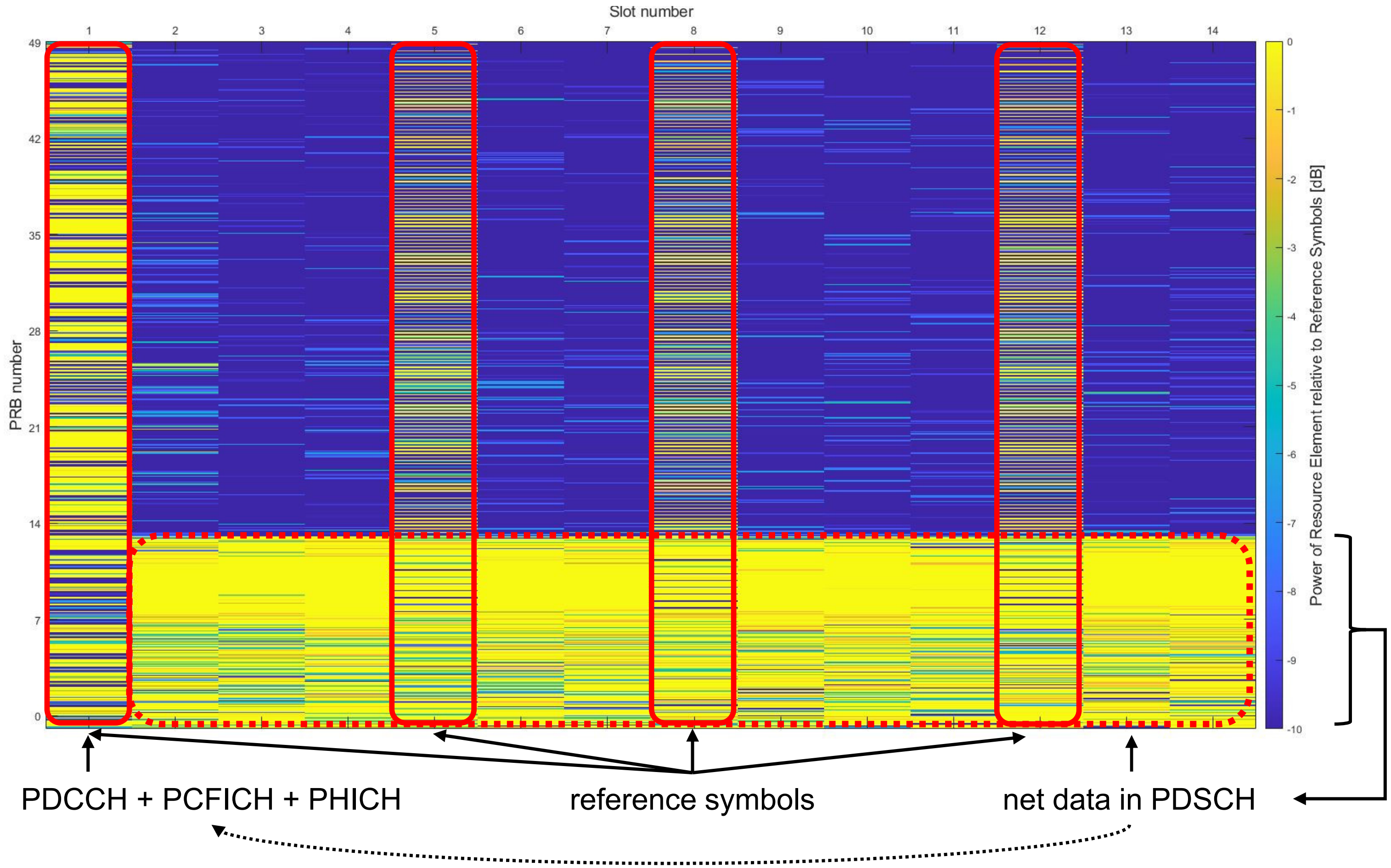


6.6 Procedures and Algorithms

Downlink Analysis of a 10 MHz LTE Cell



Downlink Subframe of a 10 MHz LTE Cell



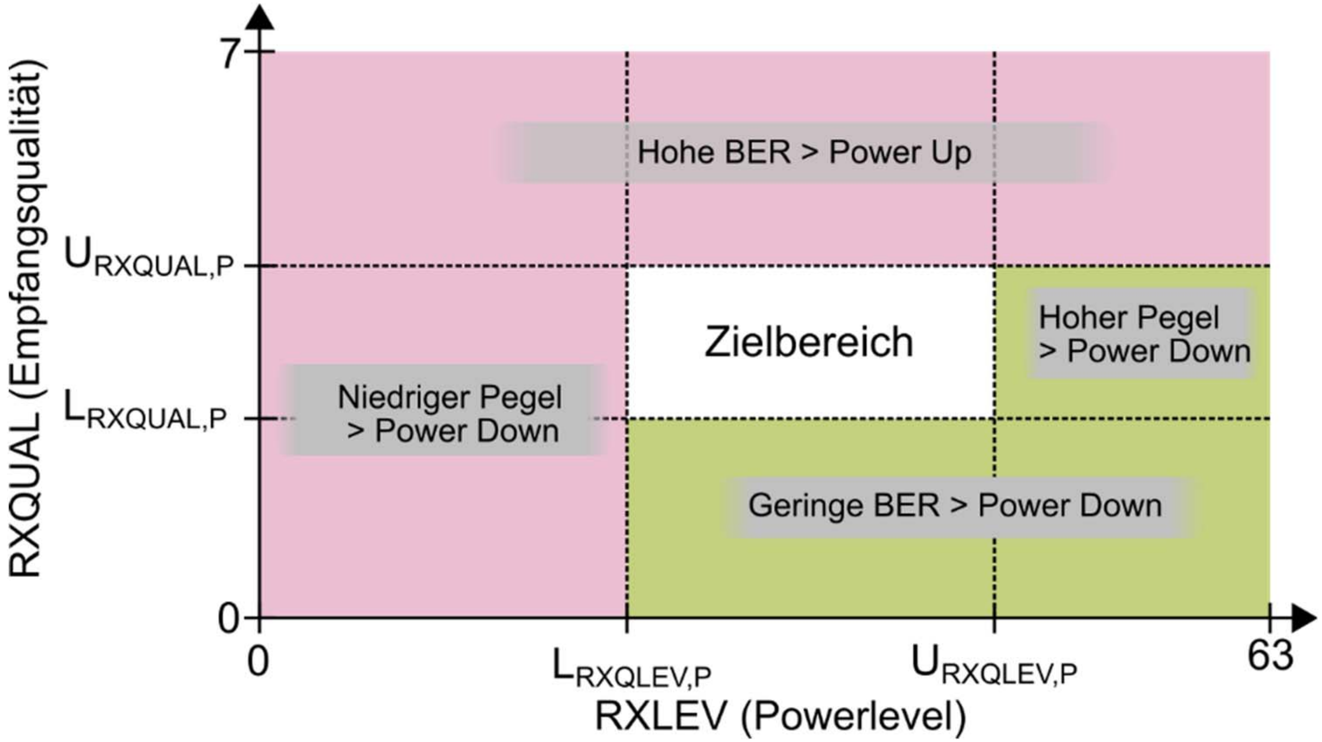
Power Control (by taking the Example of GSM)

- MS as well as BS can adapt their transmitting power automatically to the respective receive conditions
  - Benefit of power control
    - Reduction of interferences for other subscribers
    - Extension of the life span of the MS battery

- In the standard, the following is defined:
  - Each connection can be controlled separately.
  - Uplink and downlink can be controlled separately.
  - DL channels on the BCCH carrier must not be controlled.
  - The decision on a control has to be taken in the BSS.

- The decision algorithms are not standardised
  - Comparison of the preprocessed RXQUAL and RXLEV measurements with thresholds adjusted by the network operator

Power-Control Decision Criteria (Example)



Power Up: +*n* 2dB
Power Down: -*m* 2dB
m,*n*: integer, adjustable

Handover (by taking the Example of GSM)

- Handover
  - Changing the connection from an existing call to a new base station is called handover.

- Reasons for Handover
  - Two groups of reasons are distinguished:
    - Mandatory reasons (bad reception)
      - Receive level (RXLEV) is too low: level handover
      - Quality is too bad (RXQUAL): quality handover
      - Distance (TA) MS-BS is too large: distance handover
    - Reasons with regard to network planning
      - Receive level of the adjacent cell is better
      - High traffic load
      - Priorities in case of hierarchical cell structures

Reason for Handover: Power Budget

- The most important handover for network planning purposes is the power-budget handover.
- The power budget of a serving cell *b* in terms of an adjacent cell *n* is defined as:

- $\mathrm{PBGT}(b,n) = \big(\mathrm{RXLEV}(n) - \mathrm{MS\_TXPWR\_MAX}(n)\big) - (\mathrm{RXLEV}^*(b) - \mathrm{MS\_TXPWR\_MAX}(b))$

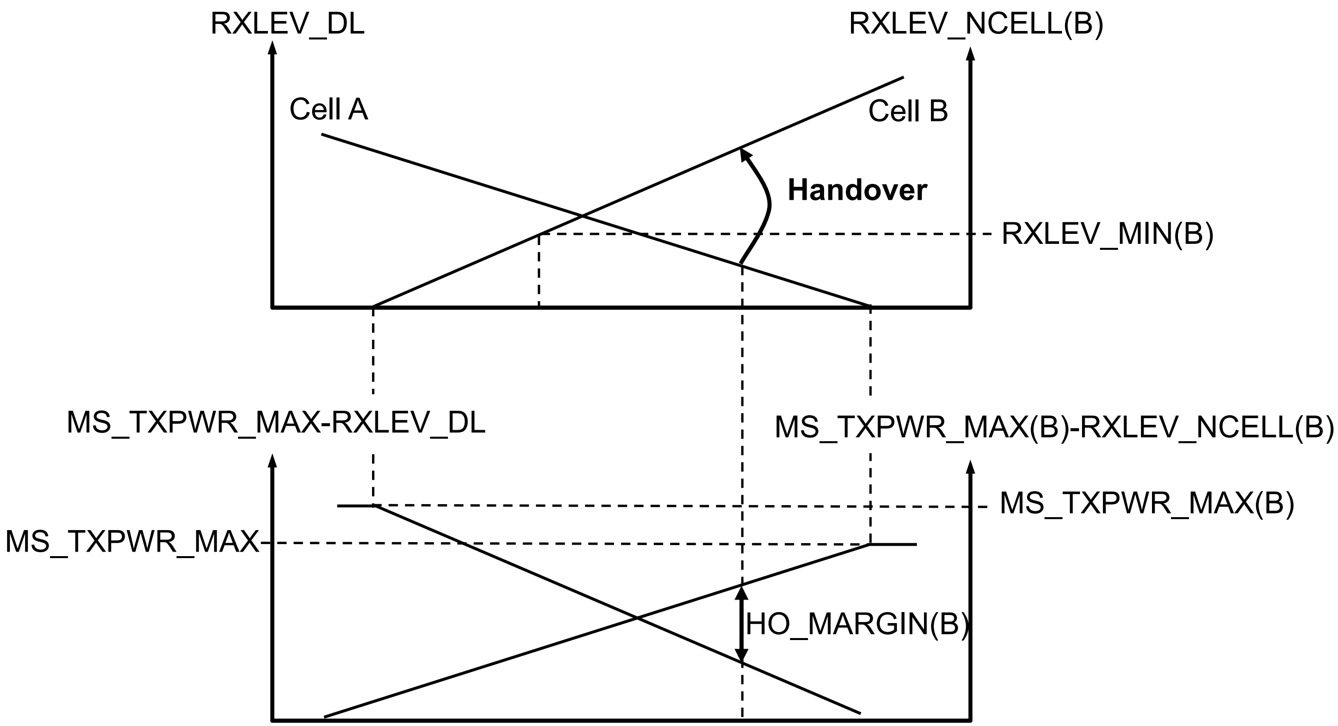
  with $\mathrm{RXLEV}^*(b) = \mathrm{RXLEV}(b) + \mathrm{PWR\_C\_D}$

  $\mathrm{PWR\_C\_D}$: reduction of the transmitting power of the BS using power control

- Criterion for power-budget handover

  1. $\mathrm{PBGT}(b,n) > \mathrm{HO\_MARGIN\_PBGT}(b,n)$
  2. $\mathrm{RXLEV}(n) > \mathrm{RXLEV\_ACCESS\_MIN}(n)$

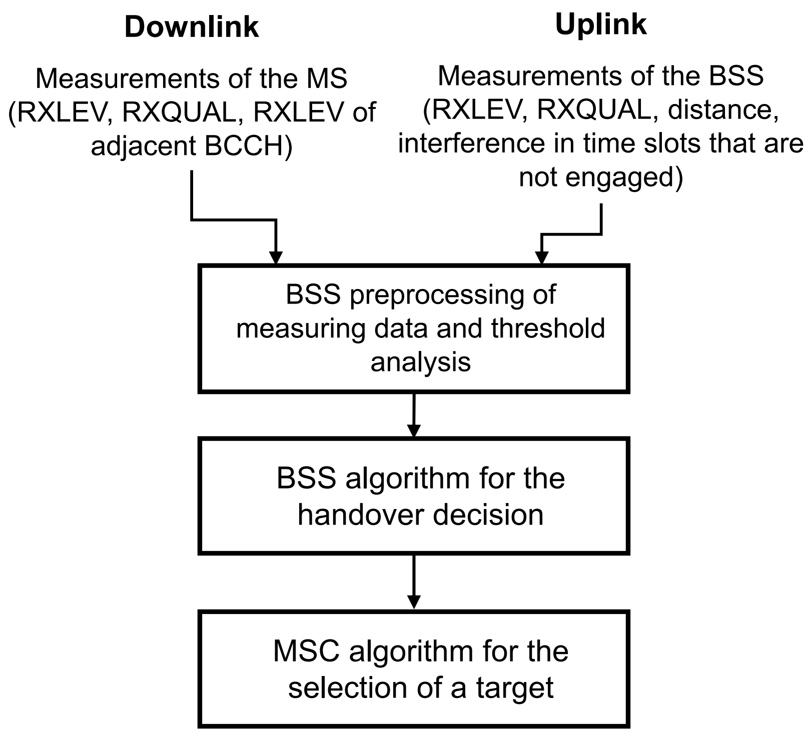
Power-Budget Handover



Source: according to C. Lüders, Mobilfunksysteme

Phases of Handover

- Principle of the procedure of the handover process in three steps:



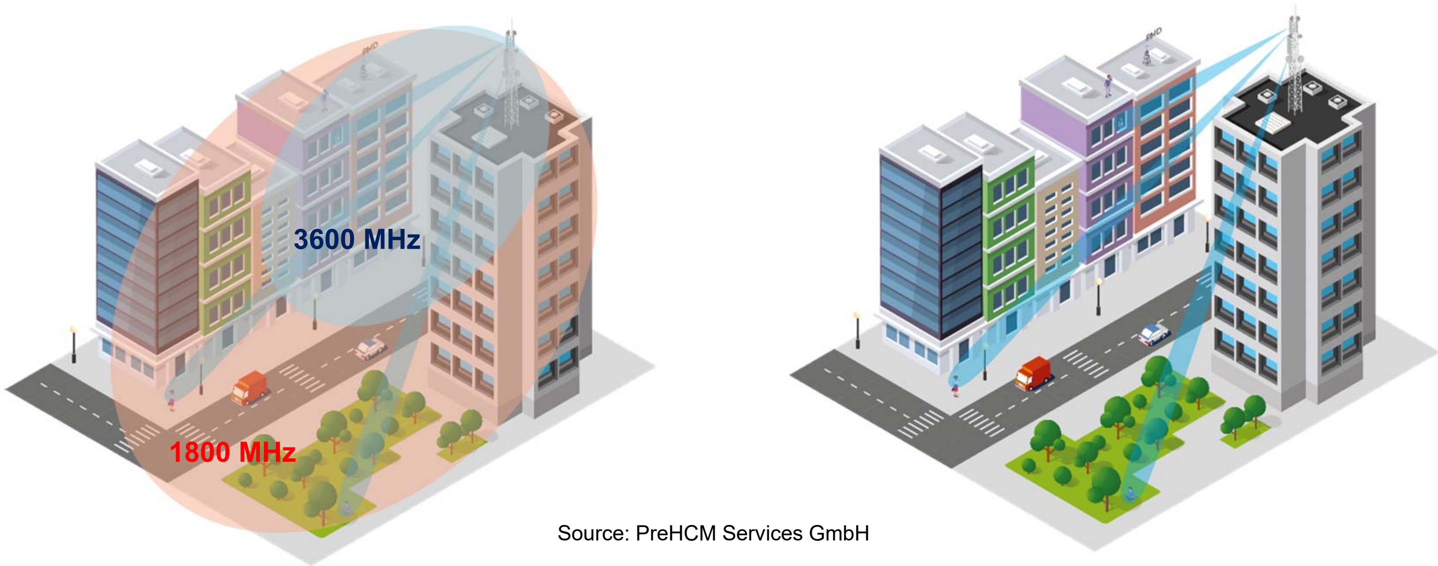
  - Analysis of the measurements obtained by BSS und MS
  - Determination whether there is a reason for handover
  - Determination of a suitable target cell and decision whether a channel in the target cell is free.

6.7 Selected Aspects of 5G

- In this section, two of the numerous aspects that (possibly) play an important role with 5G have been considered exemplarily:
  - beamforming
  - 5G broadcast
- Both aspects have far-reaching effects on radio network planning, however, in a sense, they behave really contrarily:
  - Distinctive 1:1 – communication by the use of beamforming
  - Broad 1:n – communication with 5G broadcast

Beamforming

- With 5G NR, frequency ranges at 3,5 GHz, where the propagation loss is larger and with this the coverage is shorter, are applied
- This can be compensated by using antennas with a higher gain which, however, have smaller antenna beams aligned to the user individually (beamforming)



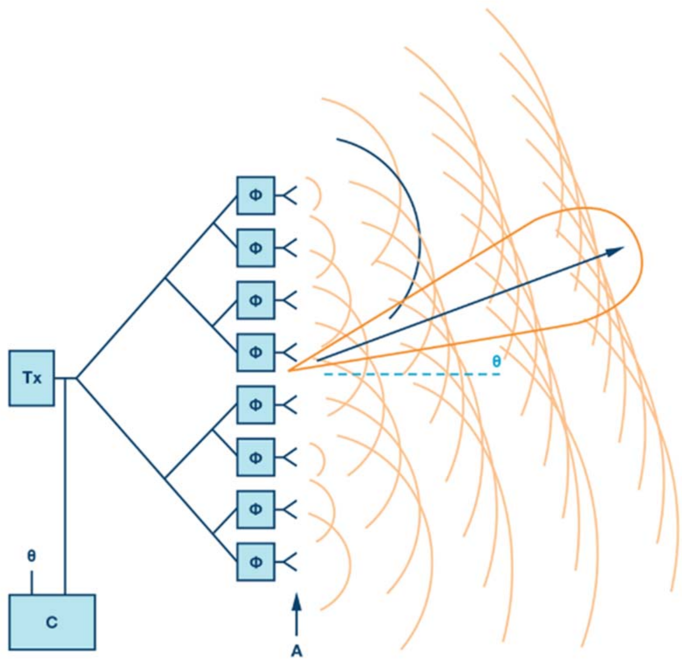
Source: PreHCM Services GmbH

Radiation using conventional antenna technologies

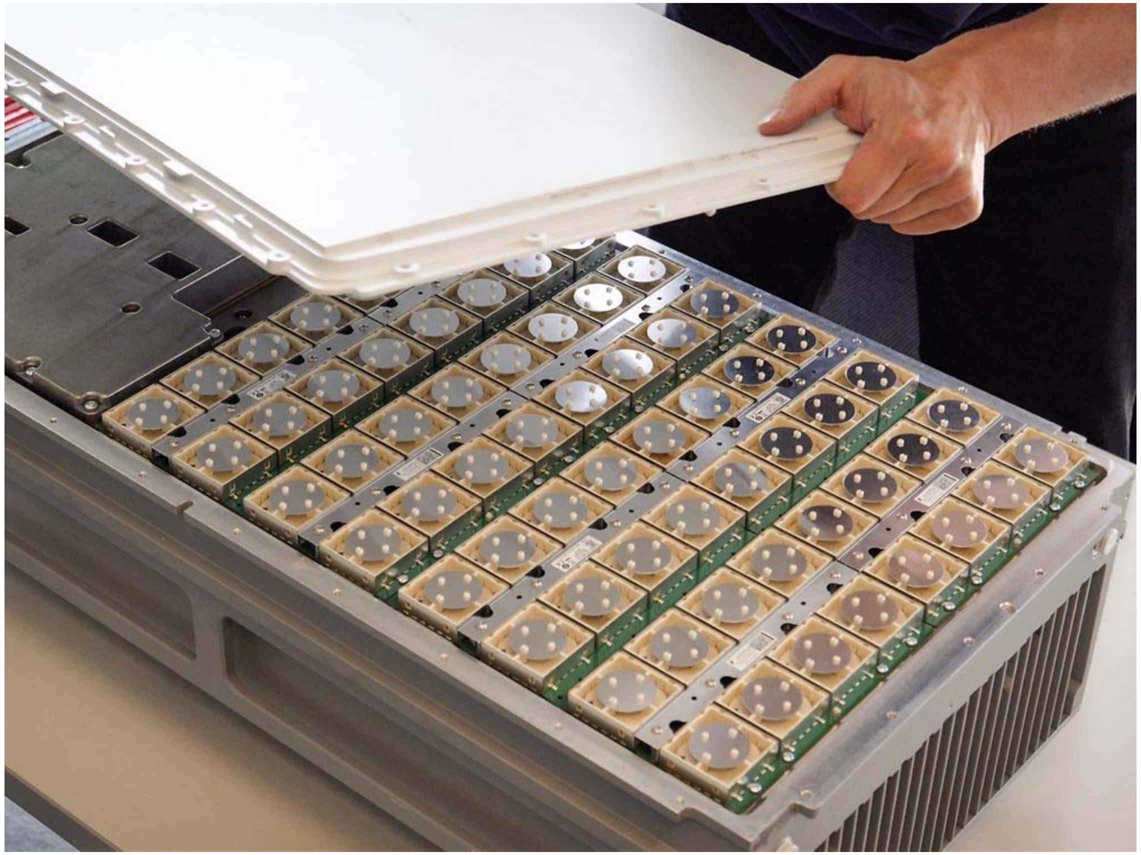
Radiation with **beamforming**, e. g. at 3600 MHz

Beamforming - Principle

- Beamforming is realised by an active antenna system (AAS),
- An AAS consists of several partial antennas firmly arranged
- Individual adaptation of the transmitted signal per partial antenna in amplitude and phase
- The radiated energy remains constant, however, it is spatially reallocated by constructive/destructive interference
- Due to the reciprocity of the radio channel, the antenna gain gilt sowohl beim Senden, als auch beim Empfangen of electromagnetic waves
- Due to the large number of antenna elements, findet beamforming at the base station statt

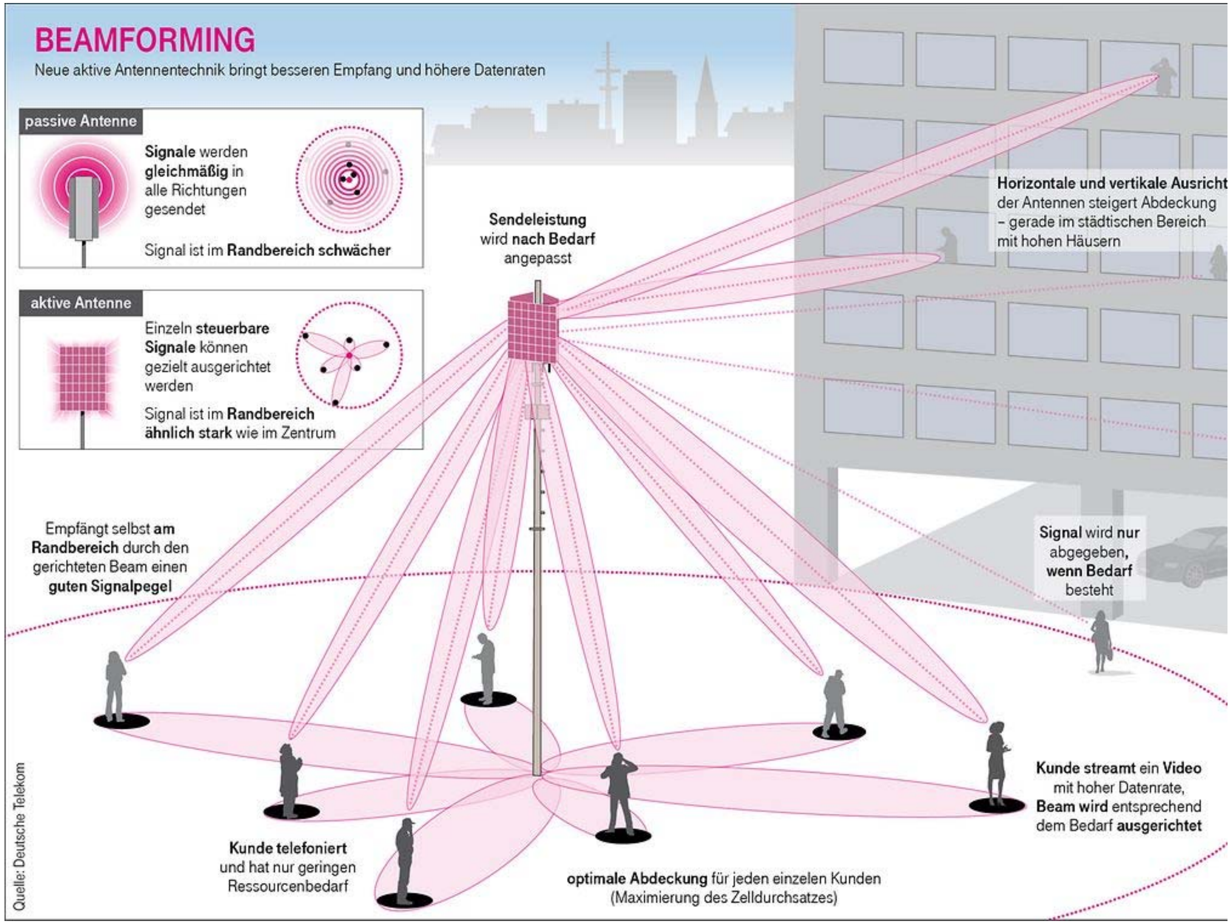


Beamforming – 5G Massive MIMO Antennas (8x8 Elements)



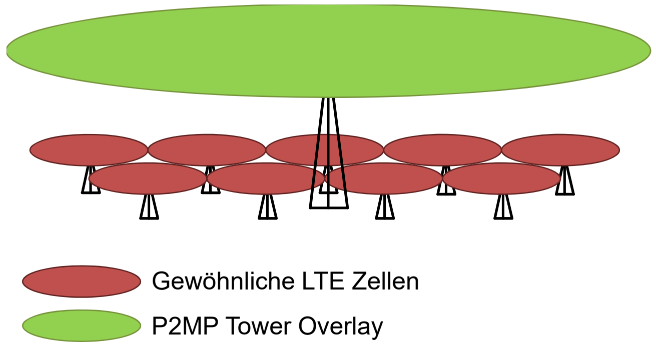
Source: https://www.telekom.com/de/blog/netz/artikel/5g-antenne-funktionen-575464

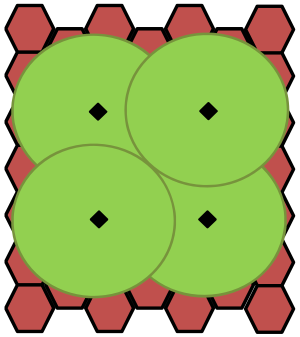
Beamforming – Effects on the Radio Network



5G Broadcast

- The distribution of television content via mobile radio networks with dedicated point-to-point connections is very inefficient.
- Thus, with 5G Broadcast a single data stream reaching all terminals in the coverage area is distributed via a high-tower high-power transmitter (HTHPs).
- Consequently, with large Live broadcasts mobile radio networks can be relieved and a high failure safety can be made possible at the same time.
- Thereby, a so-called tower-overlay concept comes into effect, where the HTHP transmitters are combined with normal radio cells.





5G Broadcast

- The idea of an overlay of dedicated broadcast transmitters was recorded in Release 14 by 3GPP in the year 2017 by introduction of Further evolved Multimedia Broadcast Multicast (FeMBMS).
  - With this, inter-site carriers of up to 60 km can be realised.
  - Introduction of a Receive-Only Mode (ROM) where broadcast content can be received „Free-to-Air", i. e. without SIM card
  - Shared Broadcast, i. e. several operators can use a mutual broadcast carrier in common
- In the 3GPP Release 16, further adaptations have been carried out that now make an inter-site separation of up to approx. 100 km possible.
  - Higher mobility of up to 250 km/h is enabled by introduction of a mode with a CP of 100 ms at a subcarrier separation of 2.5 kHz.
  - The broadcast mode in 3GPP-Release 16 is still based on LTE and not on 5G New Radio (NR) and thus is also referred to as LTE-based 5G Broadcast.

Chapter 7 – Mobile Radio Systems according to IEEE802

Introduction
Chapter 1

Basic Terms
Chapter 2

Mobile Radio Systems
Chapter 6

Media Access Methods
Chapter 5

Radio Transmission Technique
Chapter 4

High Frequency Technology
Chapter 3

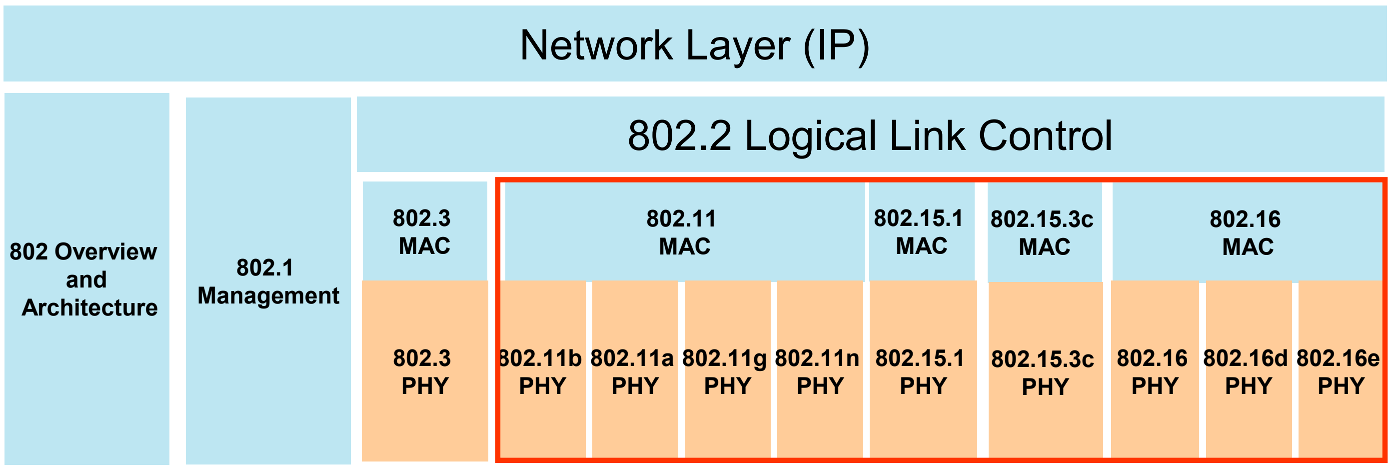
Mobile Radio Systems according to IEEE802

Mobile Radio Systems according to IEEE802
Chapter 7

- **Overview of IEEE 802**
- **WLAN (IEEE 802.11)**
- **WLAN Network Topologies**
- **Bluetooth (formerly IEEE 802.15.1)**
- **ZigBee (IEEE 802.15.4)**

7 Mobile Radio Systems according to IEEE 802

- For networking and wireless connection of terminals, respectively, via radio communication, several standards for wireless networks have been developed by the IEEE within the standard family IEEE 802 in the past years.



Overview of several standards of the IEEE 802 family

Excerpt from the List of Working Groups and Standards at IEEE 802:

- IEEE 802.1 Bridging (networking) and Network Management
- IEEE 802.2 Logical link control
- IEEE 802.3 Ethernet

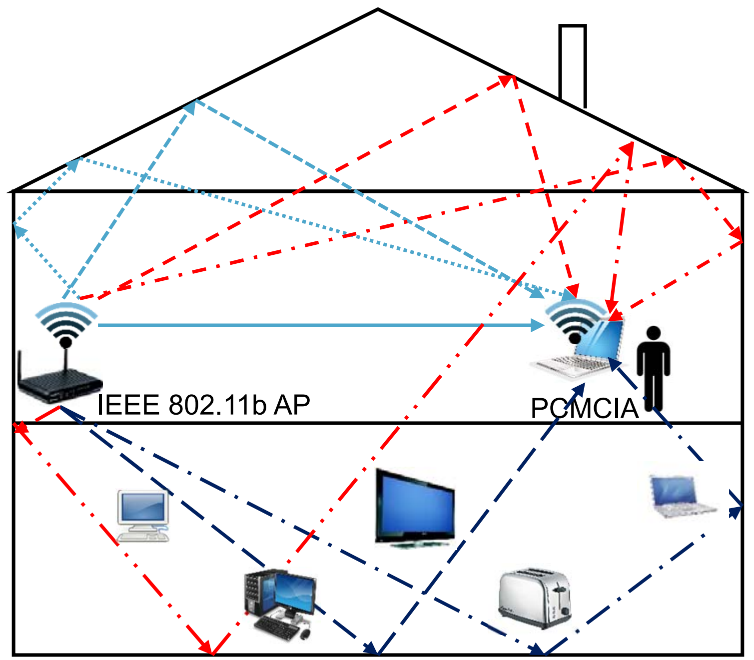
- IEEE 802.11 Wireless Local Area Networks (LAN) & Mesh (Wi-Fi certification)

- IEEE 802.15 Wireless Speciality Networks (WSN)
  - IEEE 802.15.1 Bluetooth certification (in the meantime, deleted as IEEE standard)
  - IEEE 802.15.3c 60 GHz Systems
  - IEEE 802.15.3d 300 GHz Systems 100 Gb/s wireless
  - IEEE 802.15.3e 60 GHz Systems High Rate Close Proximity
  - IEEE 802.15.4 ZigBee certification

- IEEE 802.16 Broadband Wireless Access
- IEEE 802.20 Mobile Broadband Wireless Access (Cognitive Radio)
- IEEE 802.21 Media Independent Handoff

7.1 Wireless LAN (IEEE 802.11)

- Properties and requirements of WLANs:
  - Use of a standardized WLAN as a generally accepted, wideband, flexible, wireless communication system
  - Small radio modems tailored for the use in portable computers
  - Small energy consumption (a few hundreds of mW) for the use in battery supplied systems
  - Support of terminal mobility (velocities of up to 36 km/h)
- Use of WLAN as infrastructure or as ad-hoc network



Variants of the Standard (1)

- IEEE 802.11b (WiFi 1):
  - Data rates of up to 11 Mbit/s
  - Direct sequence at 2.4 GHz
- IEEE 802.11a (WiFi 2):
  - Data rates up to 54 Mbit/s
  - OFDM at 5 GHz
- IEEE 802.11g (WiFi 3):
  - Data rates up to 54 Mbit/s
  - OFDM at 2.4 GHz
- IEEE 802.11n: (WiFi 4)
  - Data rates up to 248 Mbit/s
  - Air interface MIMO-OFDM at 2.4 and 5 GHz

Variants of the Standard (2)

- IEEE 802.11ac (WiFi 5):
  - Expansion to 802.11n
  - Data rate: up to 7 Gbit/s at 8x8 MIMO
  - OFDM at 5 GHz

- IEEE 802.11ad:
  - OFDM, 64QAM at 60 GHz
  - 4 overlap-free channels with 2.16 GHz bandwidth each
  - Data rate up to 7 Gbit/s
  - max. 10 m coverage

- IEEE 802.11ay:
  - Further development of IEEE 802.11ad
  - Channel bandwidth of n*2,16 GHz (n=1,2,3,4)
  - Data rate up to 20 Gbit/s
  - New applications such as mobile backhaul or fixed-mobile access

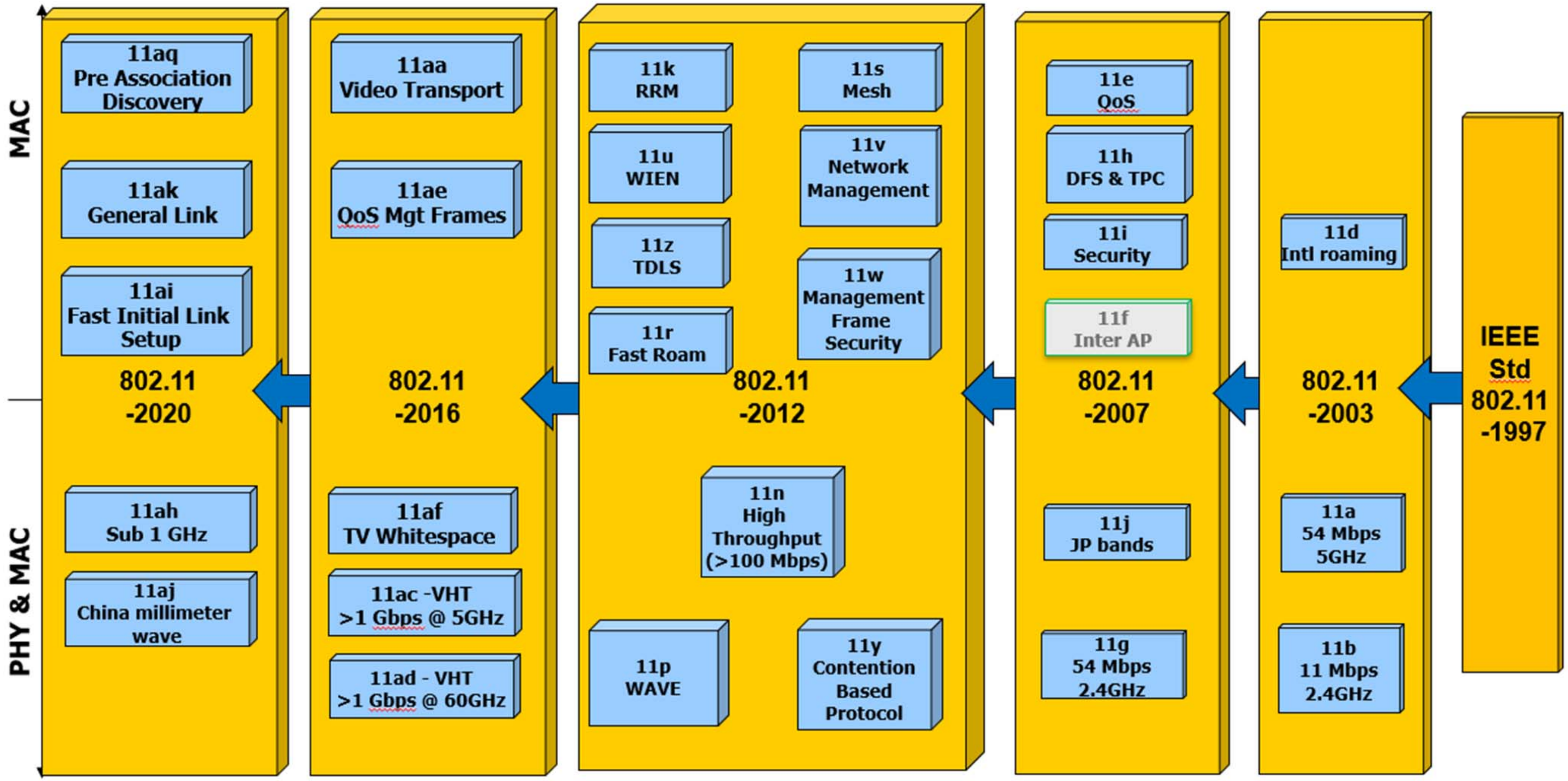
Variants of the Standard (3)

- IEEE 802.11ax (WiFi 6):
  - Further development of IEEE 802.11ac
  - Focus on efficient wireless networking of very many devices
  - Standardisation is shortly before adoption
  - Routers with the specification IEEE 802.11ax draft are already available

- IEEE 802.11p
  - Adaptation of IEEE 802.11 to Car-to-Car (C2C) Communication
  - OFDM at 5 GHz

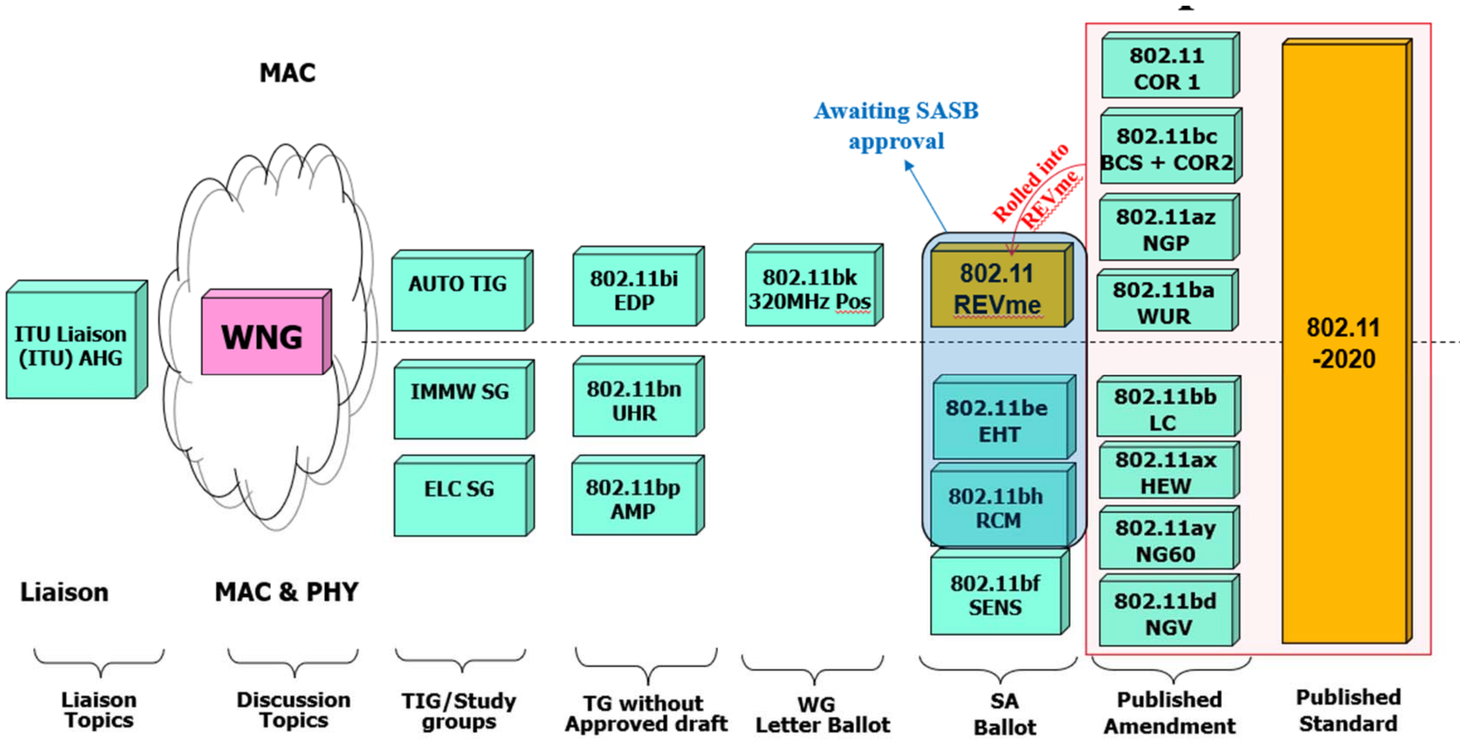
- IEEE 802.11bd
  - Further development of IEEE 802.11p
  - Standardisation is currently taking place
  - Doubling of coverage and throughput, respectively, of IEEE 802.11p

IEEE 802.11 Revisions



Quelle: https://mentor.ieee.org/802.11/dcn/24/11-24-1362-01-0000-2024-september-working-group-chair-opening-report.pptx

Current Developments at IEEE 802.11



Quelle: https://mentor.ieee.org/802.11/dcn/24/11-24-1362-01-0000-2024-september-working-group-chair-opening-report.pptx

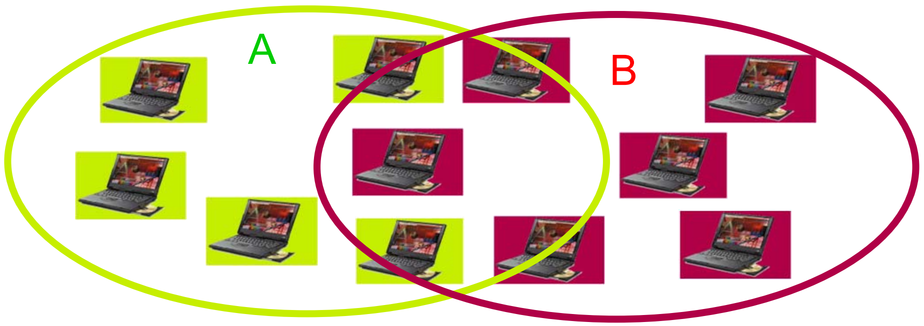
Network Topologies

- Every station (node) is distinguished from the other by a definite Node Identifier (NID).
- All stations of the same network obtain a common WLAN identifier (LID) and form a WLAN.
- Differentiation of two cases
  - Independent WLANs:
    - consisting of two WLANs A and B; no member of WLAN A is located within the transition region of a member of network B
  - Overlapping WLANs
    - In case of overlapping of the radio reach of some stations of network A with several stations of network B; partition of the communication medium in the overlap area

Overlap of WLANS

- Independent WLANs

- Overlapping WLANs



Effects occurring as a Consequence of Overlapping:

- Transmitters of both WLANs use the same frequency band
  - Interferences occur
  - As a result of interferences, possibly not all stations are able to receive information from one another => further interferences due to the effect of „hidden“ stations

- A station receives data packets from several WLANs with different LIDs
  - Evaluation of all data packets
  - Further processing only of the own packets => maximum data transmission capacity decreases

7.2 Bluetooth (previously IEEE 802.15.1)

- Background
  - The objective was to substitute cable connections between different devices by low cost and flexible radio connections
    - Bridging of short distances (some meters)
    - Preferably low power consumption
    - Low installation effort
  - 1998 Formation of the Bluetooth Special Interest Group (BSIG)
  - First specifications in May 1998
  - Since that time, Bluetooth has become a widespread industry standard and a part of the IEEE802 standards family.

Network Configuration

- In the Bluetooth terminology, the stations communicating via a radio connection form a pico network.
- A pico network consists of maximal 8 stations.
- Several pico networks can be combined to a scatter network.
- A station that wants to contact the other stations of the pico network, plays the role of the master (preset of the clock pulse and the radio channels) for some time.
  - The other stations (slaves) follow the instructions of the master.
  - Typical ad-hoc network

7.2 Bluetooth (previously IEEE 802.15.1)

Scattering Network with 2 Pico Networks

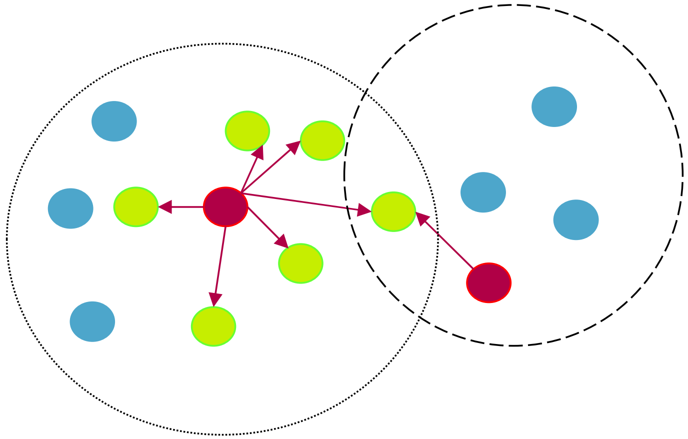
master

slave

Two possible states:

- contributes actively to a connection
- put into power saving mode
  by the master

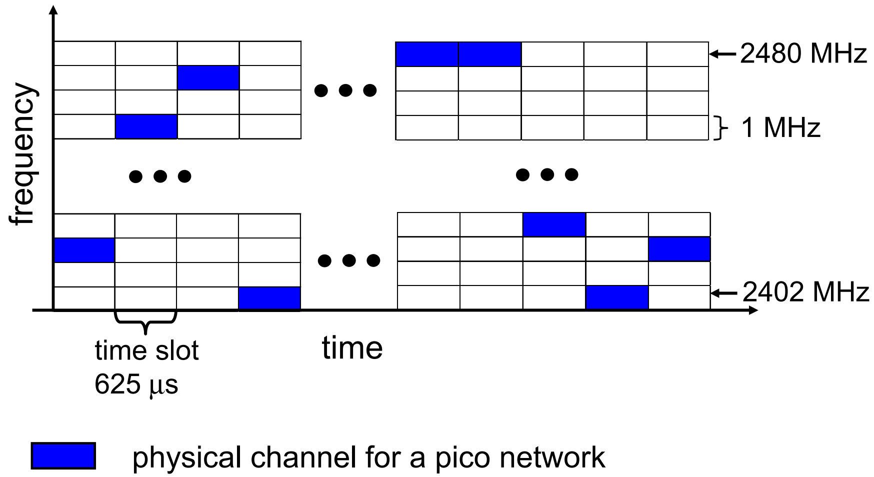
Station in standby status is not involved in a connection



Channel Occupancy with Bluetooth

- Bluetooth applies the ISM band at 2.4 GHz
- 79 carriers with a carrier frequency separation of 1 MHz
- Transmission in the form of packets with 1 to 5 time slots
- Change of the frequency carrier after every packet transmitted

Example of packets of the length of a time slot

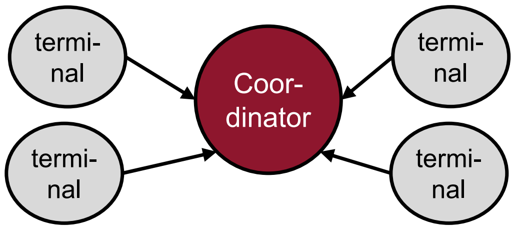


Source: according to C. Lüders, Mobilfunksysteme

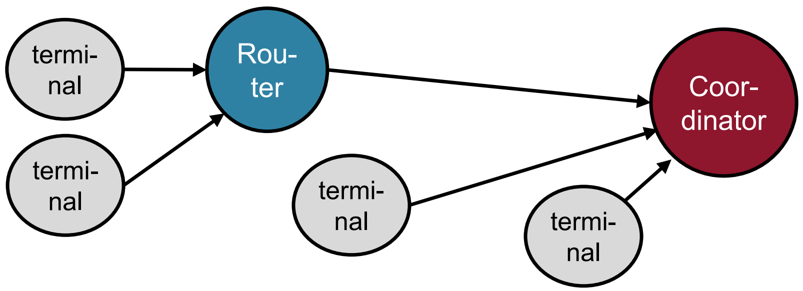
7.3 ZigBee (IEEE 802.15.4)

- Aim: interconnection of indoor devices over short cell ranges (~10 m to 100 m)
- Development by ZigBee alliance since 2002
- Network topology consists of three device classes:
  - **Terminal**: sensors and/or actuators
  - **Coordinator**: controls the complete ZigBee network; determines the channel, allows new terminals to enter the network, routes all messages
  - **Router**: optional, forwards messages to other routers or to the coordinator and thus can extend the network geographically

ZigBee supports diverse network topologies, e.g.:



Star Topology



Tree Topology

Phy Layer and Mac Layer

- ZigBee actuators/sensors can never communicate direct. The connection has to be established via router or coordinator
- A terminal is identified via a 16-bit address (at most 65.536 devices)
- Three different ISM frequency bands with different bandwidths and data rates can be used:

HF Band	Frequency range	Channels	Bandwidth	Data rate	Modulation
868 MHz	868…870 MHz	1	2 MHz	20 kbit/s	BPSK
915MHz	902…928 MHz	10	2 MHz	40 kbit/s	BPSK
2.4 GHz	2.405…2.480 GHz	16	5 MHz	250 kbit/s	QPSK

- ZigBee partly overlaps with the frequency bands of IEEE 802.11b/g/n (has to be taken into account for network planning)
- The communication is symmetrically ciphered by AES-128

Thank you for participating in the lecture and success in the exam!

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