Principles in Mobile Communications

Prof. Dr.-Ing. Thomas Kürner

Technische Universität Braunschweig

Institut für Nachrichtentechnik

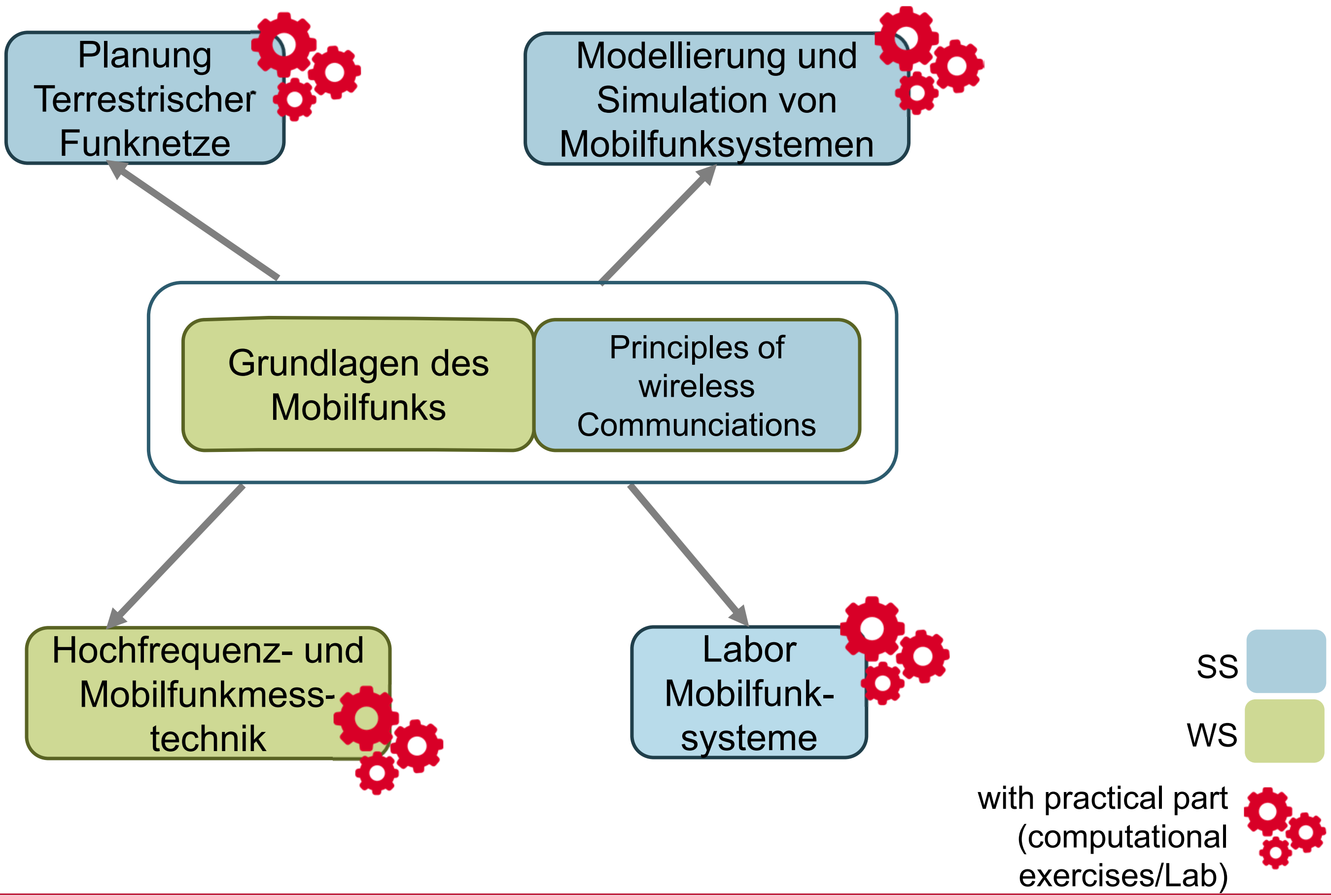
Organisation

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

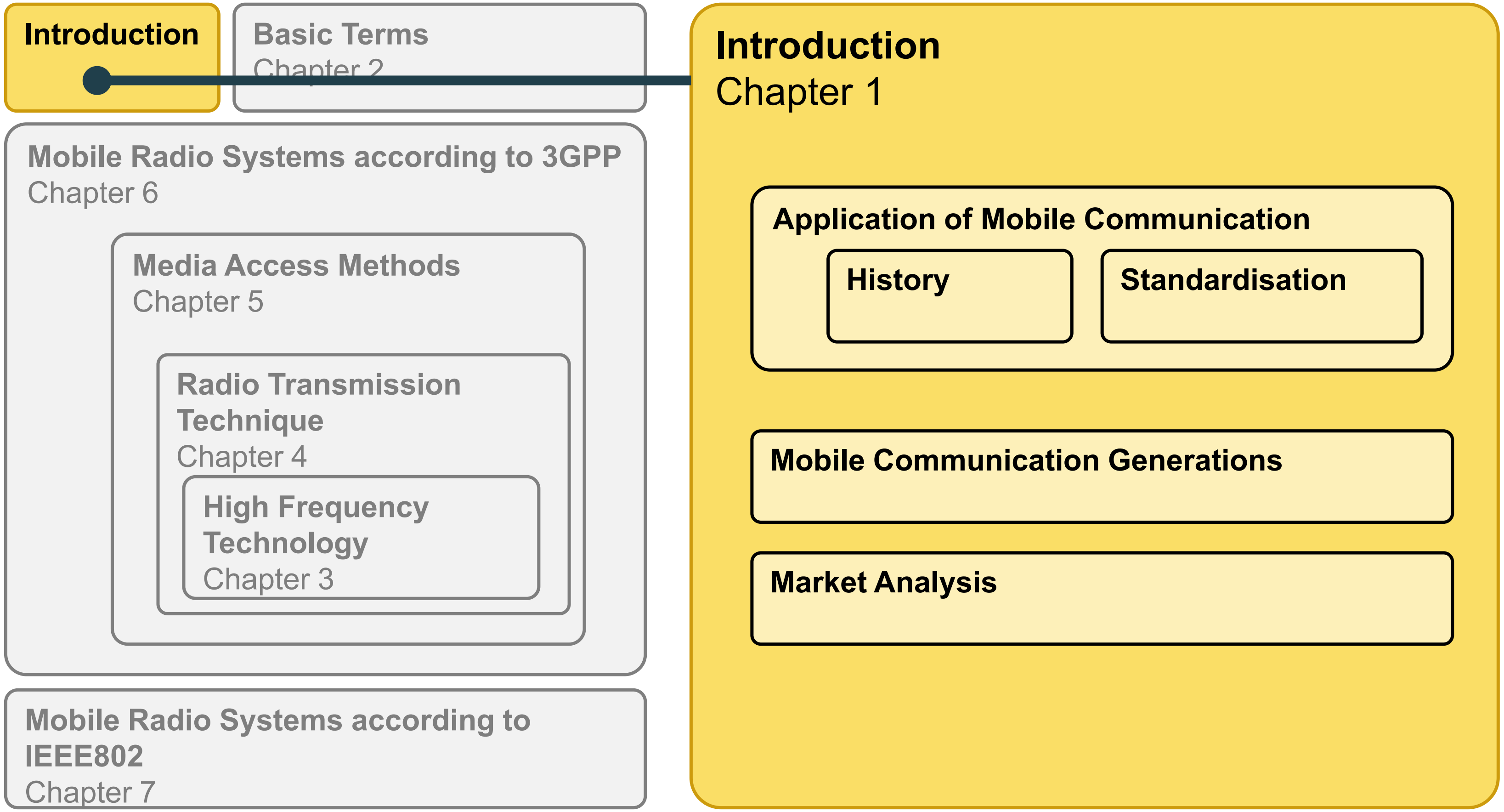
Literature

- 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

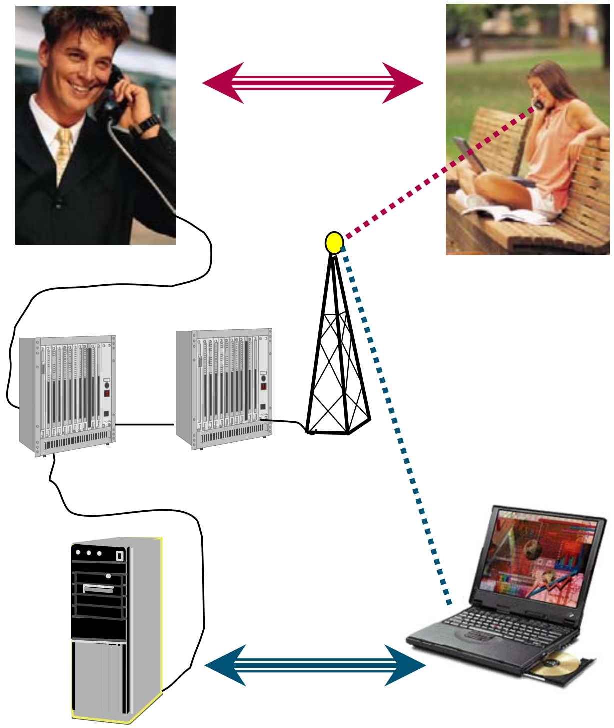


1 Introduction
1.1 Applications of Mobile Communications

- 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.

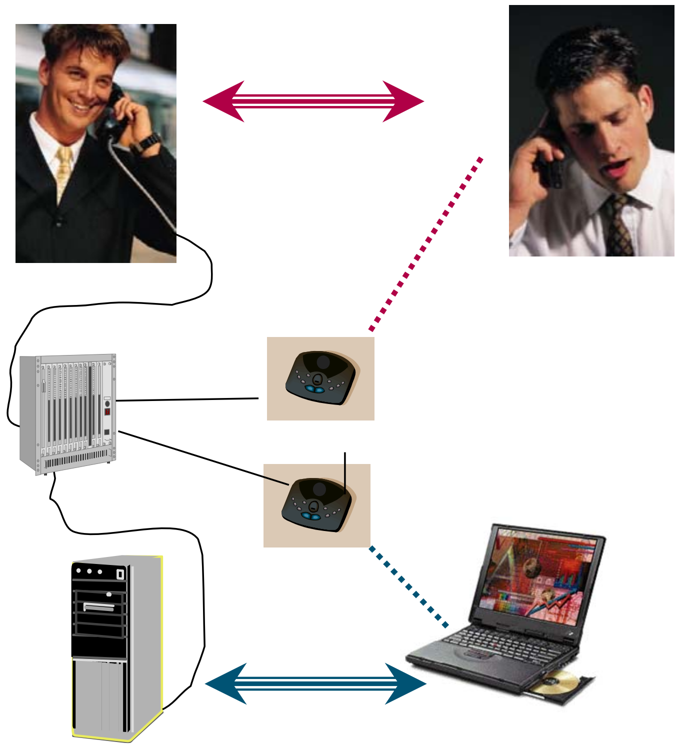
Examples (1)

- 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



Examples (2)

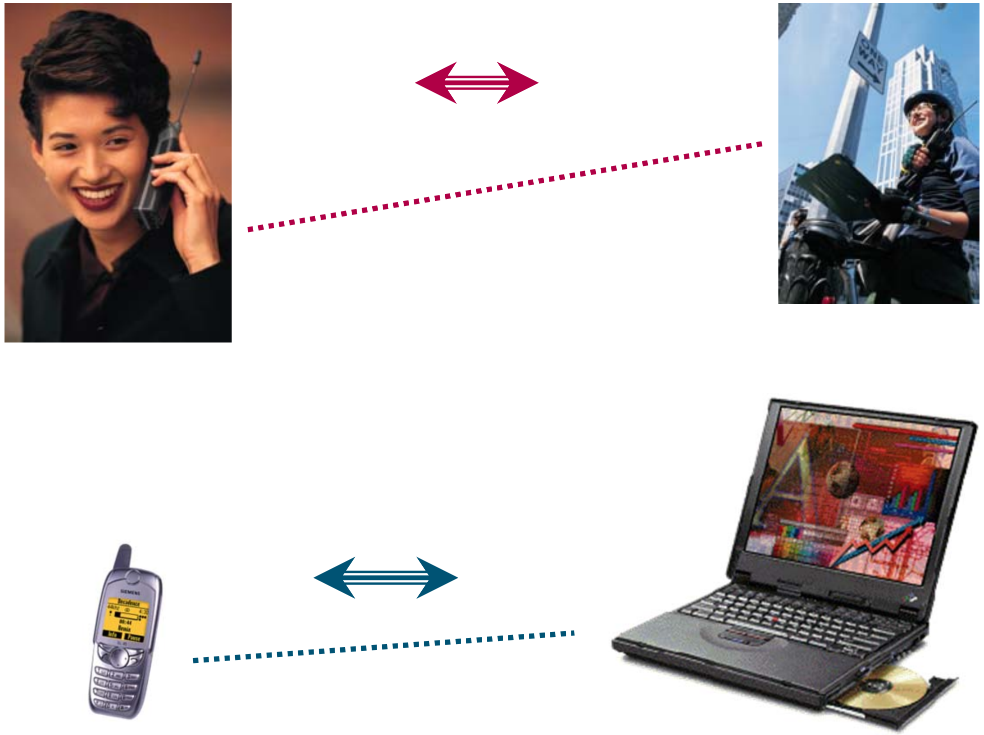
- voice communication in a public telephone network, with at least one subscriber using a cordless telephone
  - examples: cordless telephones (DECT)
  - restricted mobility within a small radius around the base station
- data communication between a laptop (mobile) or a smartphone and a server (stationary) via a wireless network access
  - examples: WLAN
  - restricted mobility within a small radius around the access point



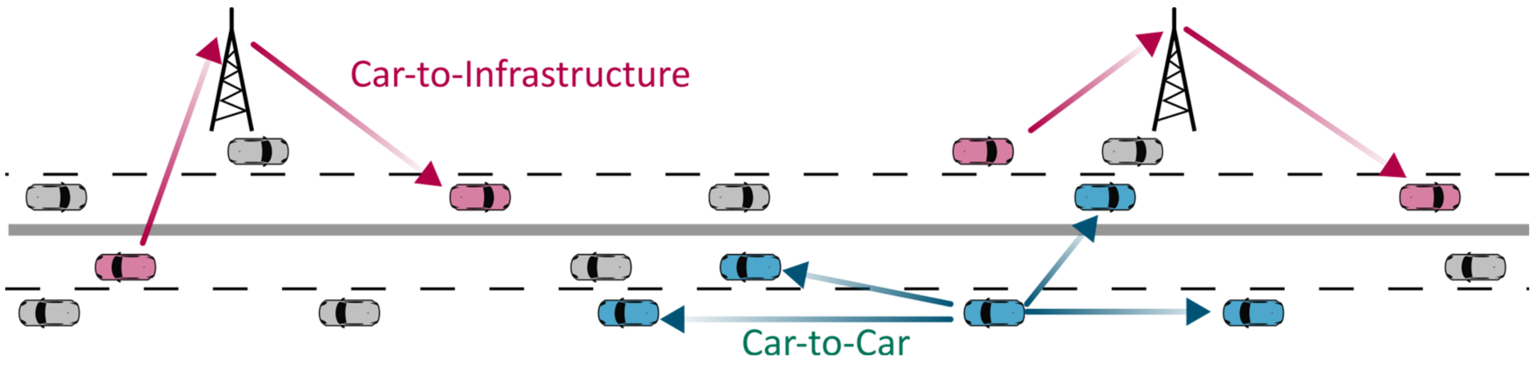
1.1 Applications of Mobile Communications

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

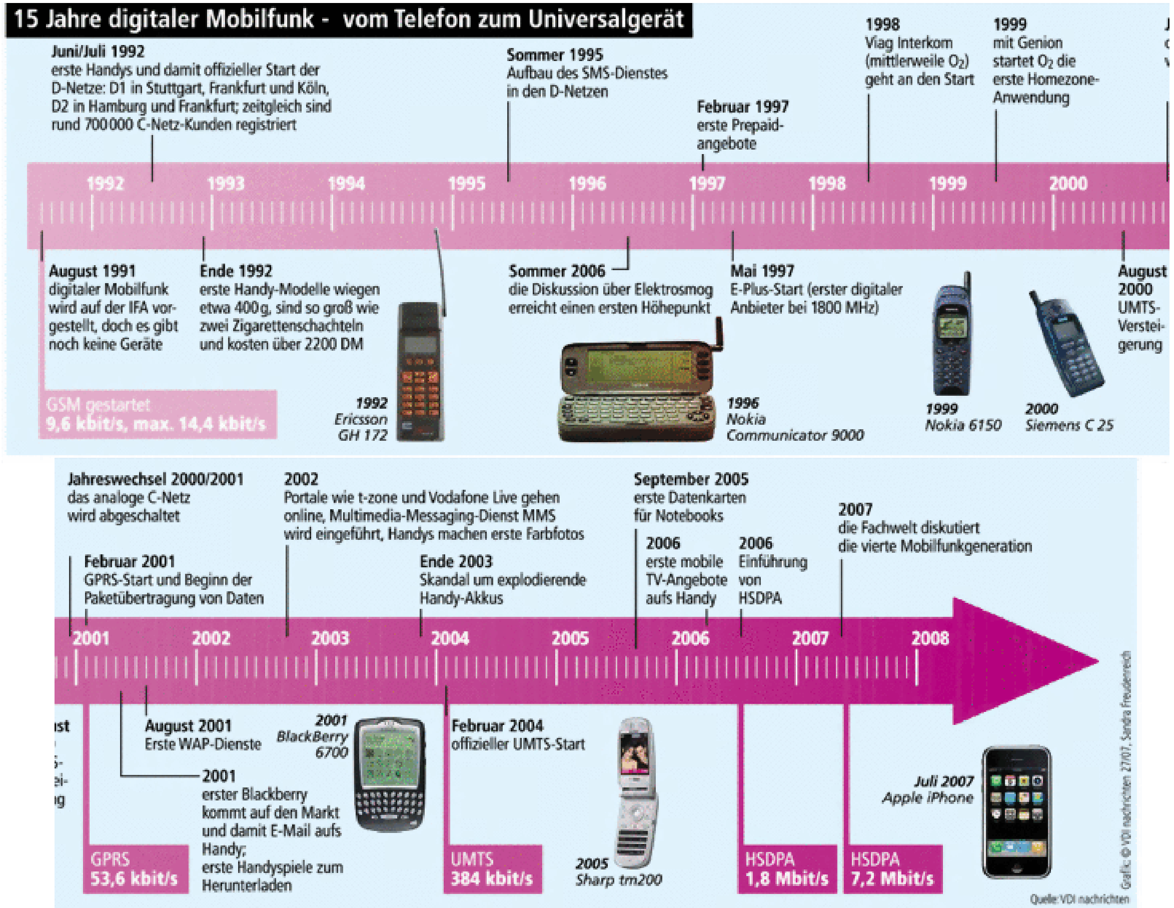
- Essential characteristics of the radio transmission technique for the European „candidate“ (UMTS) for IMT-2000 were defined
- 1999 Allocation of the first European UMTS licence (Finland)
- 2000 End of the UMTS auction in Germany
  - Allocation of 6 licences, auction proceeds 100 Mrd. DM
- 2001 Start 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

1.2 Development of Mobile Communications

Overview



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

Broadband access in dense areas

PERVASIVE VIDEO

Broadband access everywhere

50+ MBPS EVERYWHERE

Higher user mobility

HIGH SPEED TRAIN

Massive Internet of Things

SENSOR NETWORKS

Extreme real-time communications

TACTILE INTERNET

Lifeline communications

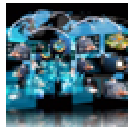
NATURAL DISASTER

Ultra-reliable communications

E-HEALTH SERVICES

Broadcast-like services

BROADCAST SERVICES



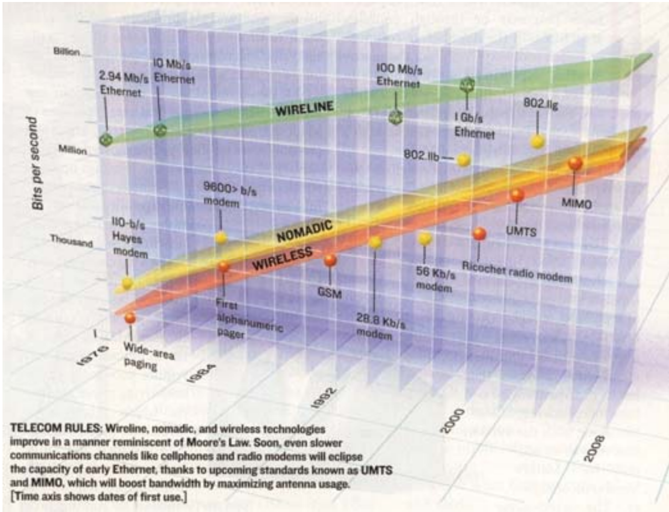
Source: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

1.5 WLAN and WSN Standard for Local Radio Networks

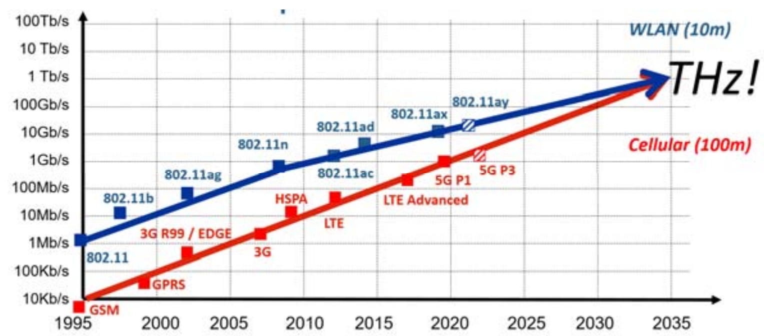
- **IEEE 802.11 (Institute for Electrical and Electronics Engineers):** American system; data rates up to 54 Mbit/s; use of the ISM band (ISM: Industrial, Scientific and Medical) at 2.4 GHz, 5 GHz and 60 GHz with data throughput > 1Gbit/s
- **Bluetooth (IEEE 802.15.1, meanwhile not an IEEE 802 standard 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 Introduction

1.6 Data Rates of Telecommunication Systems



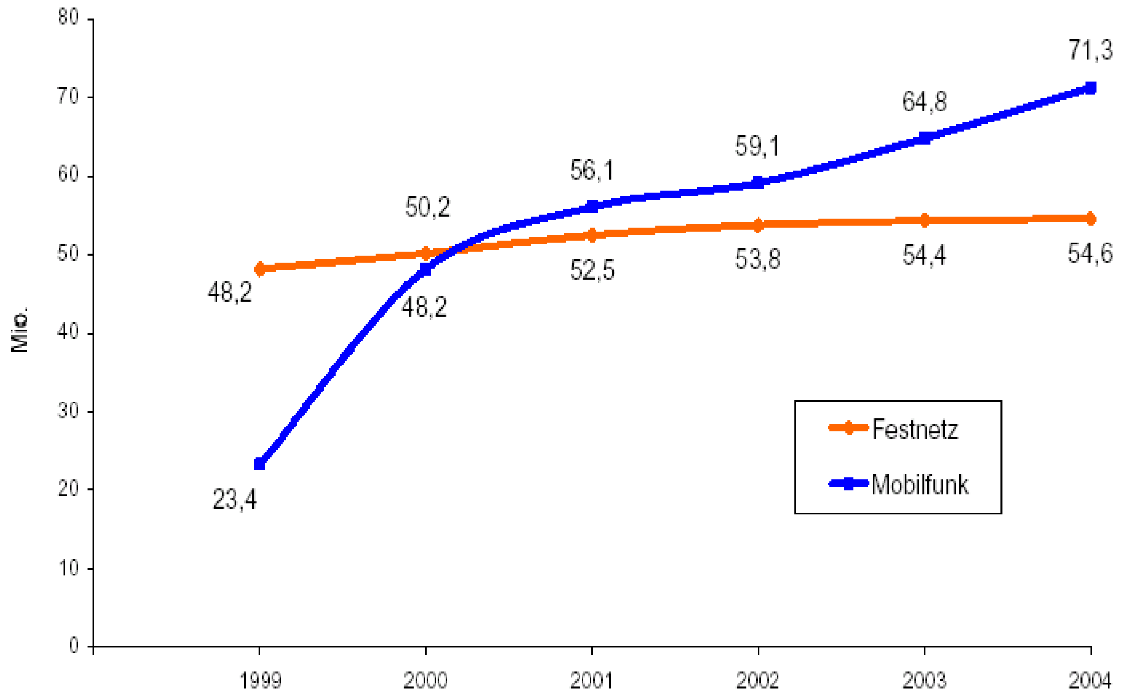
Source: IEEE Spectrum, Juli 2004



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

Fixed Network and Mobile Radio Communication

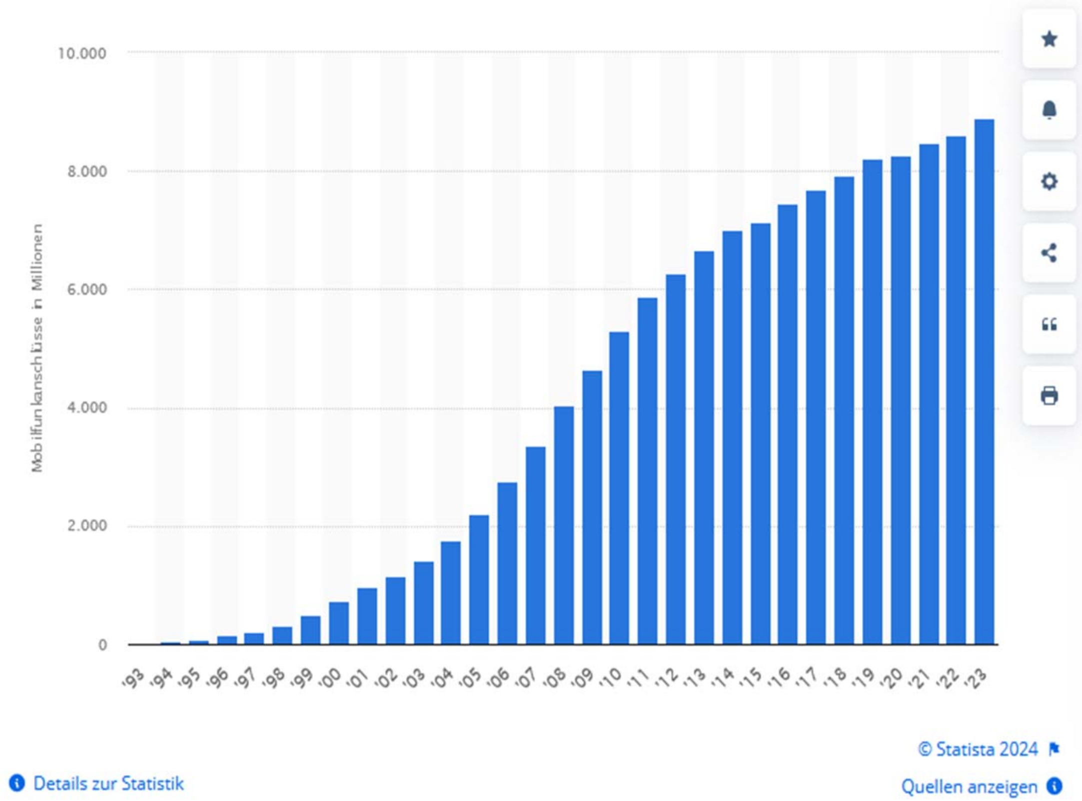
Comparison mobile users / fixed network connections in Germany



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

1.7 Markets for Mobile Communications

- Development of the number of mobile users worldwide

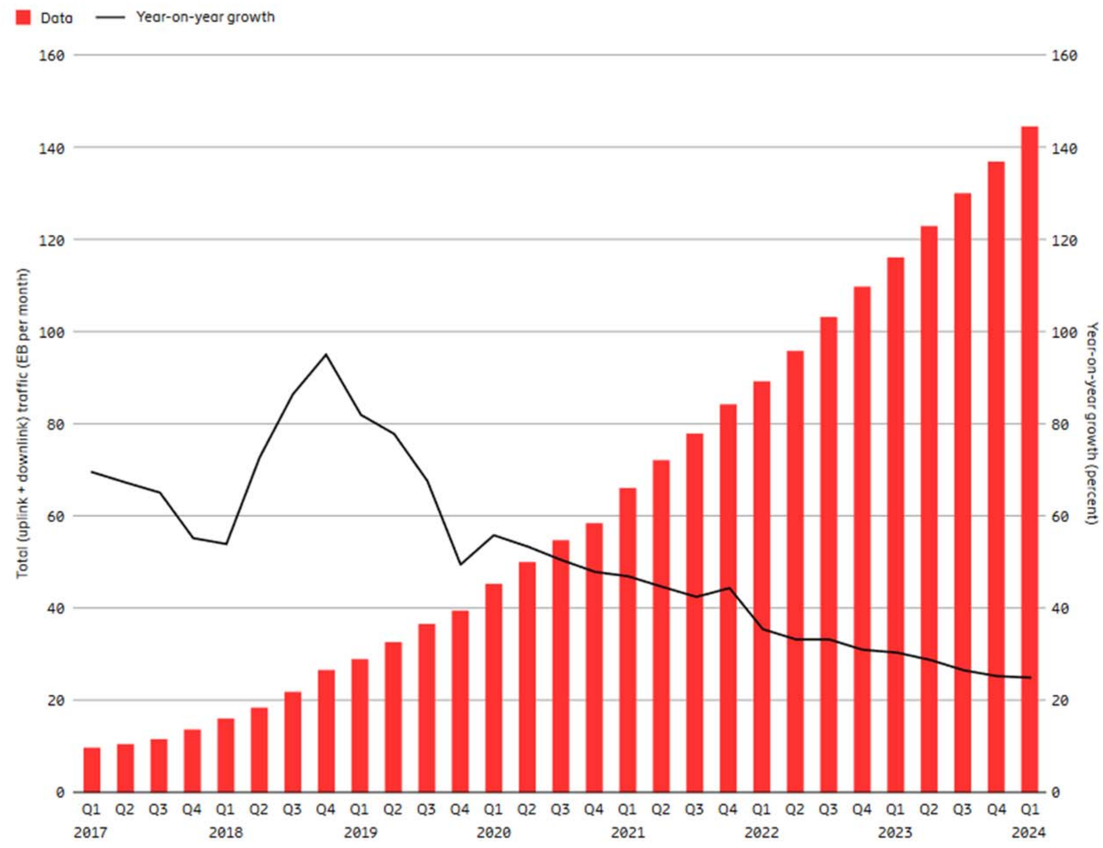


Source: https://de.statista.com/statistik/daten/studie/2995/umfrage/entwicklung-der-weltweiten-mobilfunkteilnehmer-seit-1993/

Data Traffic

Development of Mobile Data Traffic

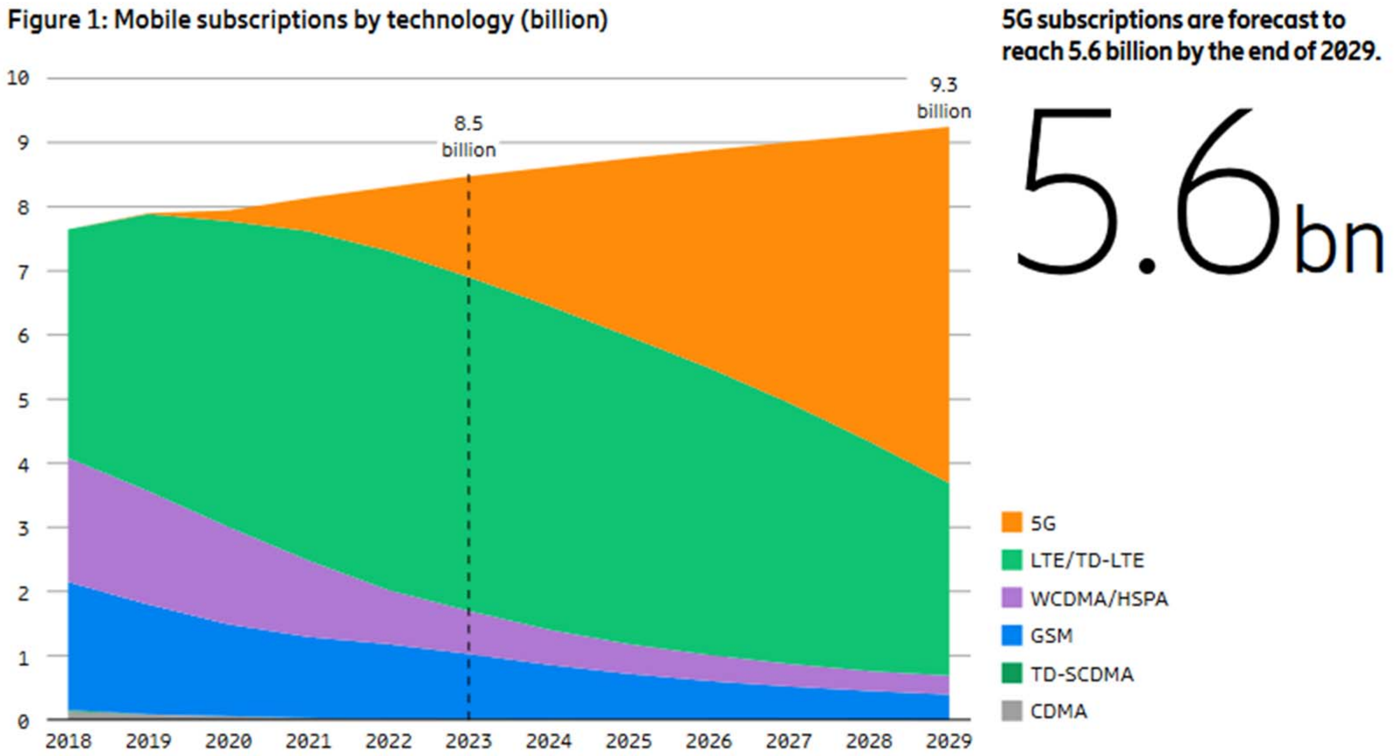
Figure 5: Global mobile network data traffic and year-on-year growth (EB per month)



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

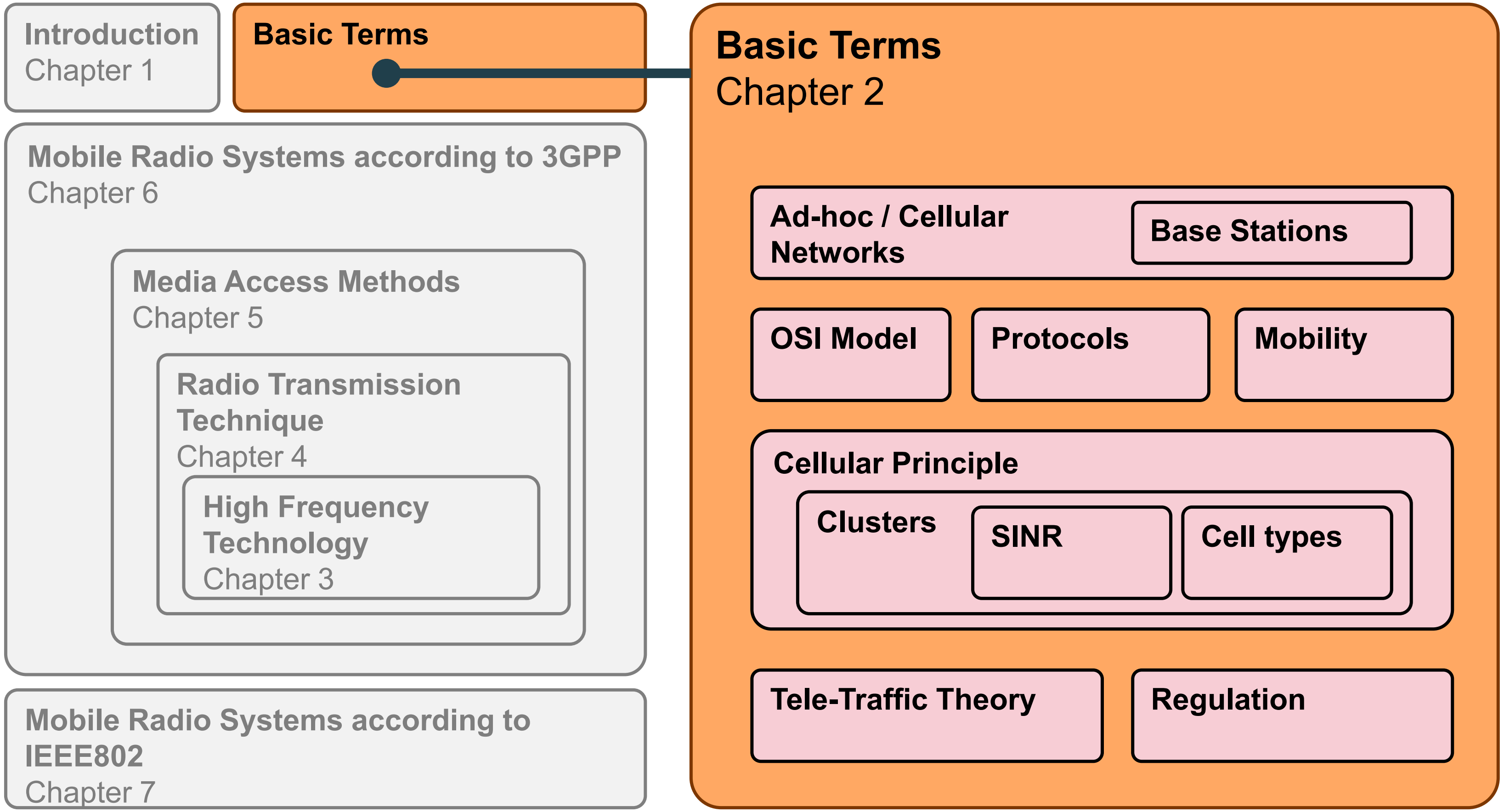
Worldwide Subscriptions



[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“:

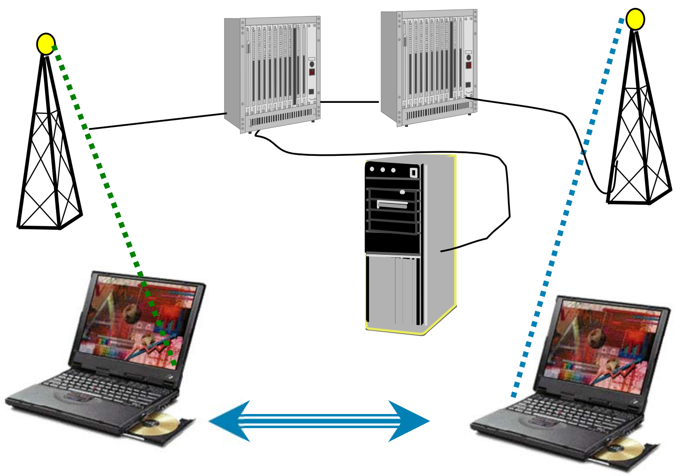
- Telecommunication system consisting of the components
  - terminals (interfaces between user and system)
  - transmission equipments
  - Switching equipments

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

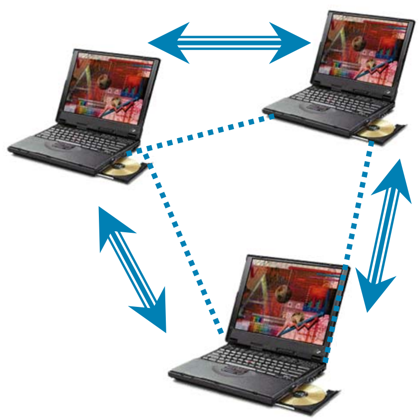
- Radio channel as transmission medium
  - strong variations of the received power level
  - Normally mutual interferences between radio links

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

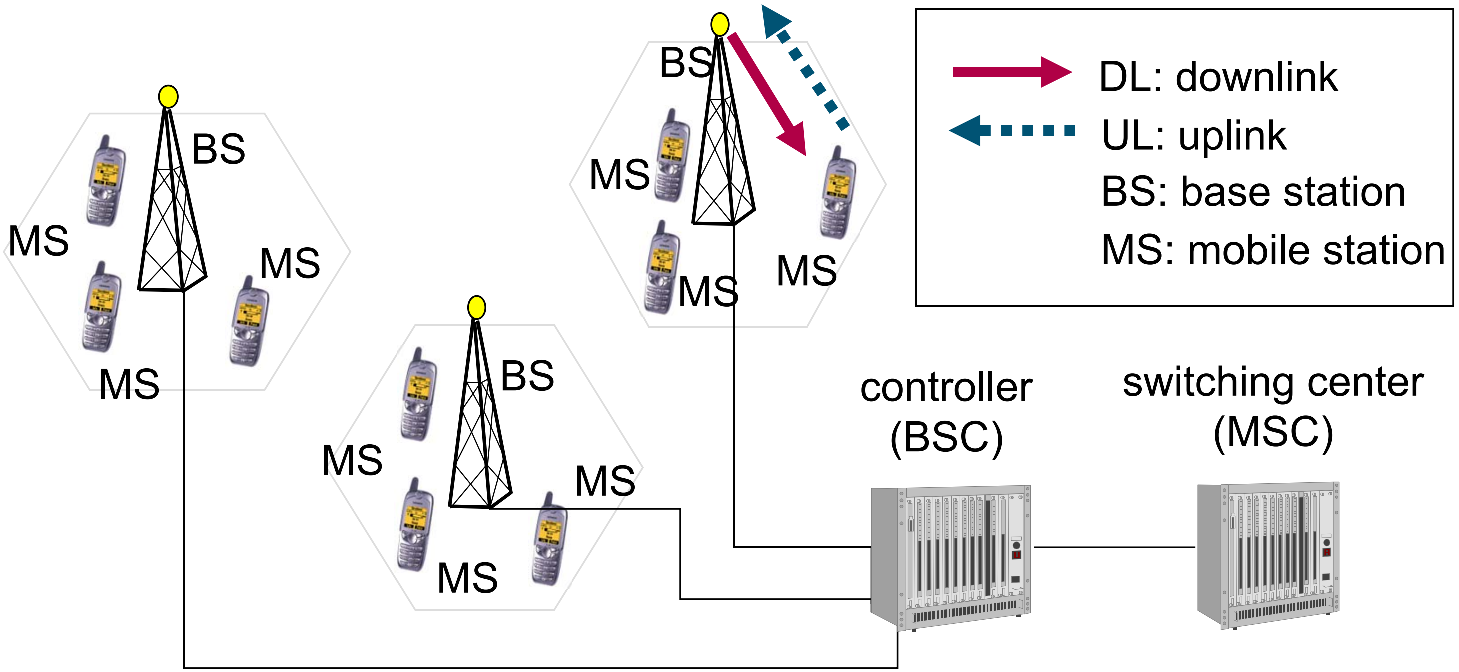
- Ad-hoc networks

  - 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)

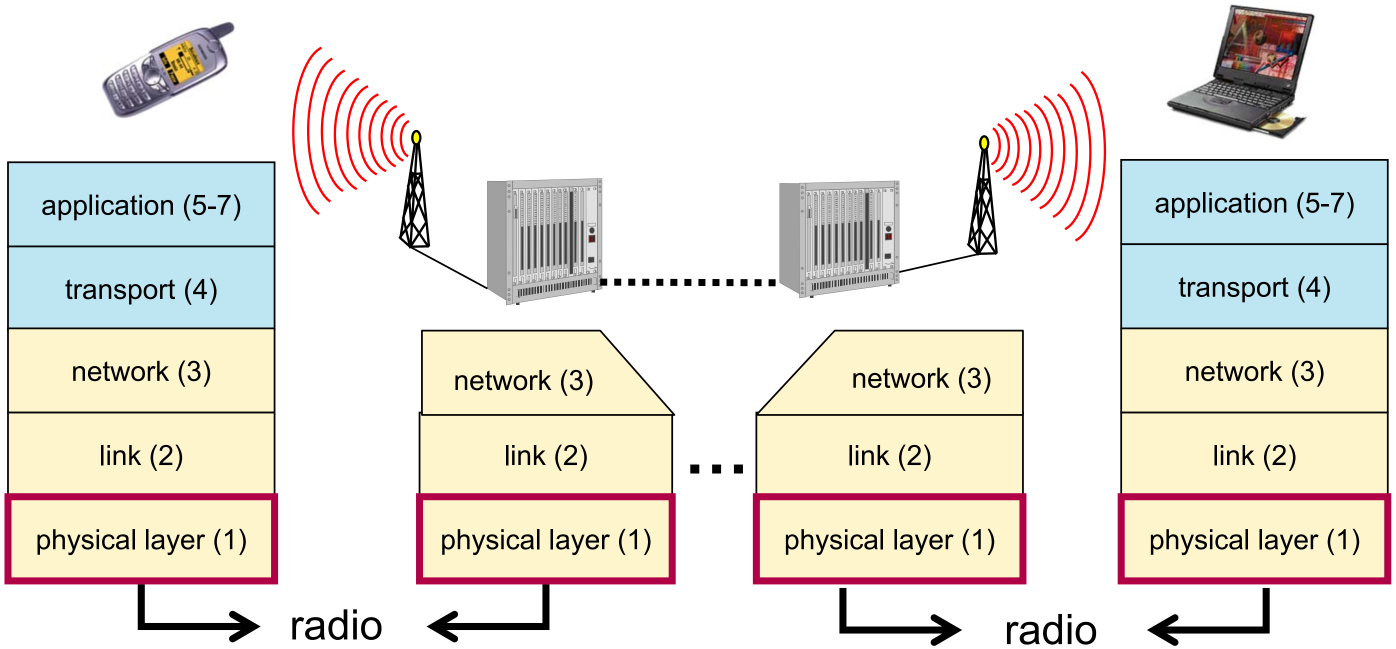


Base Station

- 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)

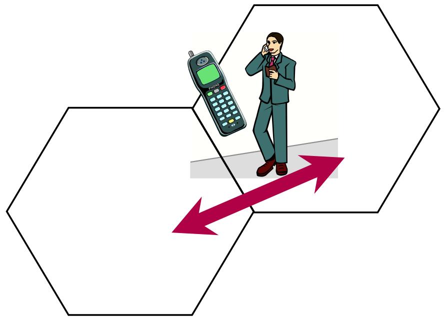
Bearer service

- 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

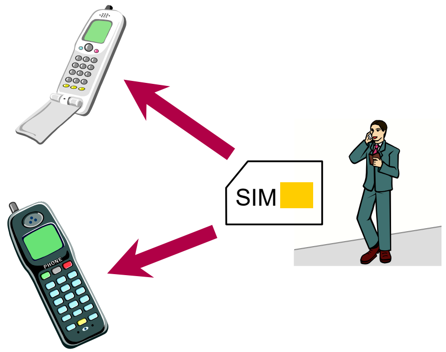
Terminal Mobility

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



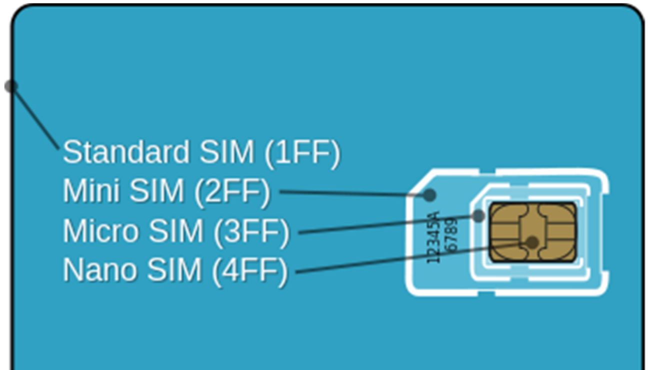
Personal Mobility

- 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

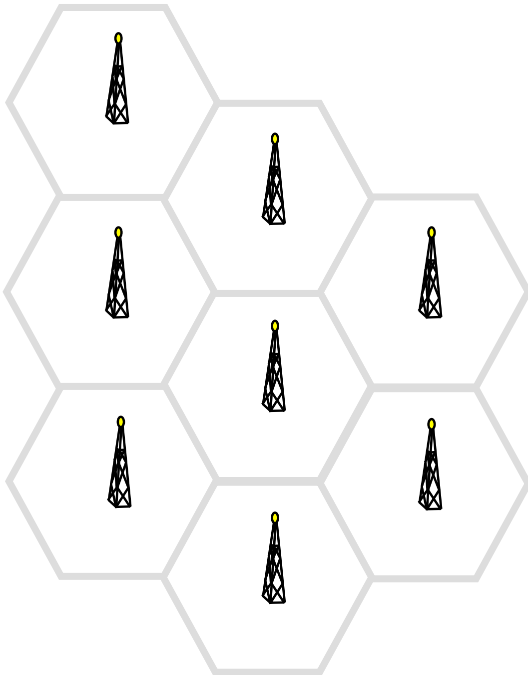
  - Subscriber is allowed to move arbitrarily in the network and is found automatically in case of incoming calls
    - Mobile radio system requires a mobility management
    - The respective mechanism is called roaming (general case: international roaming).

2.7 Cellular Principle

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

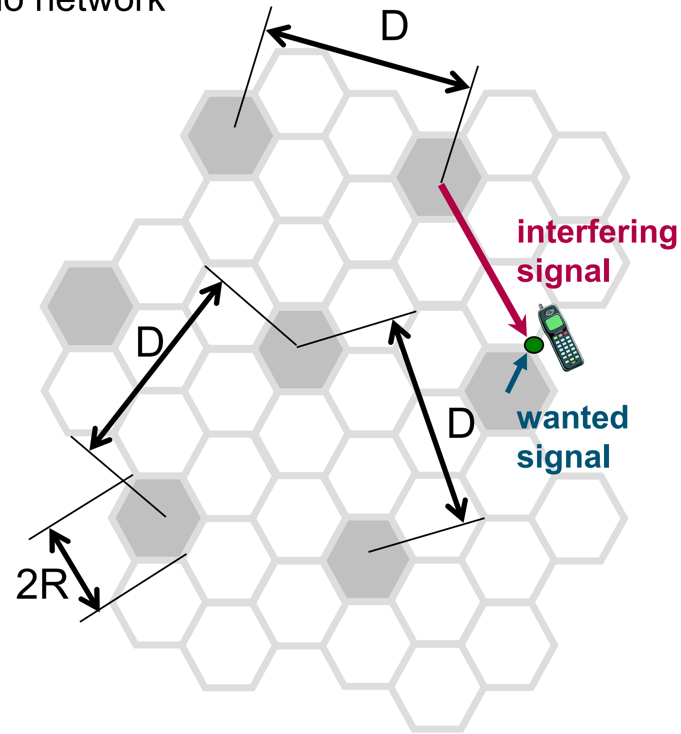
- Problem: limited frequency bands => relatively small number of speech channels

- 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 separation 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)*

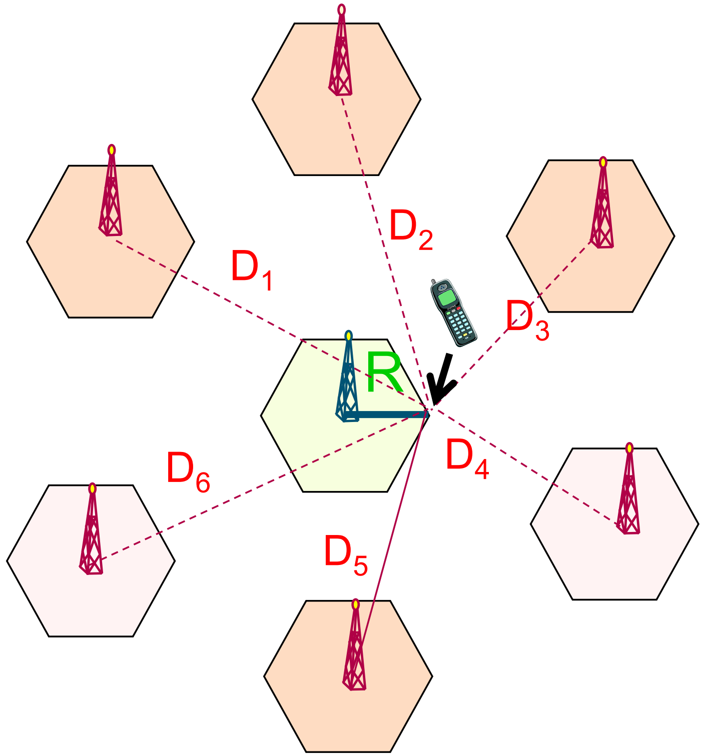
$$SINR = \frac{\text{wanted signal}}{\text{adjacent cell interference +noise}} = \frac{P}{I+N} \qquad (1.1)$$

- Essentially, intensity of the interference by cochannel interferences depending 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:

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

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

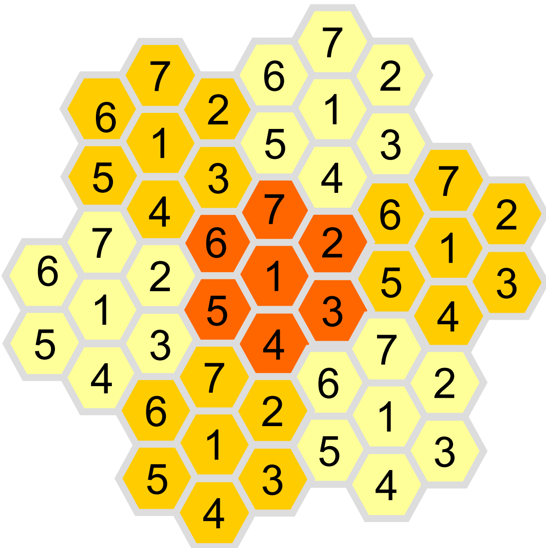
- Size of the cluster k indicates the number of cells per cluster
- A cluster can have all frequencies of the mobile radio system
- Inside a cluster no re-use of frequencies; re-use of frequencies f_i in the adjacent cluster at the earliest
- k defines the frequency re-use separation D
- Dependency between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

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

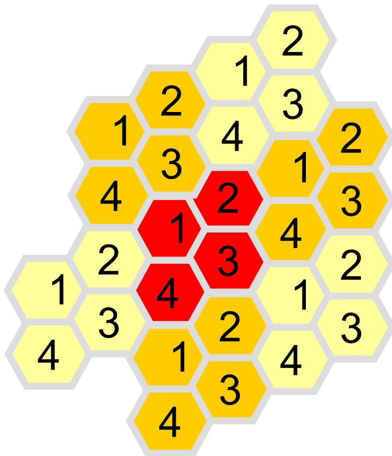
- Dependency between SIR and k from equations (1.3) and (1.4):

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

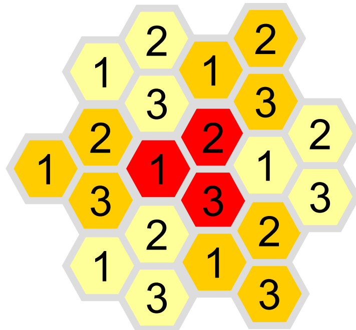
Examples of Clusters (Omni-Cells)



k=7

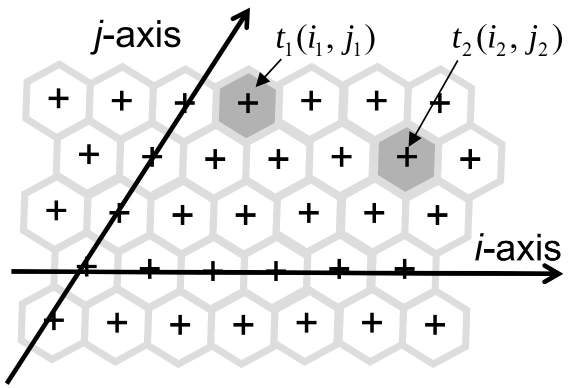


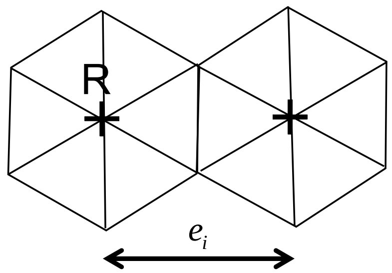
k=4



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

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

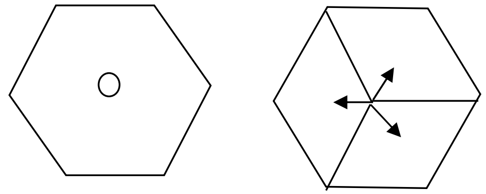
possible cluster sizes k = 1,3,4,7,9,12,13,16,19,21 etc.

Sectorisation

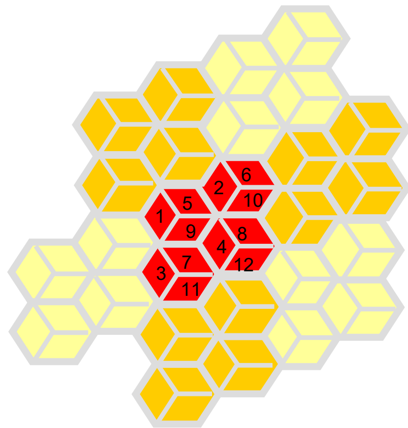
- Common measure to reduce the interferences in the network
- At every position, coverage of n = 2, n = 3 or n = 6 sectors with an angle of 180°, 120° or 60° by several antennas with distinctive directivity
- Re-use pattern is called (k, n) cluster
- For SIR applies: $SIR \approx \frac{n}{6}(3k)^{\frac{\gamma}{2}}$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



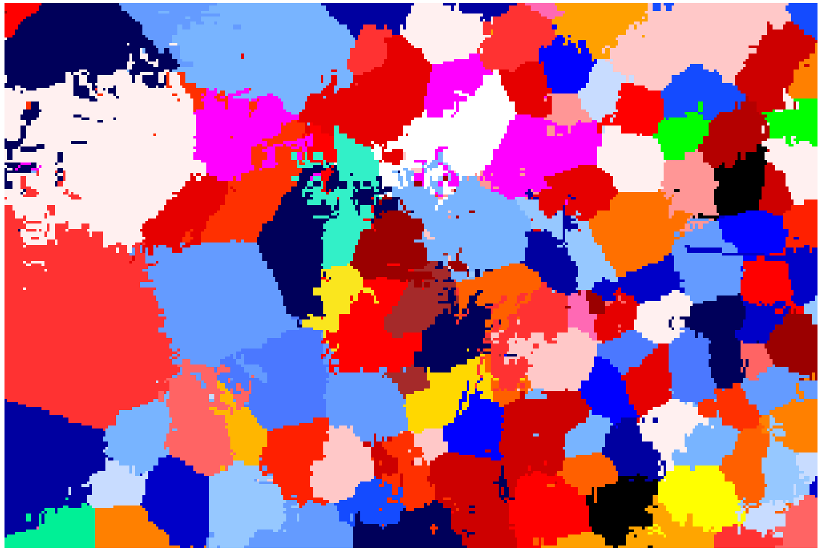
„Omni“ position 3-sector position



(4,3)-frequency re-use pattern

Cell Depiction 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 popagation conditions.
- Cell boundaries are not sharp; allocation of a mobile station to a cell can only be indicated with a certain probability.



Cell depiction for a real network; definition of a cell by the strongest received signal at a time

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	Anbindung of the cell via DSL; installation by the user (comparable to a WLAN router)

2.8 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.

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

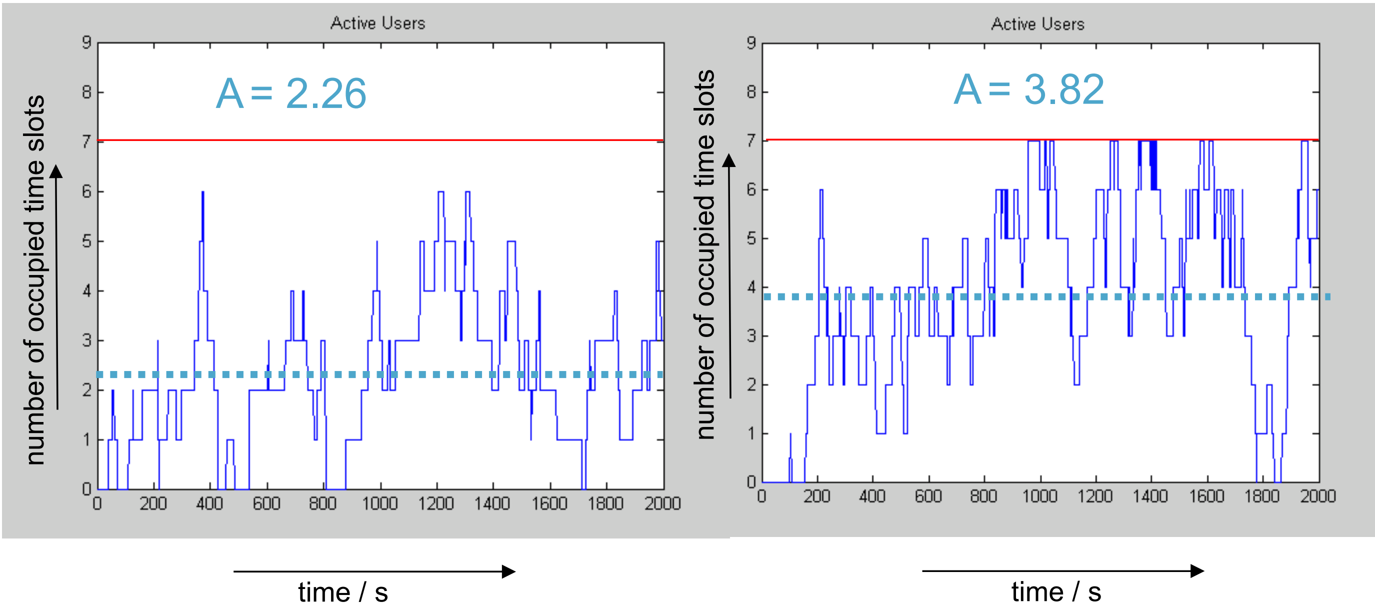
Y: mean number of busy channels
t: observation period in hours

- 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:

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

n : number of available channels

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

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

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

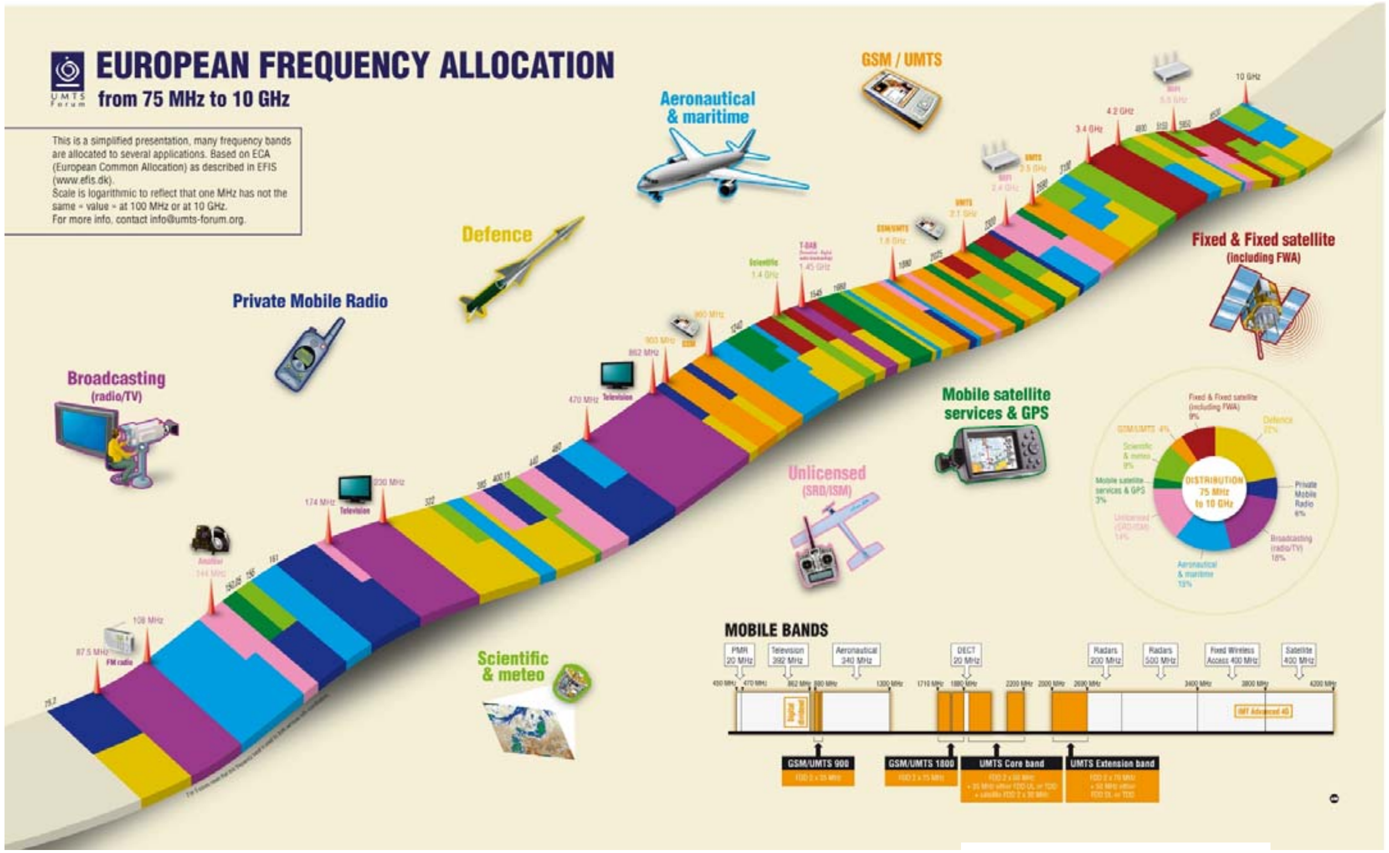
T_{m}: mean call duration (in hours)

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



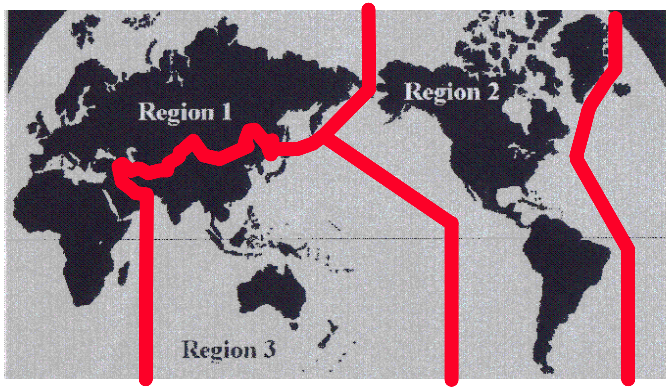
Source: UMTS Forum

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



region 1	region 2	region 3
1930-1970 FIXED MOBILE S5.388	1930-1970 FIXED MOBILE Mobile-satellite (Earth-to-space) S5.388	1930-1970 FIXED MOBILE S5.388
1970-1980 FIXED MOBILE S5.388		
1980-2010 FIXED MOBILE MOBILE-SATELLITE (Earth-to-space) S5.388 S5.389A S5.389B S5.389F		

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).

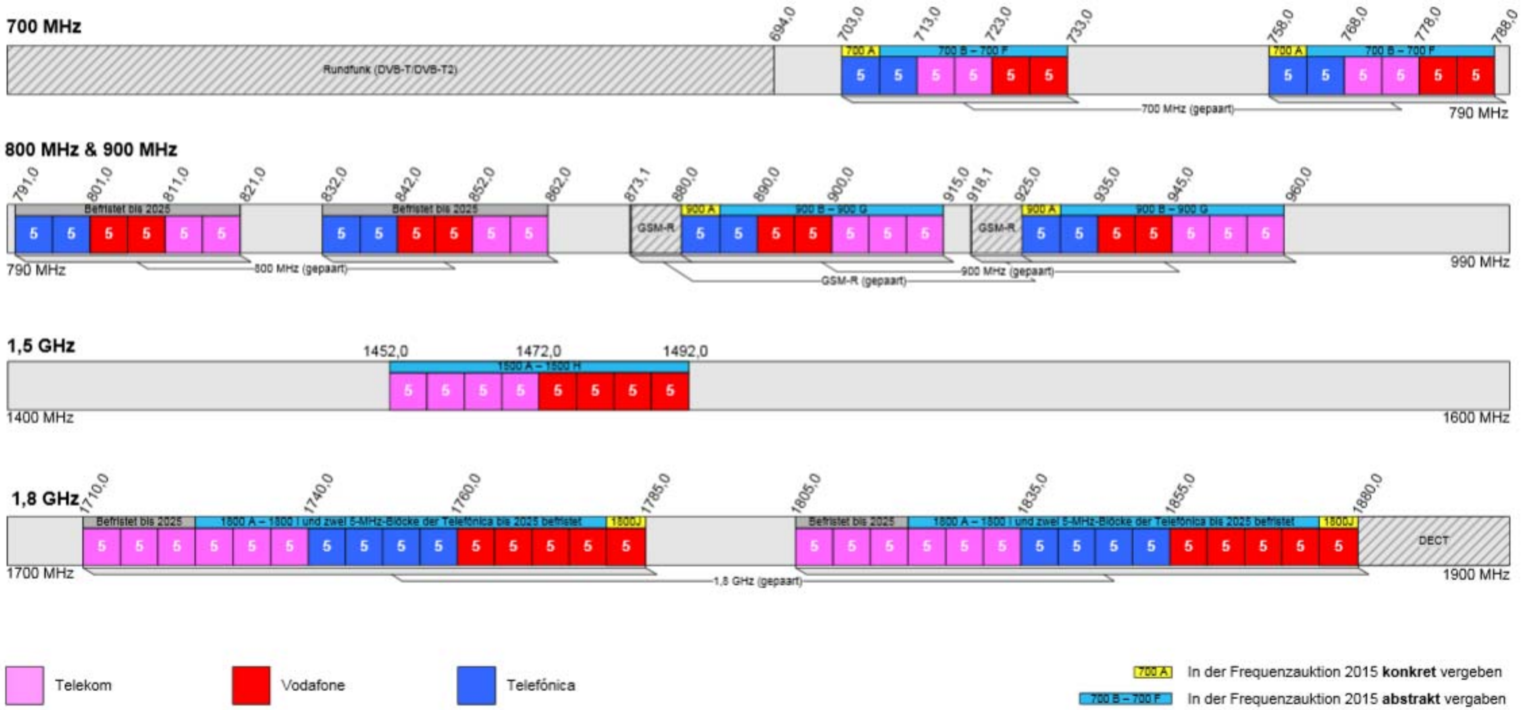
Quelle: ITU-R Radio Regulations

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 €**

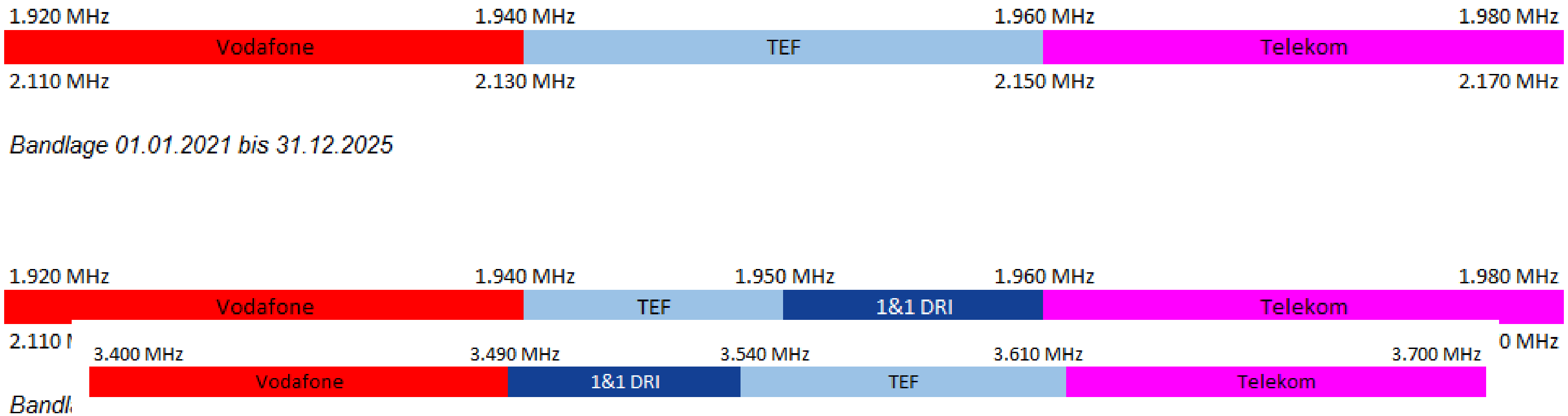
Source: www.bundesnetzagentur.de

Frequency Allocation in Germany (as of 2015)



Source: www.bundesnetzagentur.de

Result from the Auction 2019 in Germany



Bandlage im Bereich 3,6 GHz

Source: www.bundesnetzagentur.de