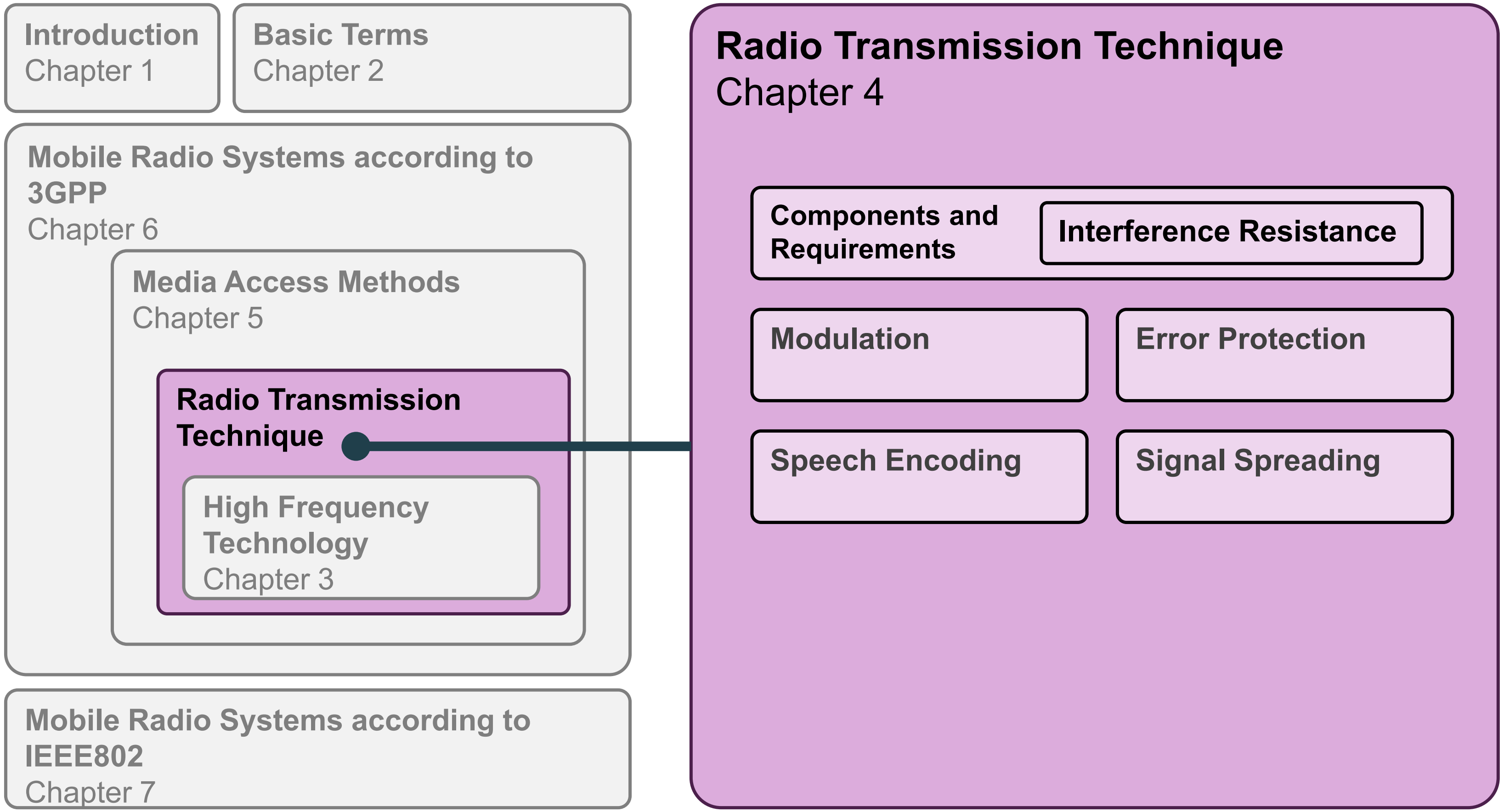
Chapter 4 – Radio Transmission Technique



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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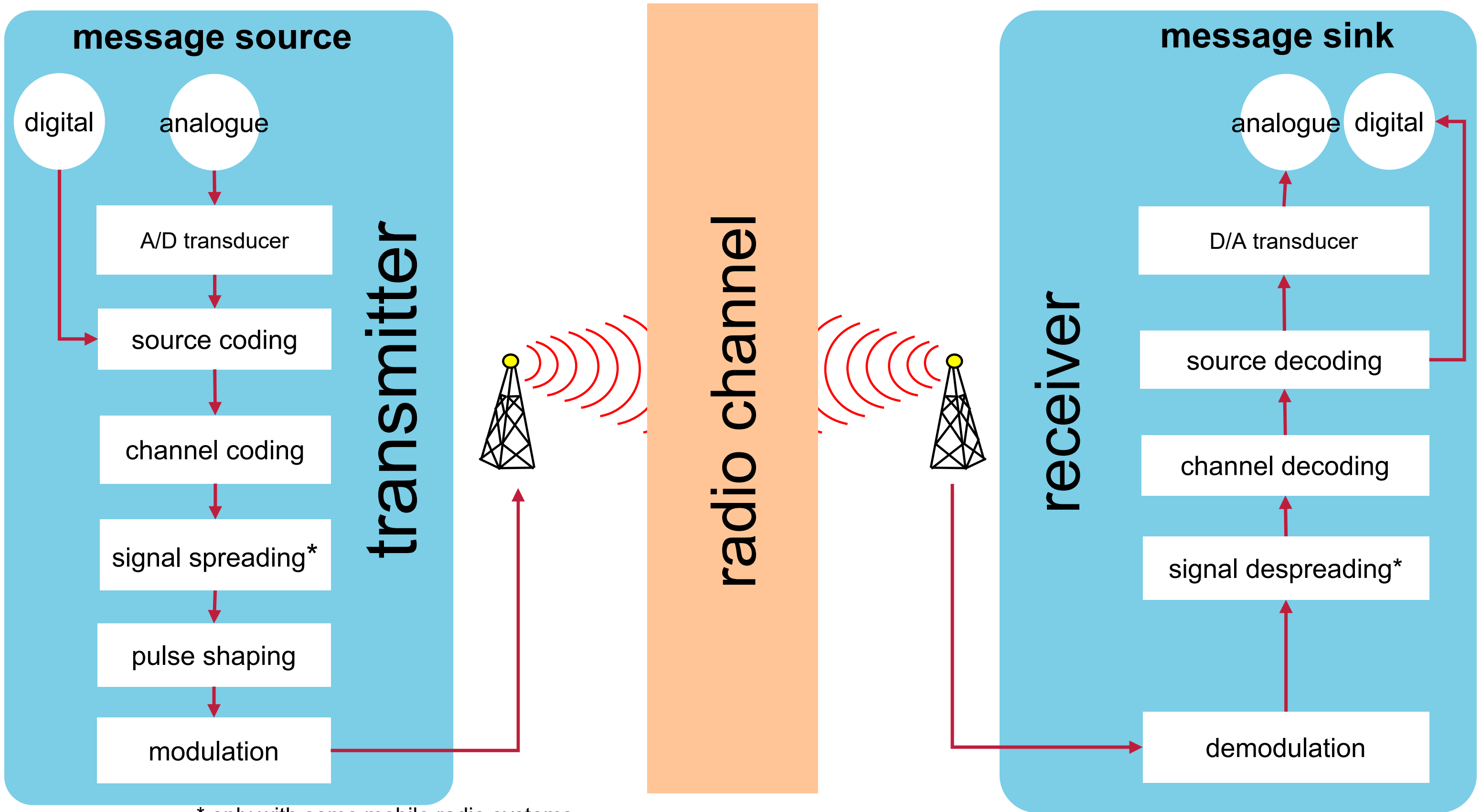


* only with some mobile radio systems

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

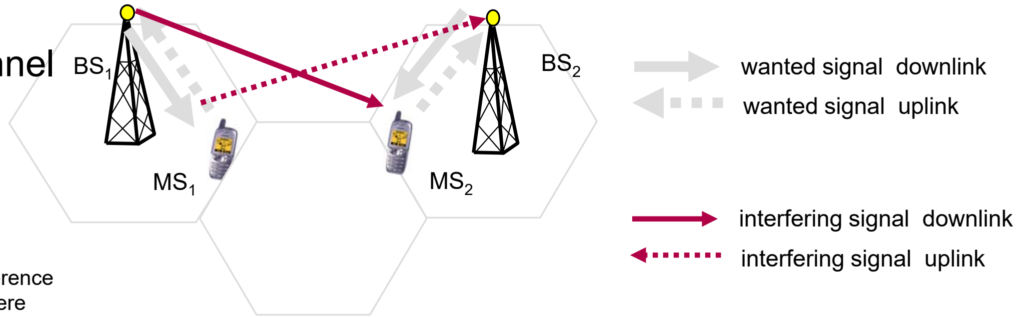
$$N = N_0 B = \mathrm{k} B T z \qquad (4.1b)$$

  - *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

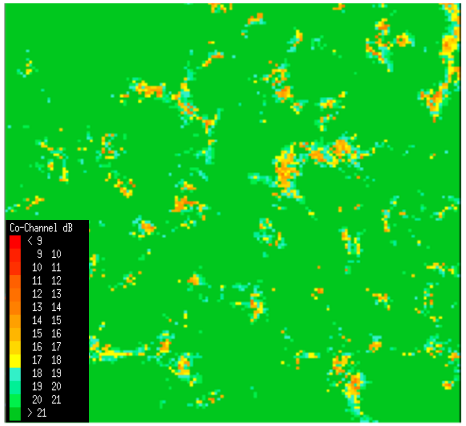
- Noise limitation:
  - Noise power dominates compared to the co-channel and adjacent-channel interference: $N >> I$
  - Typical situation for sparsely populated rural areas, but also for indoor coverage

- 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.

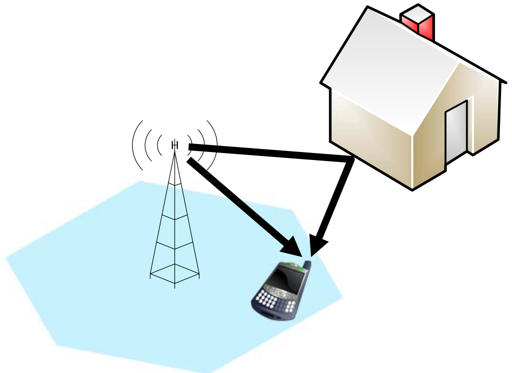
- Interference immunity
  - The interference immunity of a method is described by C/I_{min} and SNR_{min}, respectively, that at least has to be kept to fulfil a required bit error rate criterion.
  - For the determination of C/I, only local mean values (without short-term fading) are considered.

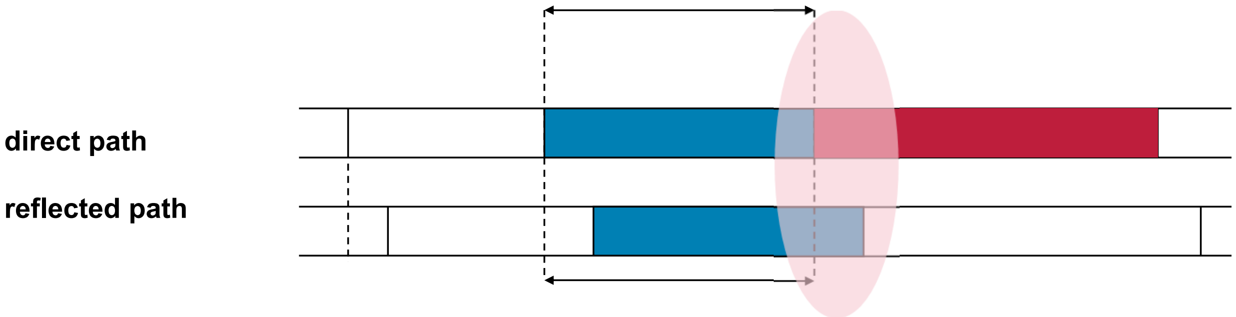


Example of the C/I distribution in a GSM network

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

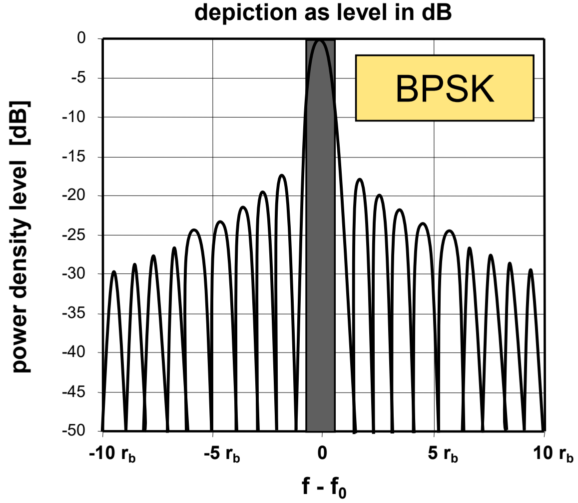
RMS: root mean square

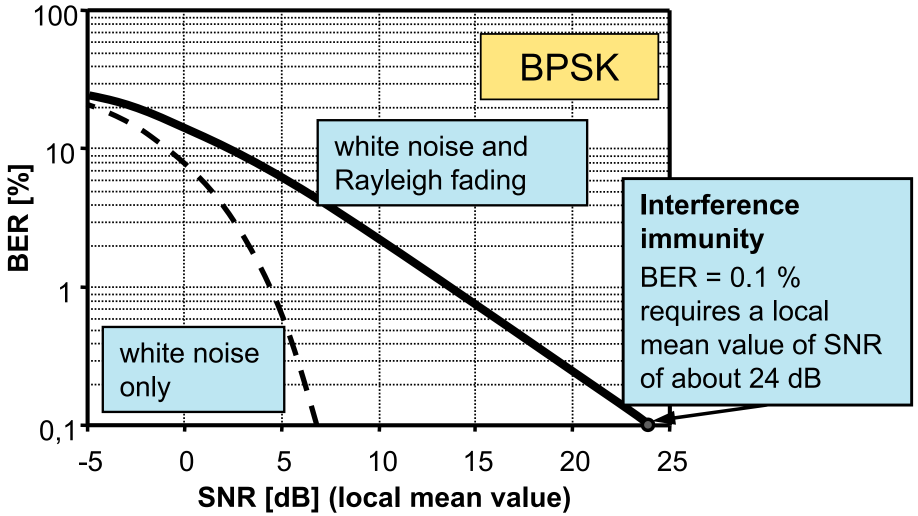
- In case that the value of the RMS delay spread exceeds a system-dependent quantity, it is assumed that error-free reception is no longer possible.

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!

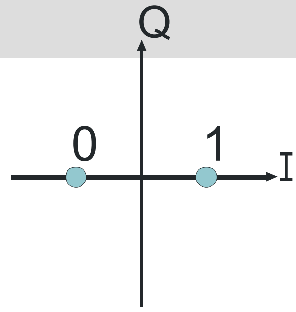
$\Rightarrow$ further measures for error protection required

4.3 Modulation

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:

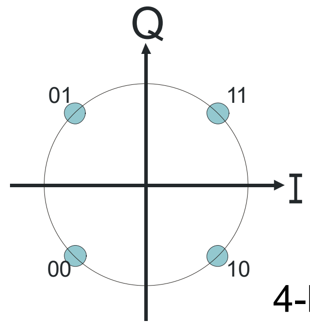
$$\epsilon = \frac{r_b}{B} = \frac{1\text{bit/s}}{1\text{Hz}} = \frac{1\text{kbit/s}}{1\text{kHz}} = \frac{1\text{Mbit/s}}{1\text{MHz}} \qquad (3.4)$$



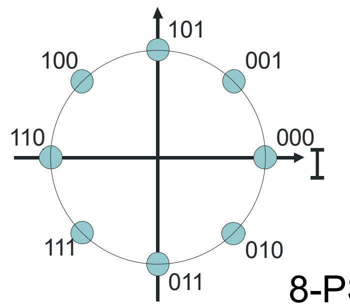
BPSK

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

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



4-PSK



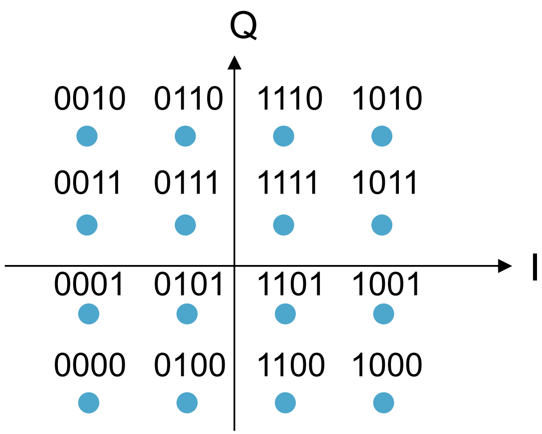
8-PSK

  - 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

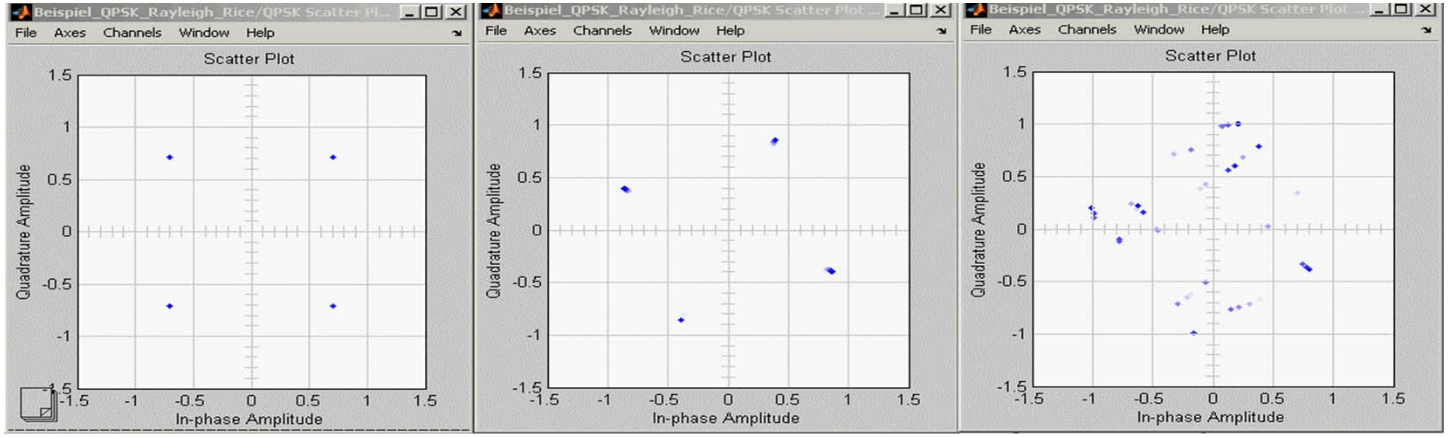
=> Balancing between the criteria spectral efficiency and interference immunity

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

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

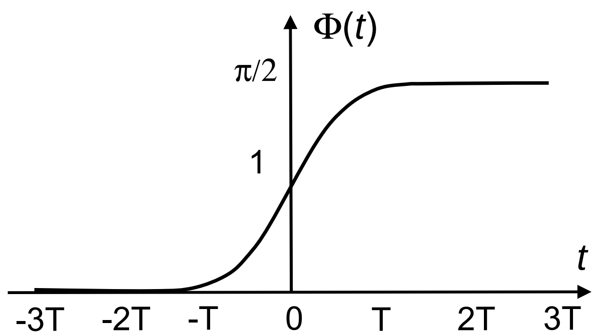
$$\phi(xT) = \frac{\pi}{2}(G\left(x + \frac{1}{2}\right) - G\left(x - \frac{1}{2}\right)) \qquad (3.9)$$

GMSK (2)

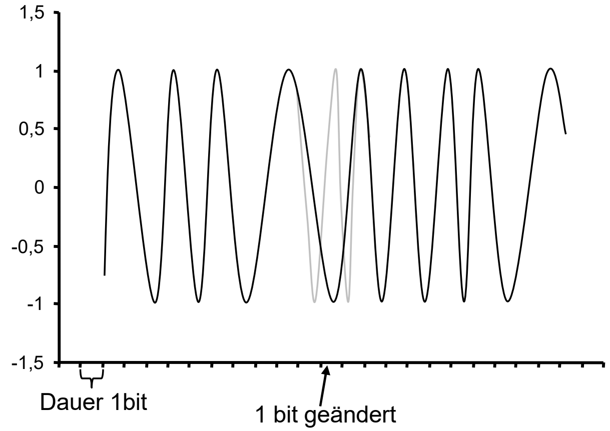
$$T = \frac{48}{13}\,\mu s \qquad (3.10)$$

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

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



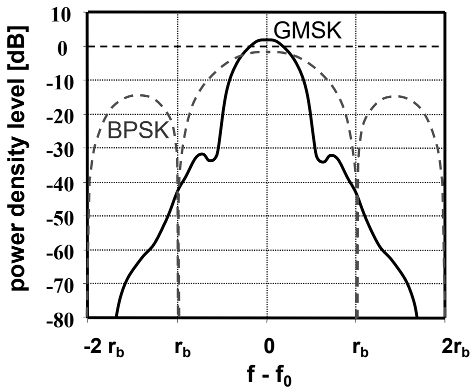
$\Phi(t)$ with GMSK modulation



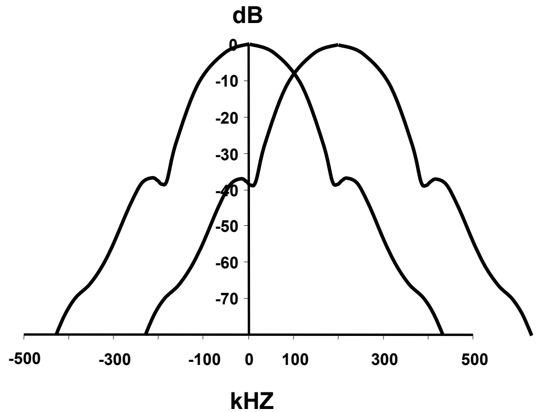
Effect of the alteration of a bit on the modulated signal

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

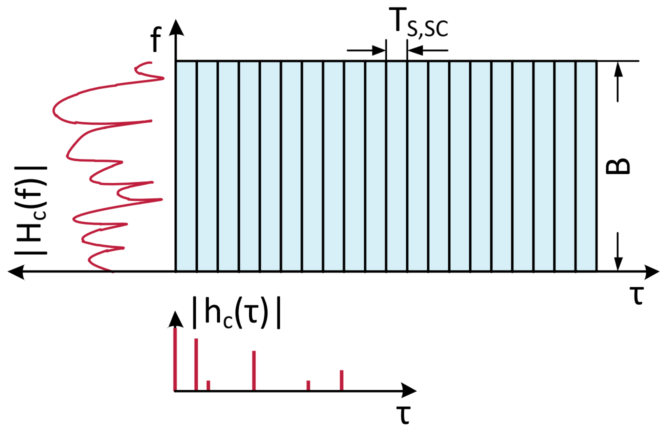
4.4 Orthogonal Frequency Division Multiplexing (OFDM)

- Transition from the single carrier system (SC) to the multicarrier system (MC):

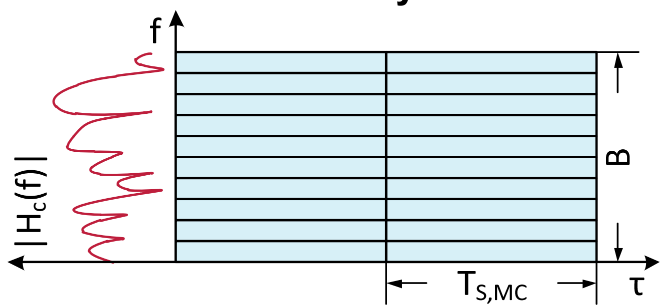
  - With SC systems, an **increase of the data rate** with constant spectral efficiency is only possible if the bandwidth is increased
  - This leads to a **reduction of the symbol duration**, so that intersymbol interferences (ISI) occur

  - 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

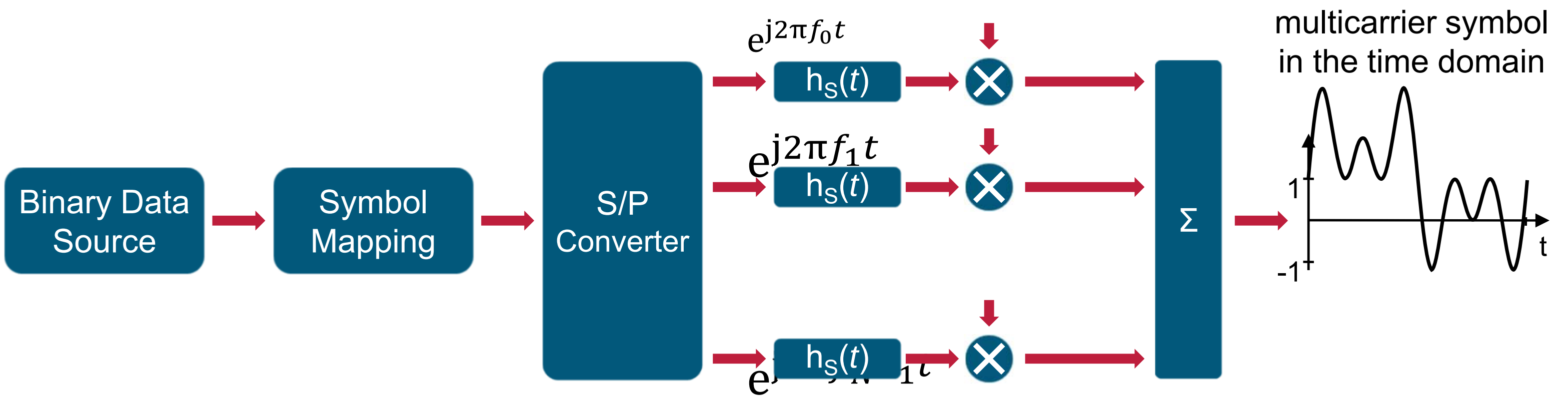


multicarrier system



Realisation of a Multicarrier System

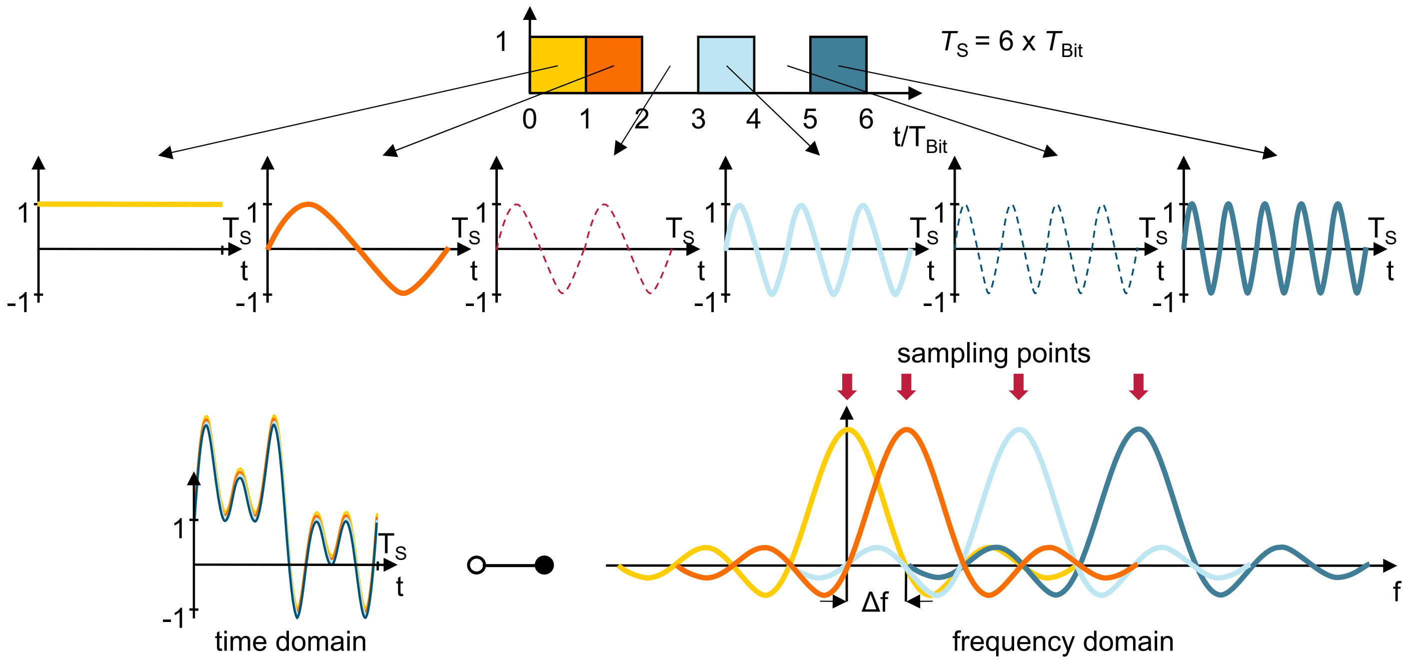
- At first, the bit stream is mapped to complex symbols and then is parallelised
- Each symbol passes a pulse shape filter and is transformed to the respective subcarrier frequency
- After superposition of the single partial signals, a multicarrier symbol is obtained



- 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!)

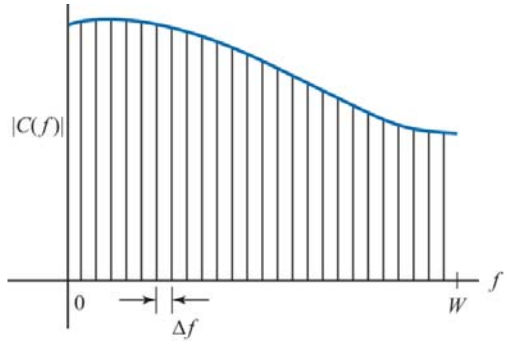
Orthogonality of the Subcarrier

- 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



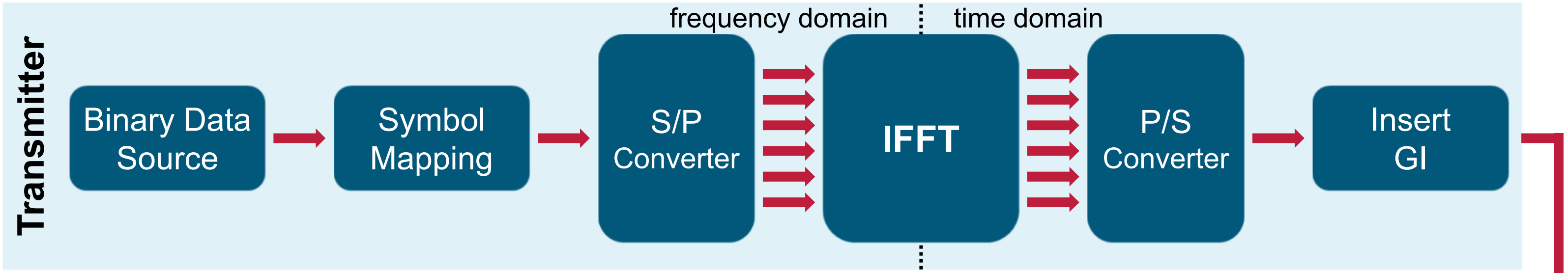
- A carrier is assigned to each subchannel: $x_k(t) = \sin 2\pi f_k t$, k=0,1,2,…,K-1 (3.13)
- Selection of the symbol rate 1/T for each subcarrier so that the subcarriers over the symbol interval T are orthogonal

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

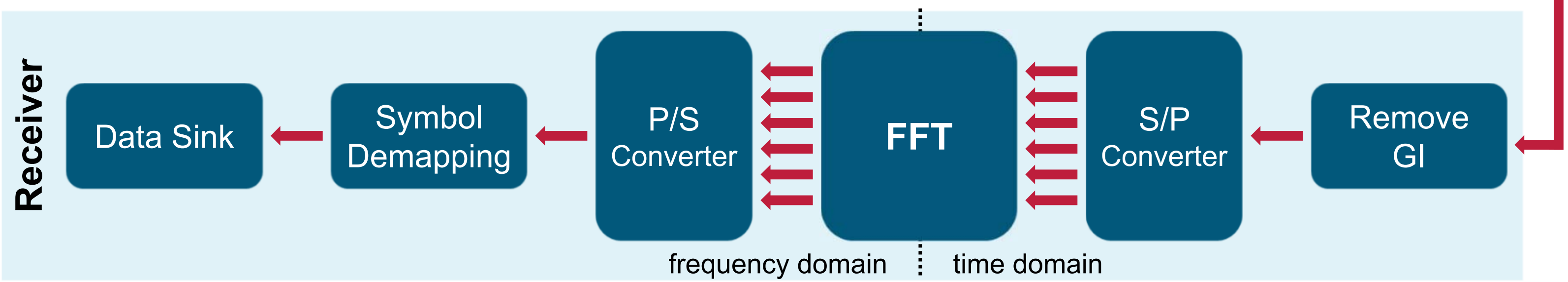
- T_S: symbol interval of a single carrier system that requires the total bandwidth B and transmits the data with the same rate as the OFDM system
- By selection of K, T can be made much larger than the time of the channel impulse response

4.4 Orthogonal Frequency Division Multiplexing (OFDM)

Model of the OFDM Transmission Chain in the Equivalent Baseband

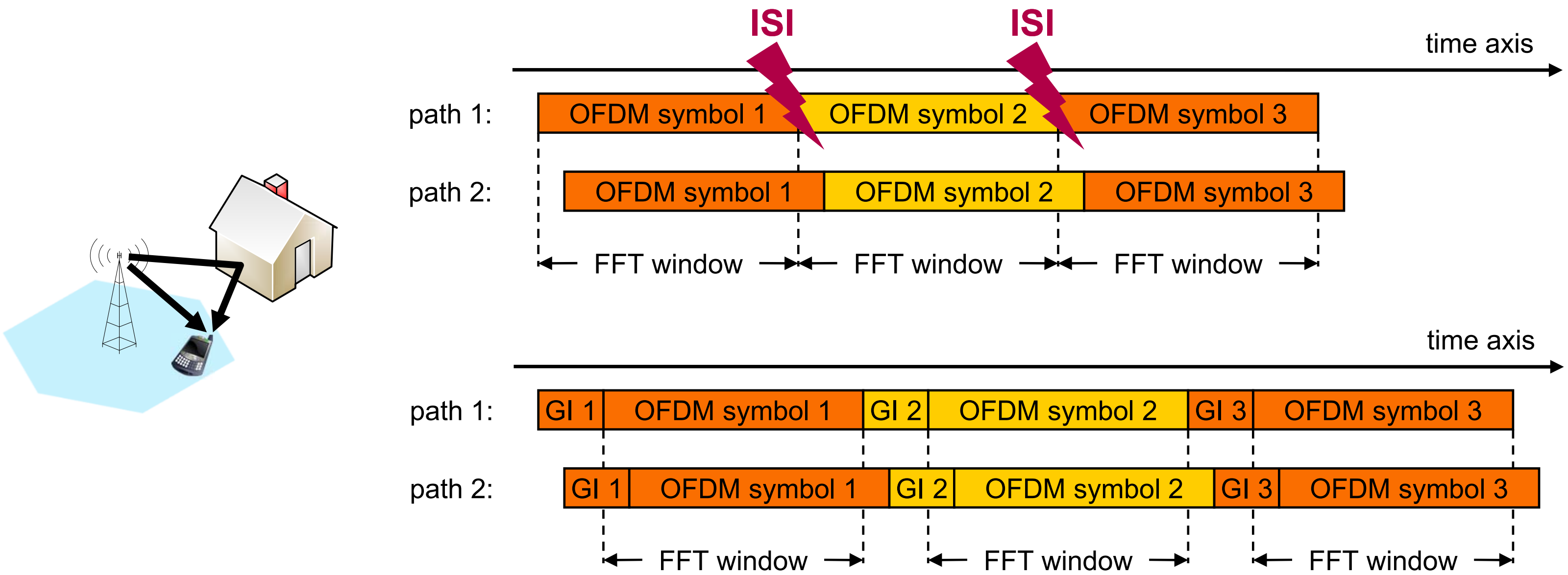


- Processing chains at the transmitter and at the receiver are reciprocal to each other
- OFDM modulation at the **transmitter** by means of **IFFT** (frequency domain → time domain)
- OFDM demodulation at the **receiver** by means of **FFT** (time domain → frequency domain)
- The so-called Guard interval (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



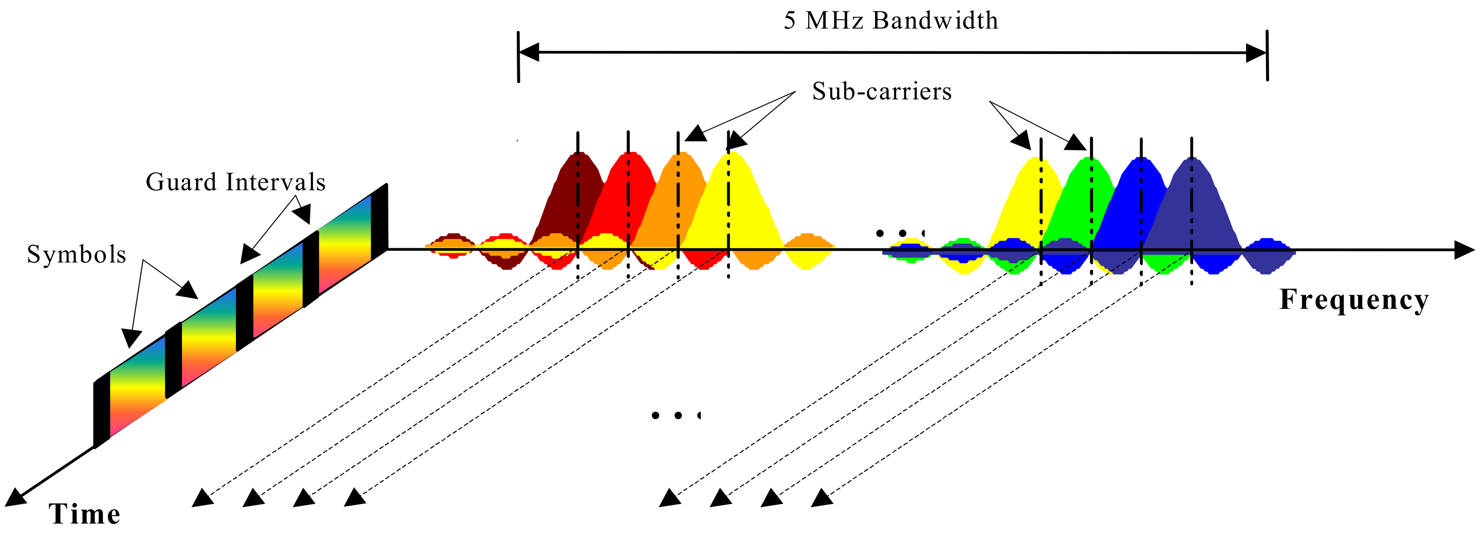
Intersymbol Interferences and the Introduction of the Guard Interval

- 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

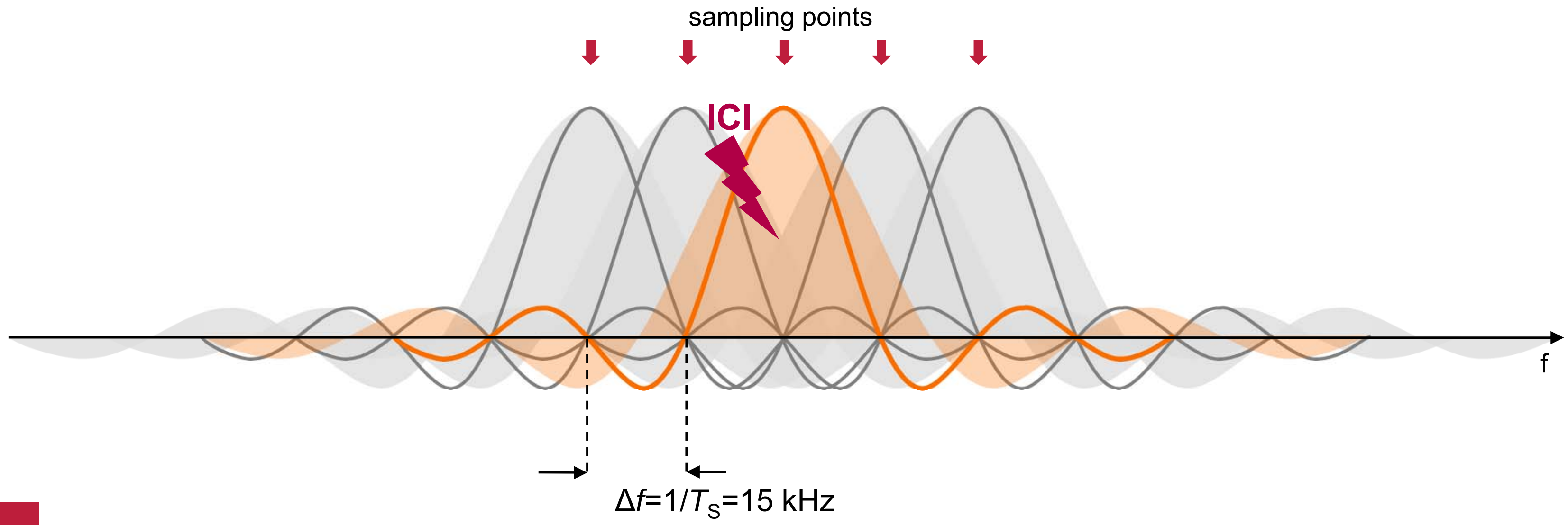
Representation of the OFDM Signal in the Time-Frequency Domain



Source: 3GPP TR 25.892, V6.0.0

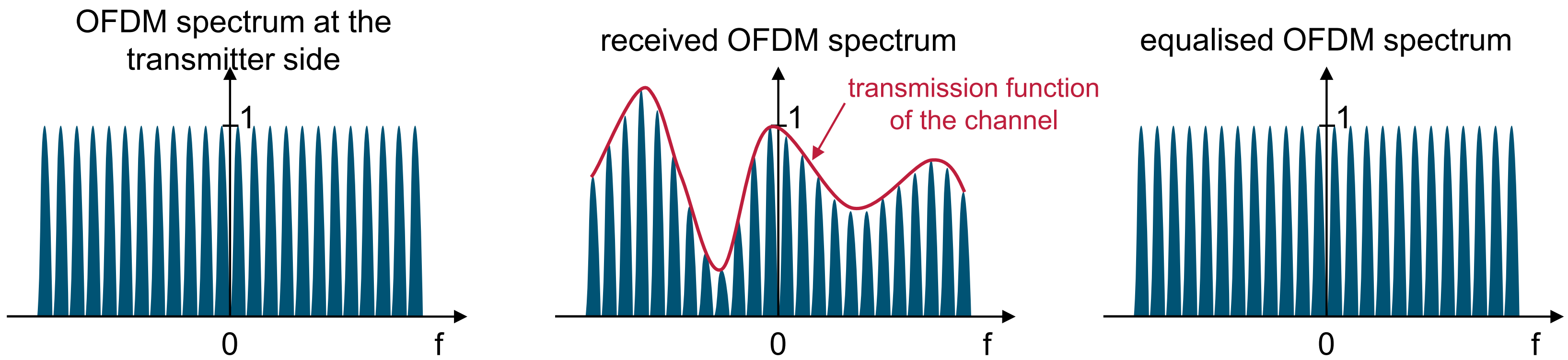
Intercarrier Interference (ICI) and the Subcarrier Separation

- 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**



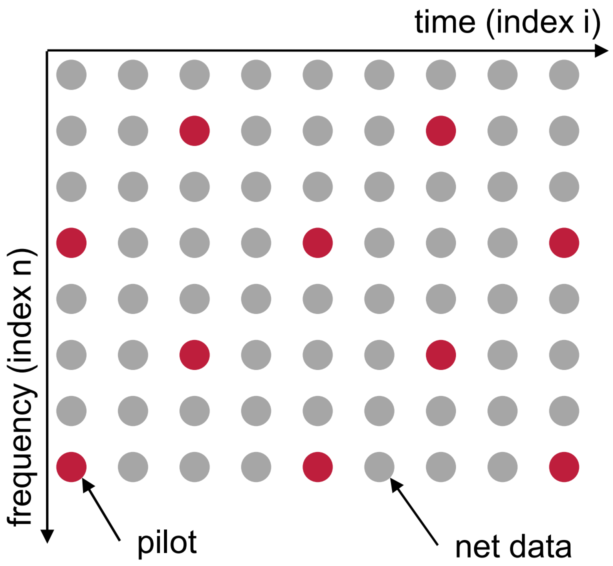
Channel Estimation and Channel Equalisation with OFDM Systems

- 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:

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

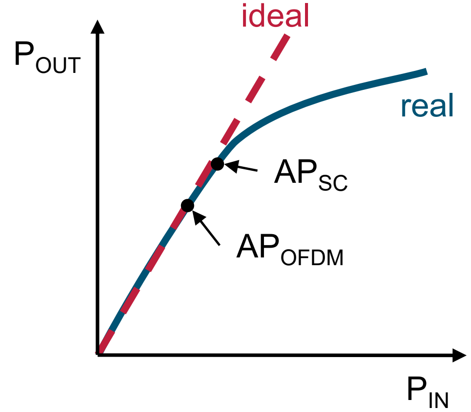
Advantages and Disadvantages of OFDM at a Glance

- 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

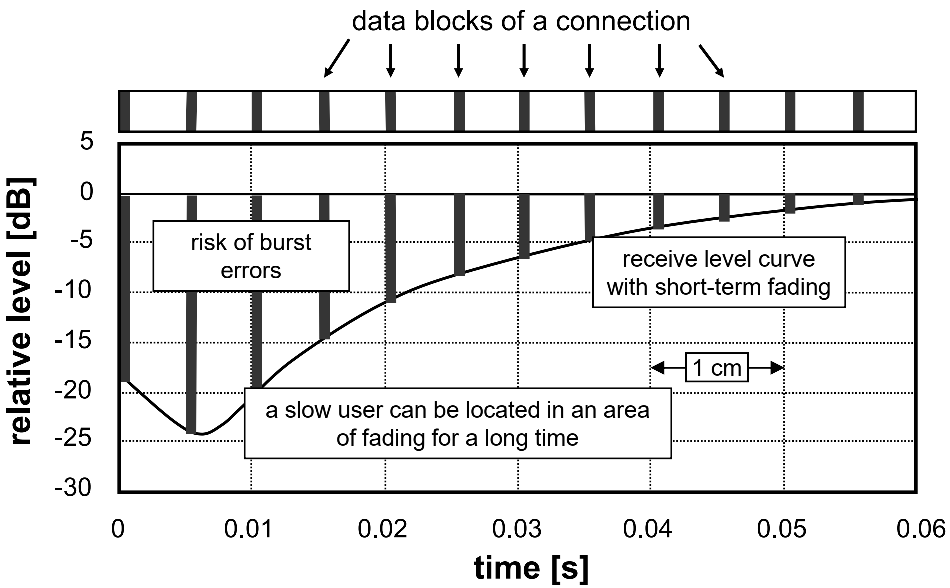
- Channel Coding to improve the interference immunity:
  - Adding of redundancy bits that allow error detection and correction

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

- 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.



rate	v = 3.6 km/h
	= 1 m/s
frequency	f = 2 GHz
wavelength	λ = 15 cm

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).

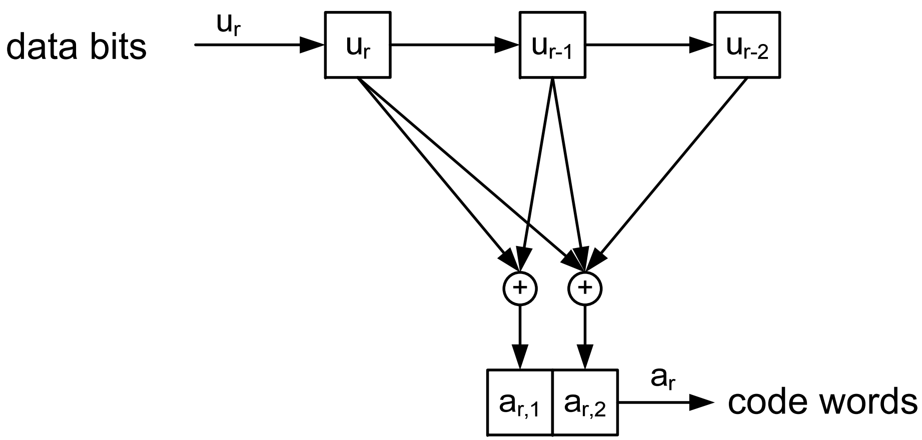
- Differentiation of two code families for forward error correction:

  - 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)

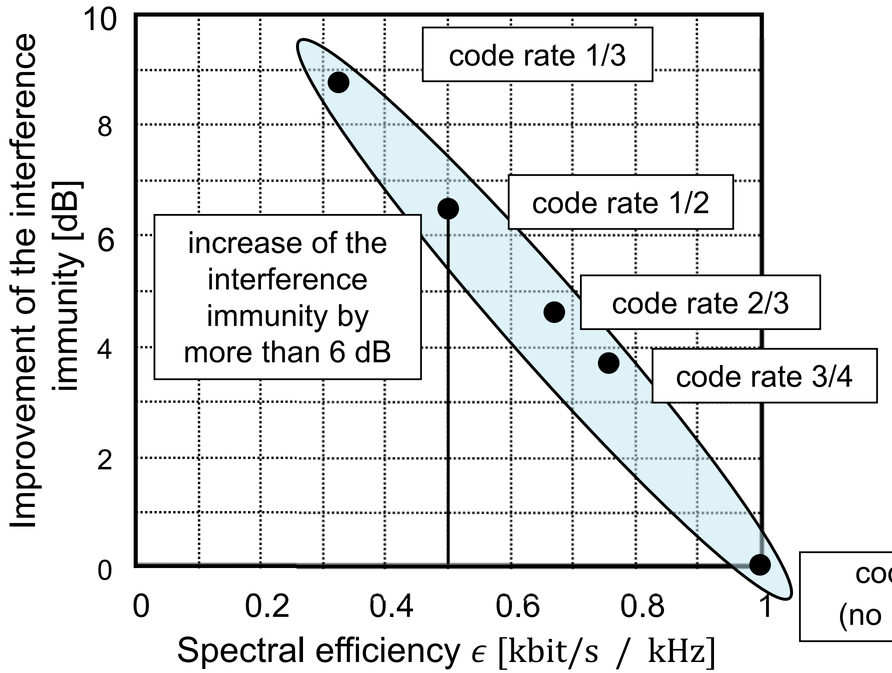
- Decoding is effected by Viterbi algorithm and Maximum-Likelihood decision
- Convolutional codes work efficiently in case of single errors
- Burst errors are not adjusted by the decoder
- Increase of the code rate by puncturation of convolutional codes:

- 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

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

Coding Gain by Convolutional Codes



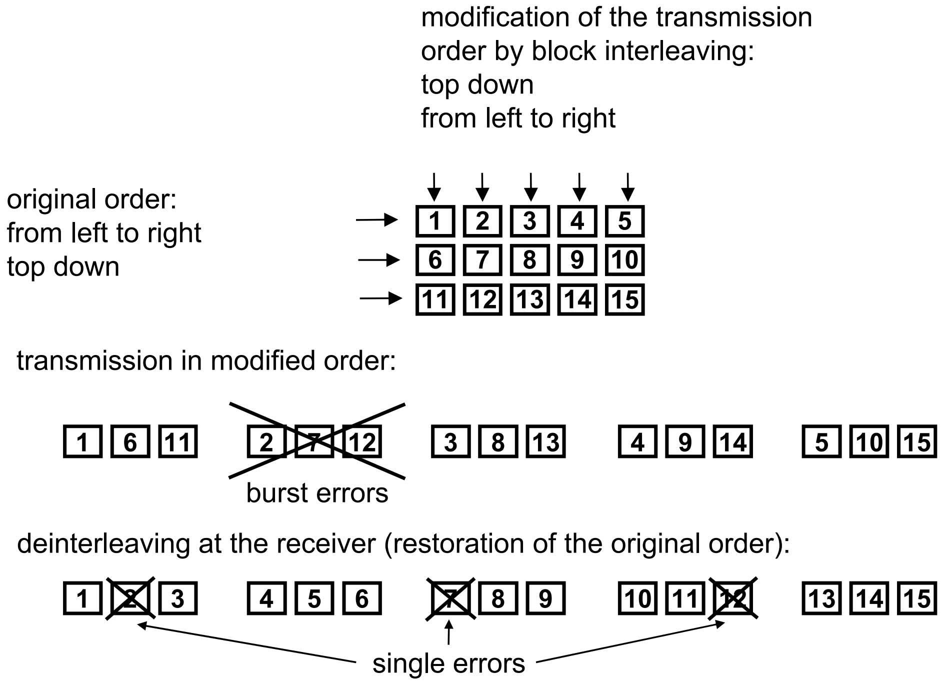
Boundary conditions
- memory length *K*=6
- no Rayleigh fading
- demanded BER: 0.1 %
- BPSK modulation

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

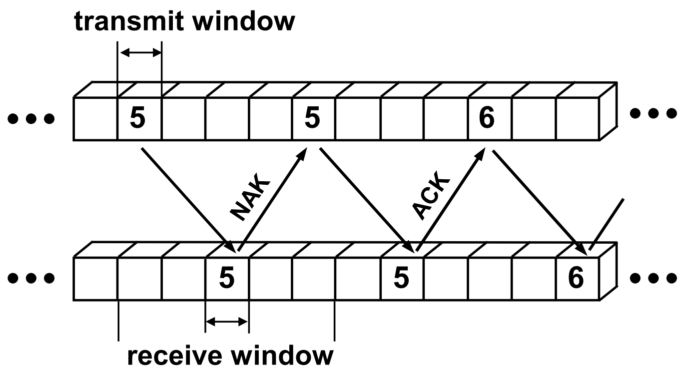
- Blocks recognised by the receiver as erroneous are requested again by the transmitter
- Efficiency in frequency spectrum use, especially in case of very good receive conditions
- Disadvantage: Due to repetitions, incalculable delays can occur => for voice transmission, no application possible
- Return 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

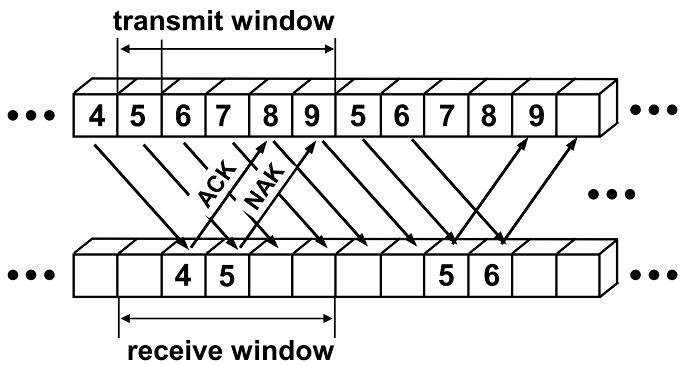
$$t_{\mathrm{rd}} = 2t_{\mathrm{f}} \qquad (3.22)$$

t_f: transfer time for the channel



Go-back-N ARQ Protocol

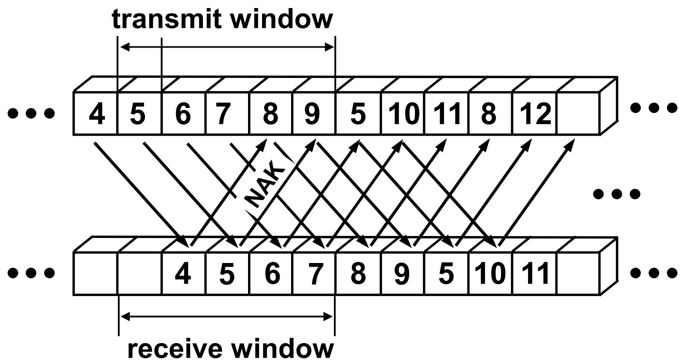
- Transmitter can send several data packets one after the other without waiting for an acknowledgement.
- The maximum number of unconfirmed data packets is defined through the size of the transmit window.
- After receipt of a certain number of data packets (receive window), the receiver sends ACK and 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

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

- Go-back-N

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

- Selective-Reject*

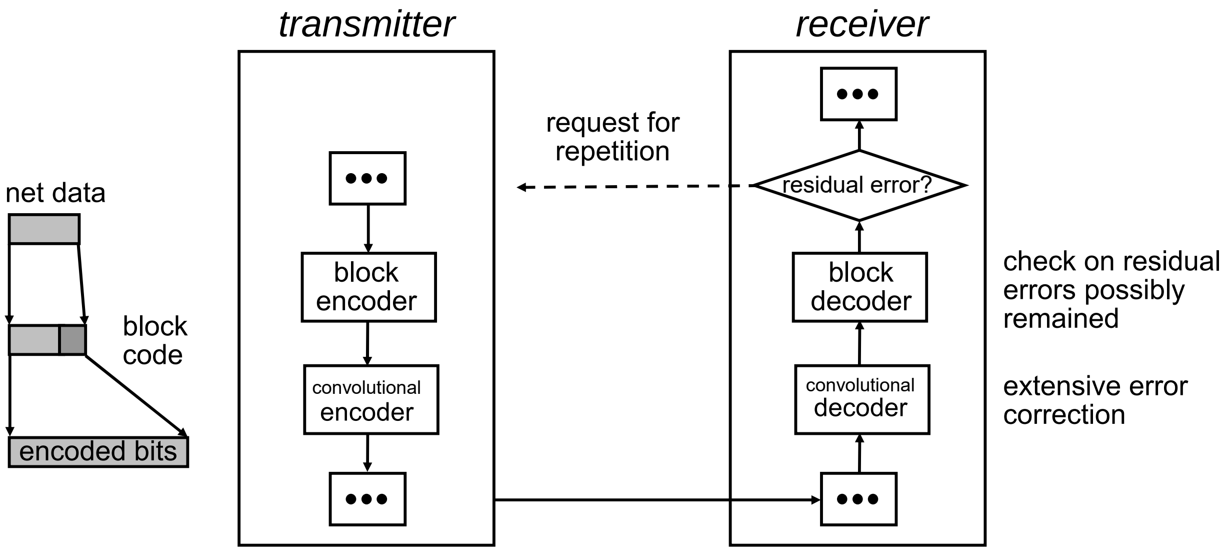
$$D_{\mathrm{SR}} = (1-PER) \quad (3.25)$$

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



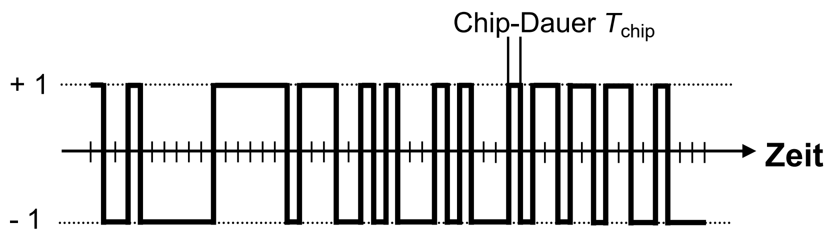
Source: nach C. Lüders, Mobilfunksysteme

- 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.

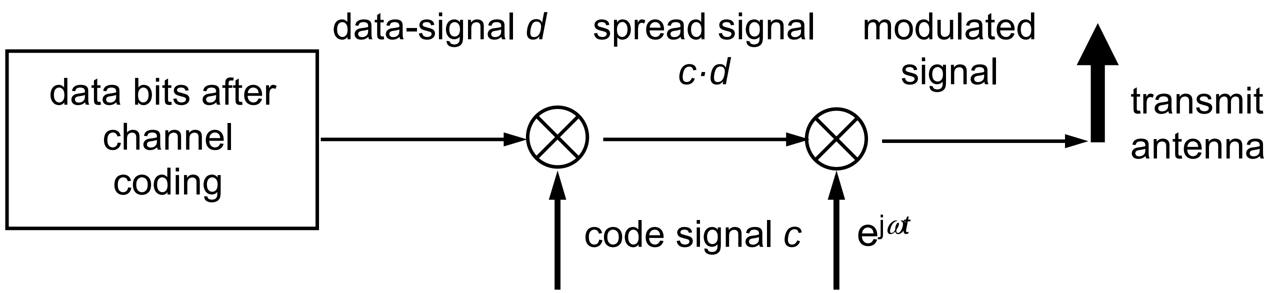
- Application of signal spreading
  - Multiplication of the digital data signal before the modulation with a code signal c



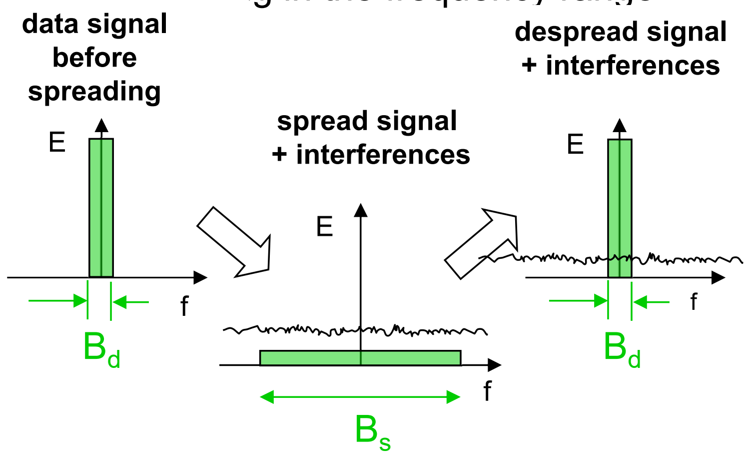
Quelle: nach C. Lüders, Mobilfunksysteme

- 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



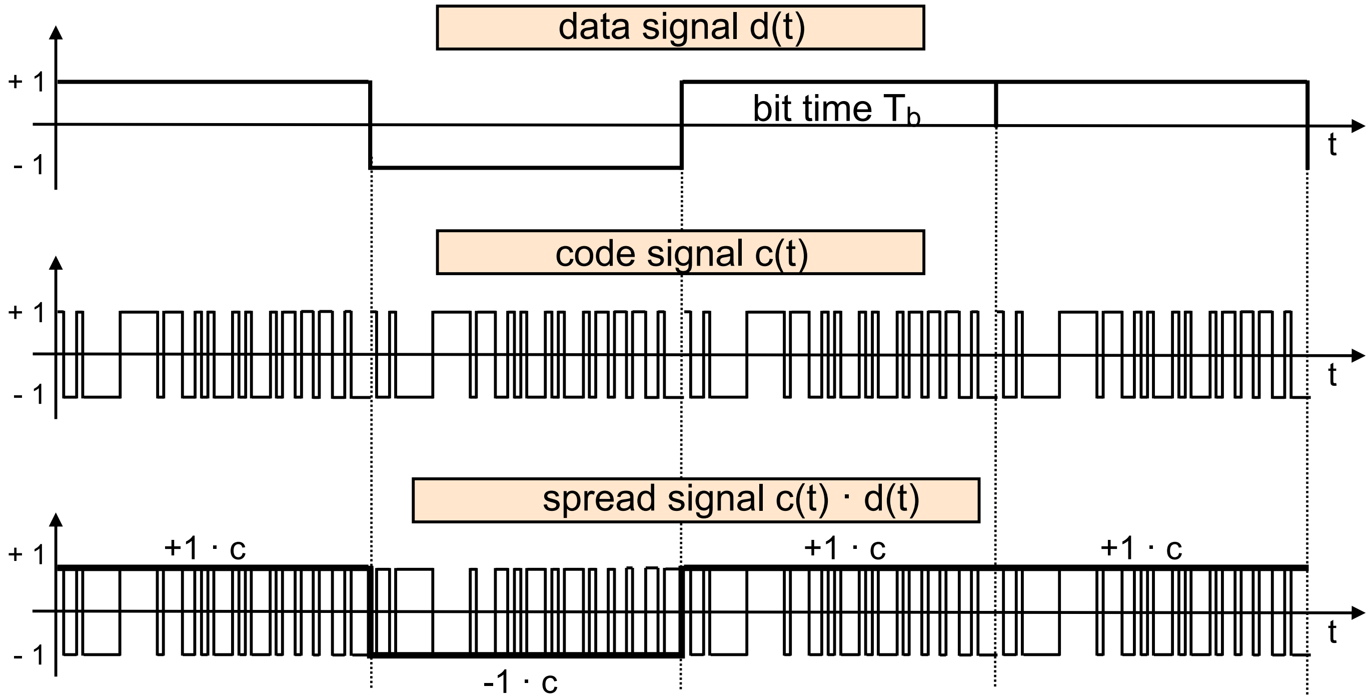
- spread factor

$$SF = \frac{r_{\text{Chip}}}{r_{\text{bit}}} = \frac{T_{\text{bit}}}{T_{\text{Chip}}} \approx \frac{B_{\text{S}}}{B_{\text{d}}} \qquad (3.26)$$

- process gain

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

Transmission Procedure with Code Multiplex



Source: nach C. Lüders, Mobilfunksysteme

4.7 Signal Spreading (Code Multiplex)
Despreading

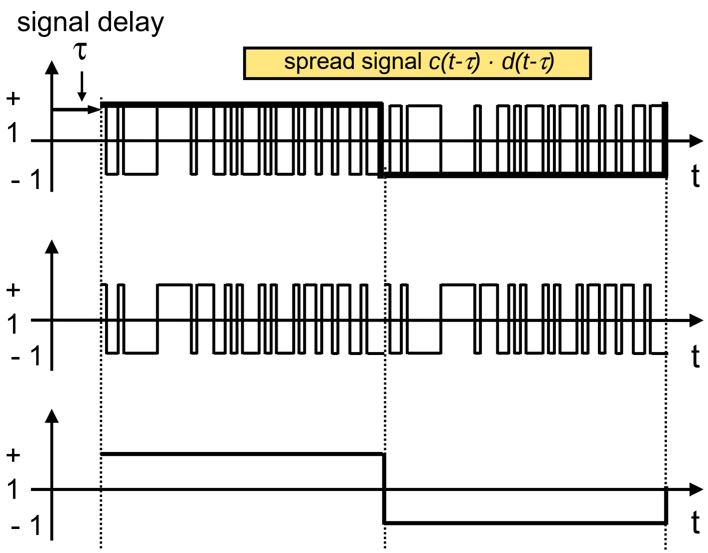
- Multiplication of the demodulated signal by the same signal as with transmission taking into account the signal delay (chip-synchronal)

- 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: $\frac{1}{T_\mathrm{b}} \int$

$$\int_0^{T_\mathrm{b}}$$



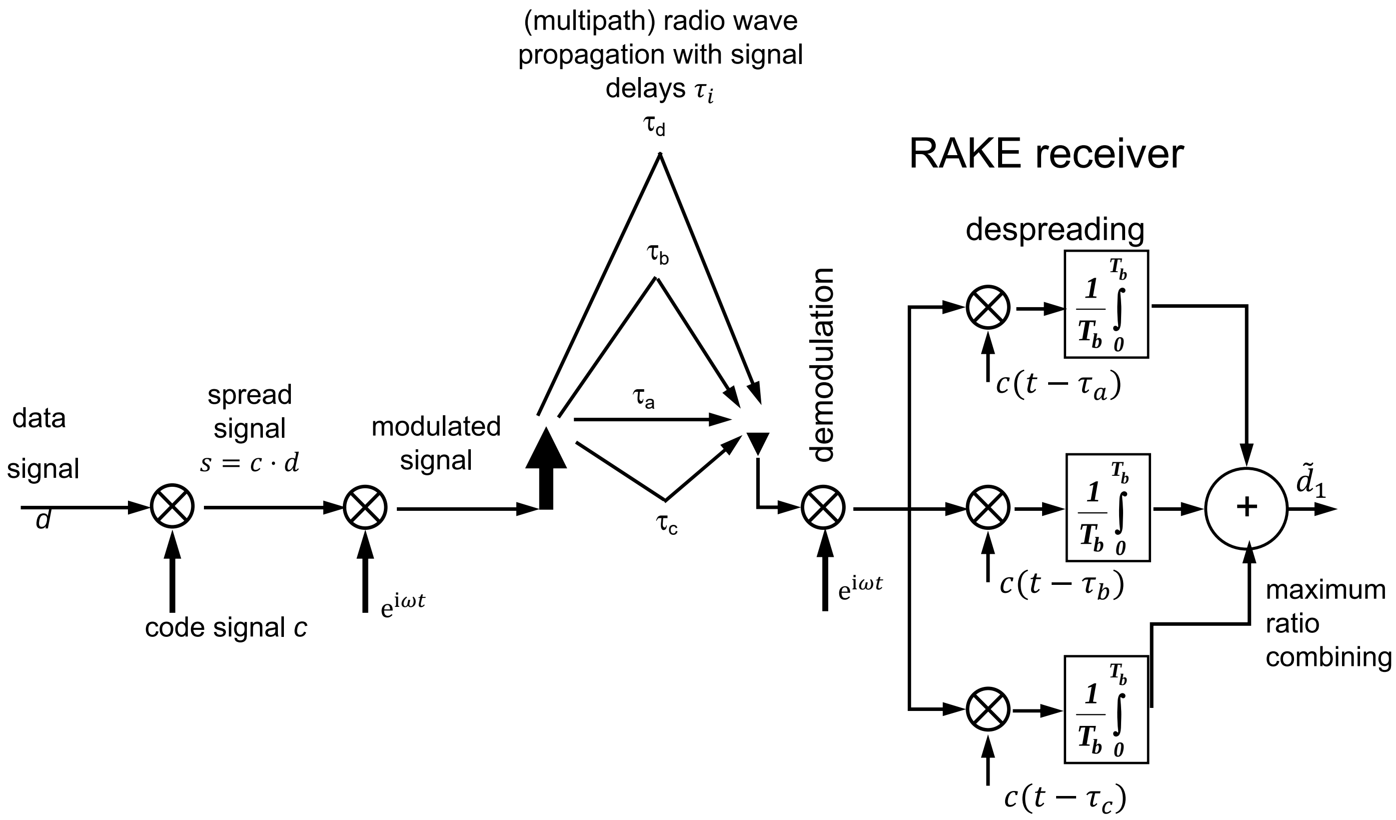
Source: nach C. Lüders, Mobilfunksysteme

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

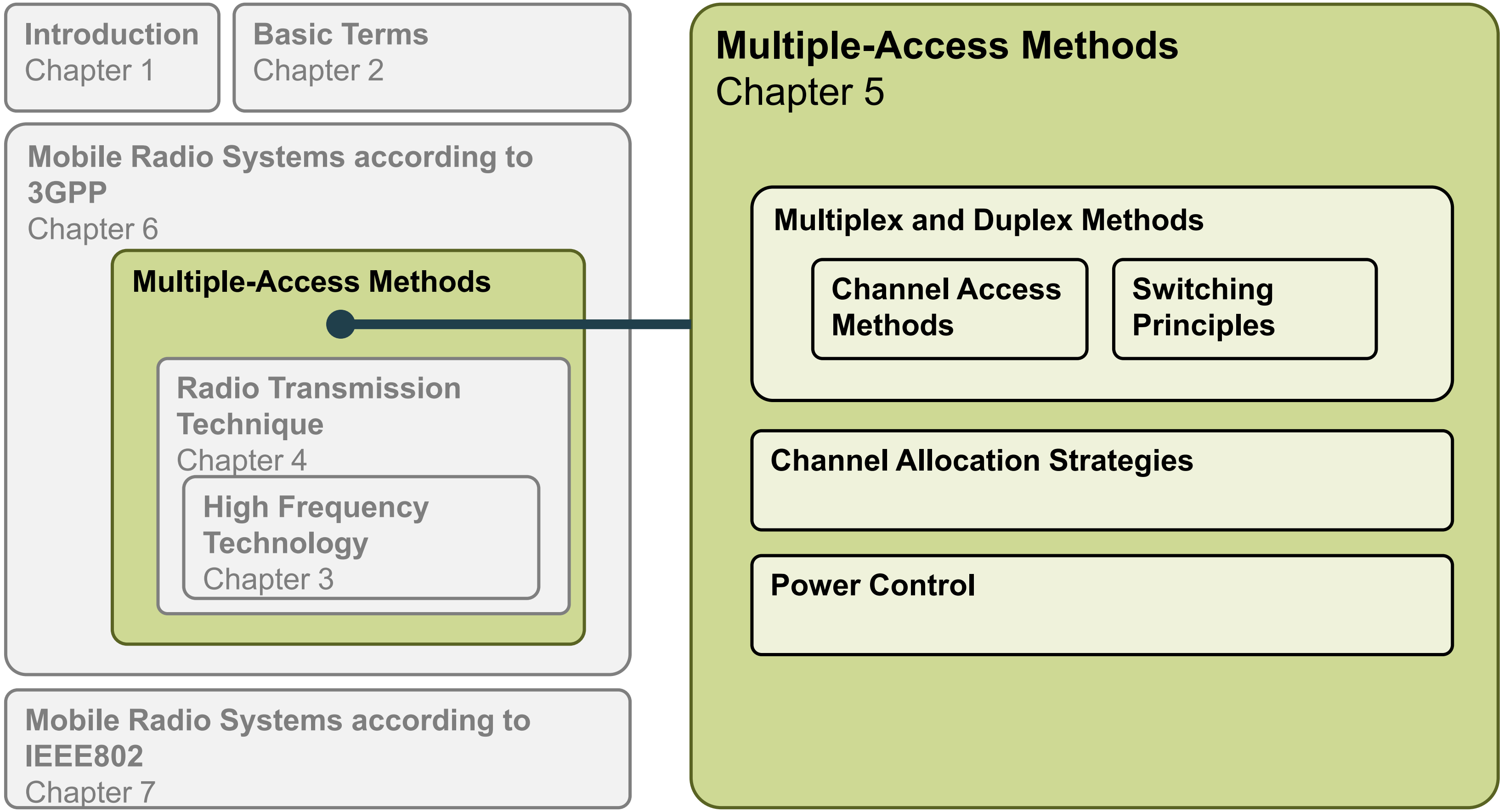


Source: nach C. Lüders, Mobilfunksysteme

4.8 Speech Encoding

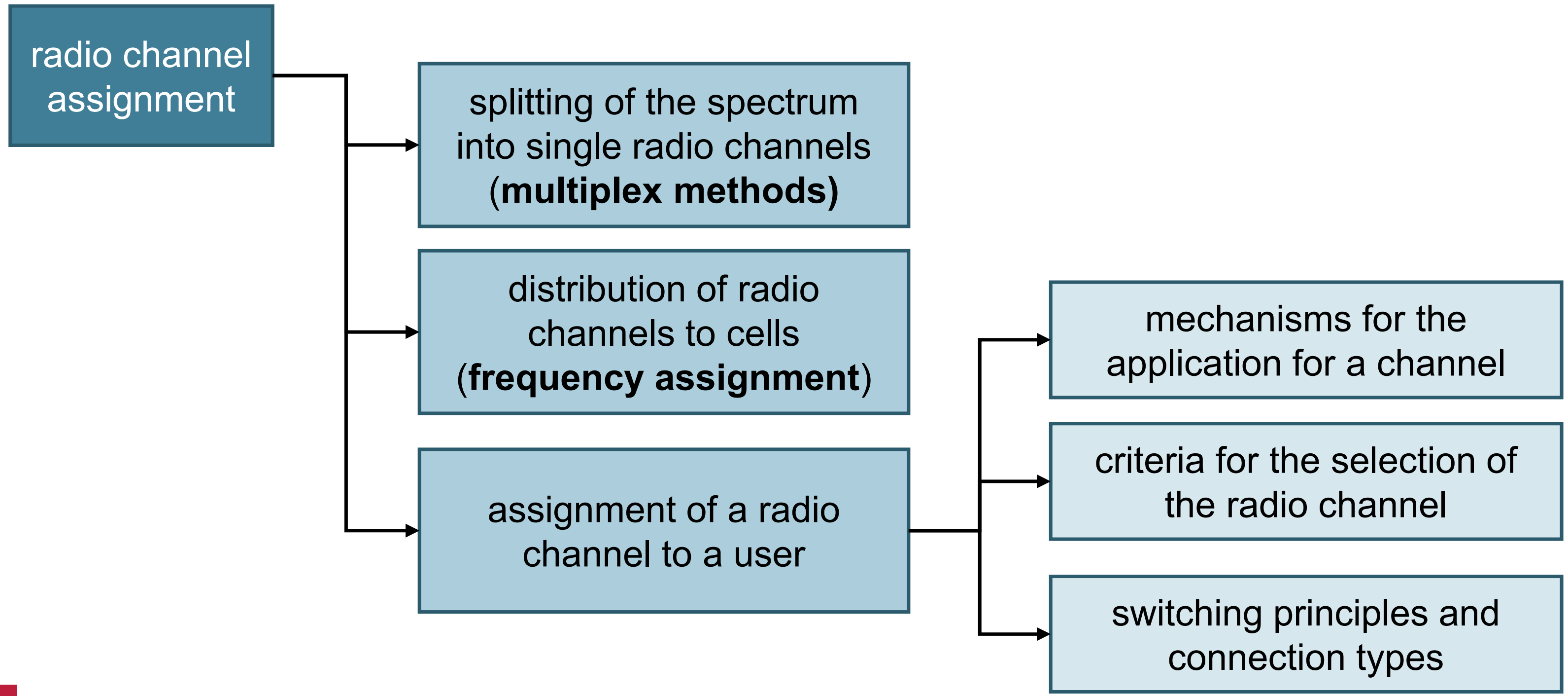
- ISDN (basis for DECT):
  - Puls Code Modulation (PCM); sampling with 8 kHz and quantisation with 8 bit => speech bit rate of 64 kbit/s
- In mobile radio systems, a reduction of the data rate is required
  - Modelling of the generation of human speech by excitation coefficients and parameterizable filters
  - 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



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

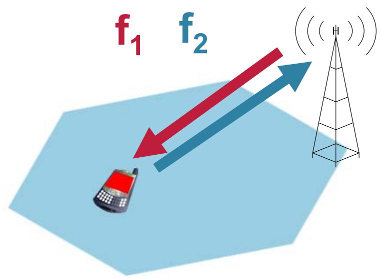
- Duplex method:
  - describes the splitting of the radio channels for the use in UL and DL

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

Duplex Methods

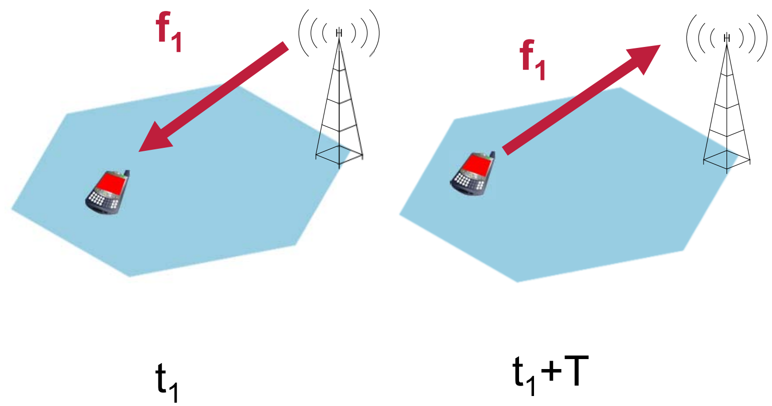
Frequency duplex

- 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)



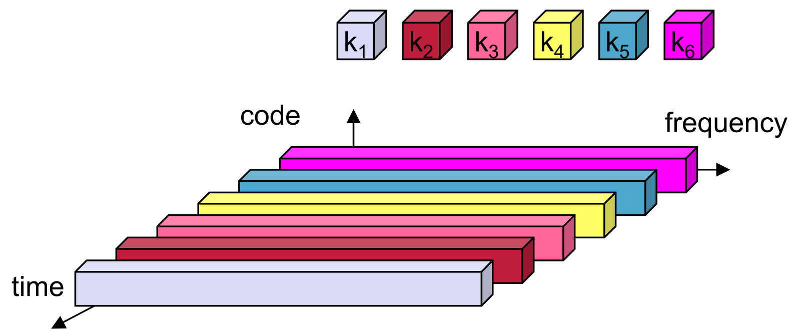
Time duplex

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



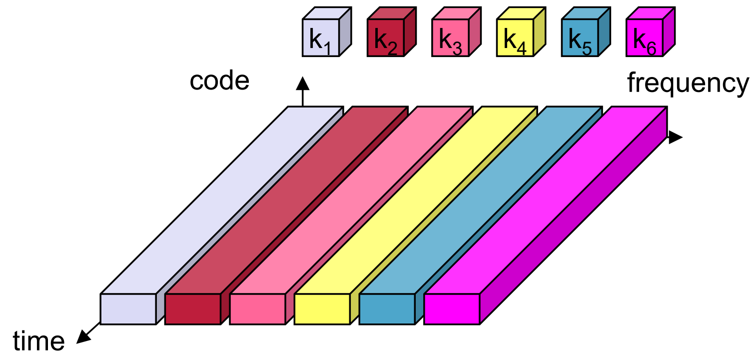
Time Division Multiple Access (TDMA)

- 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)

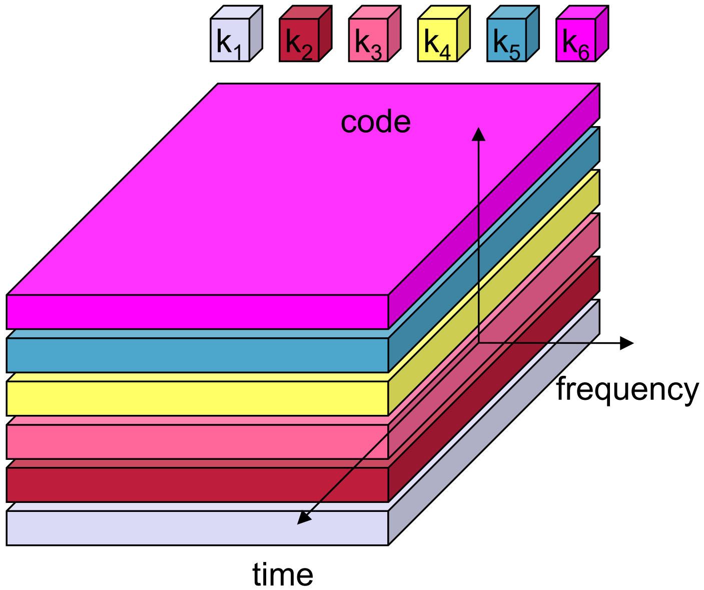
- Splitting of the complete spectrum into subbands (frequency carrier)
- Carrier separation in the order of magnitude of the modulation bandwidth
- Directional separation UL/DL can be effected over the frequency (FDD)
  - Assignment of 2 frequency bands with a gap
  - Duplex separation: distance between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



Code Division Multiple Access (CDMA)

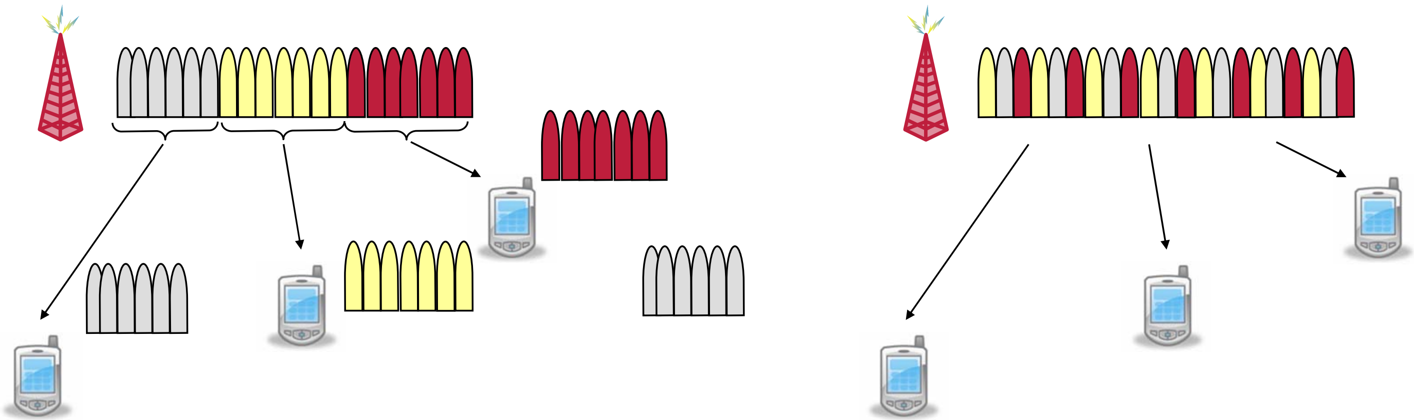
- All users send at the same time and with the same frequency.

- 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.



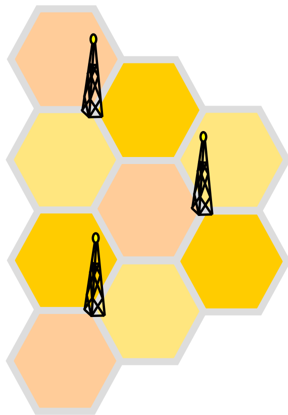
Orthogonal Frequency Division Multiple Access (OFDMA)

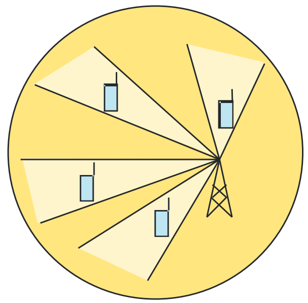
- OFDM can also be used as multiple-access technology where the subcarriers are distributed to different mobile users



Space Division Multiple Access (SDMA)

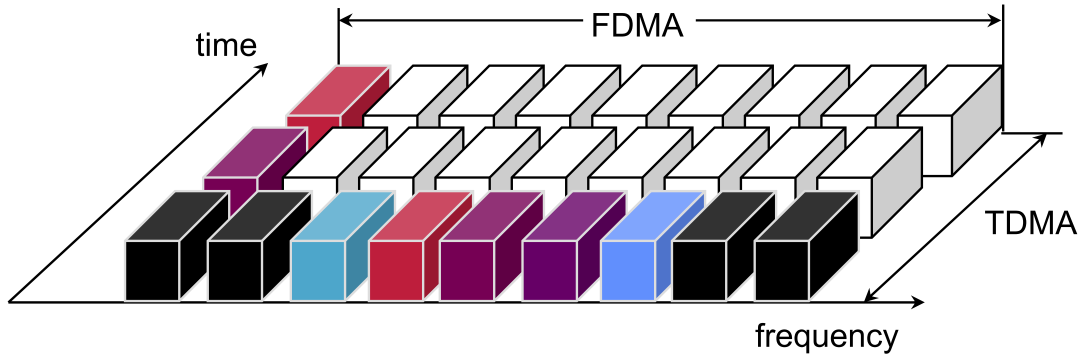
- Application in all mobile radio systems for multiple use of radio channels in different, spacially separated radio cells
  - Standard use case: spatial frequency repetition
  - Special case: application of smart antenna systems
    - Forming of narrow antenna beam lobes by special signal processing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





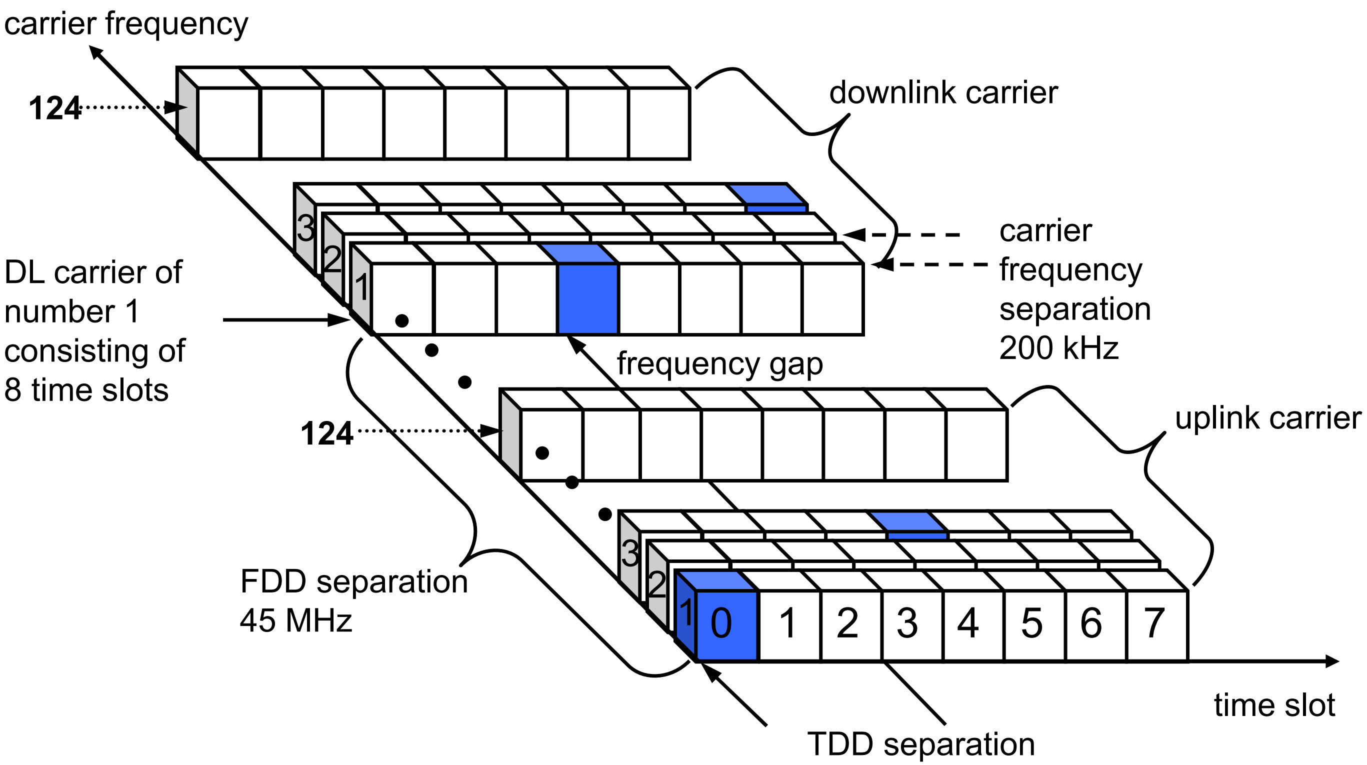
5.2 Realisation of Multiplex Methods

- 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

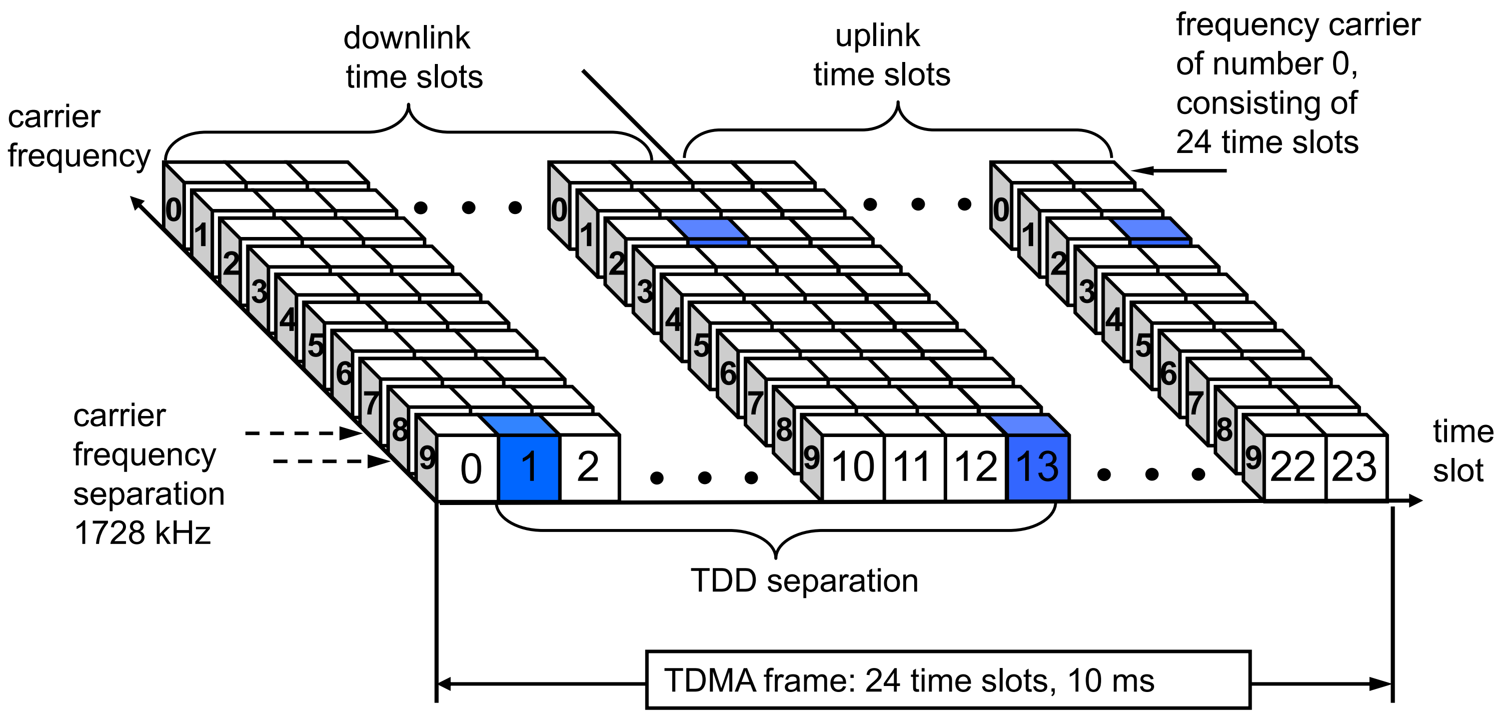
- Application of frequency duplex with time shift (UL and DL at different frequencies and shifted by 3 time slots)



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

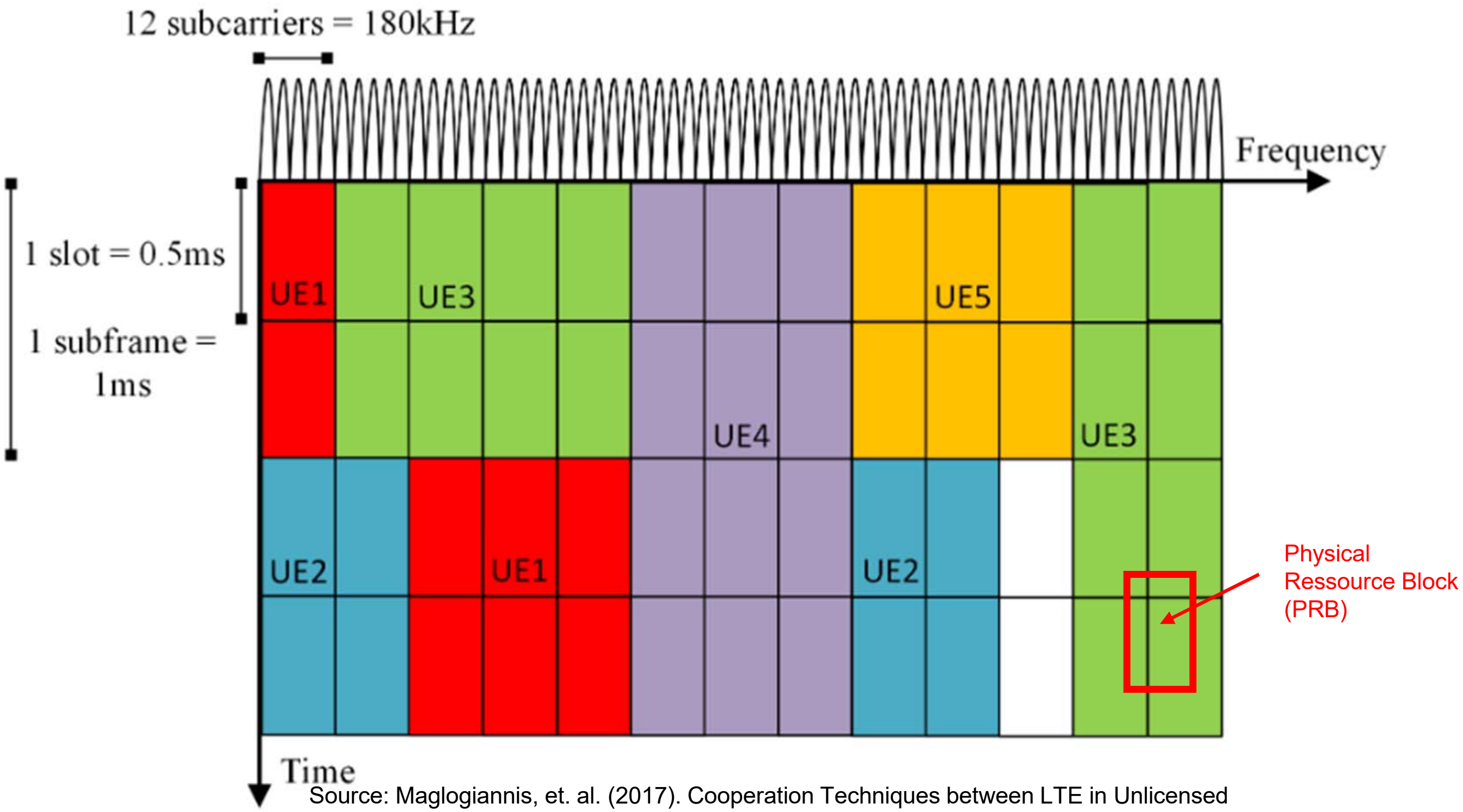
FDMA/TDMA Combination for DECT

- 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

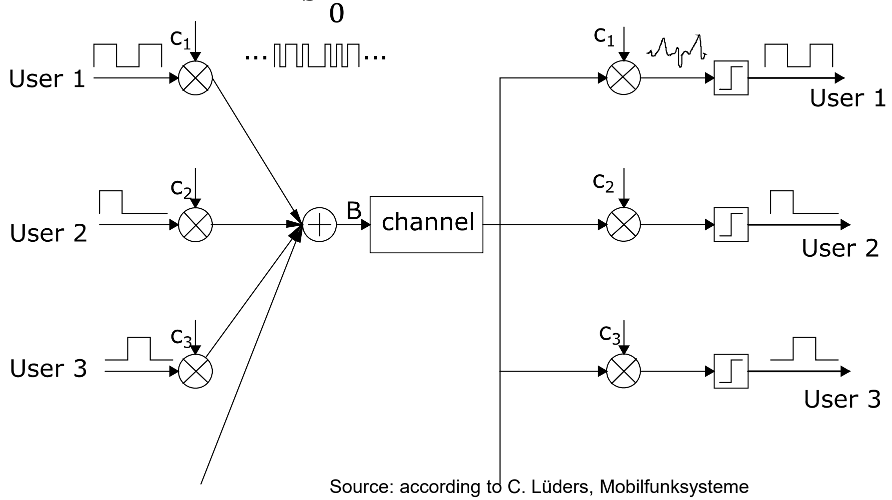


Source: Maglogiannis, et. al. (2017). Cooperation Techniques between LTE in Unlicensed Spectrum and Wi-Fi towards Fair Spectral Efficiency. Sensors. 17. 10.3390/s17091994.

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:

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

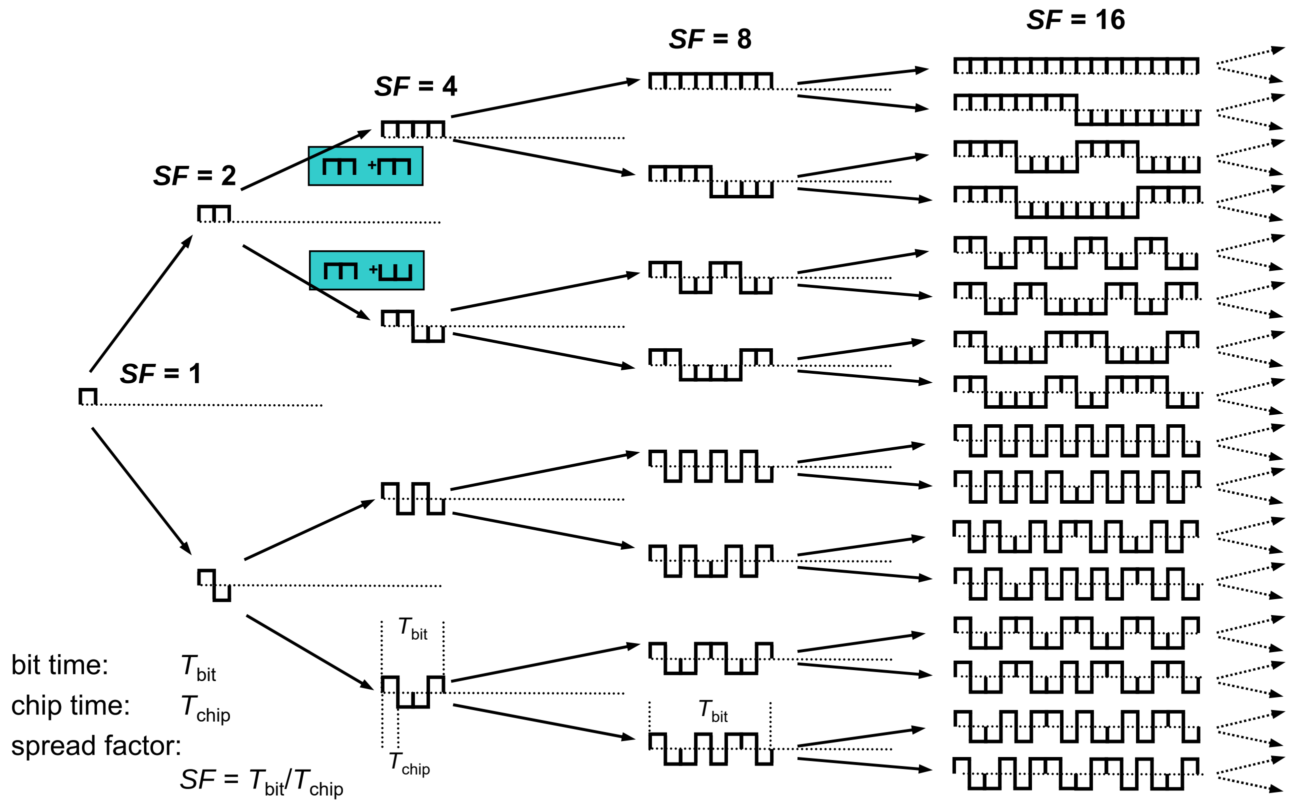


Source: according to C. Lüders, Mobilfunksysteme

- 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)

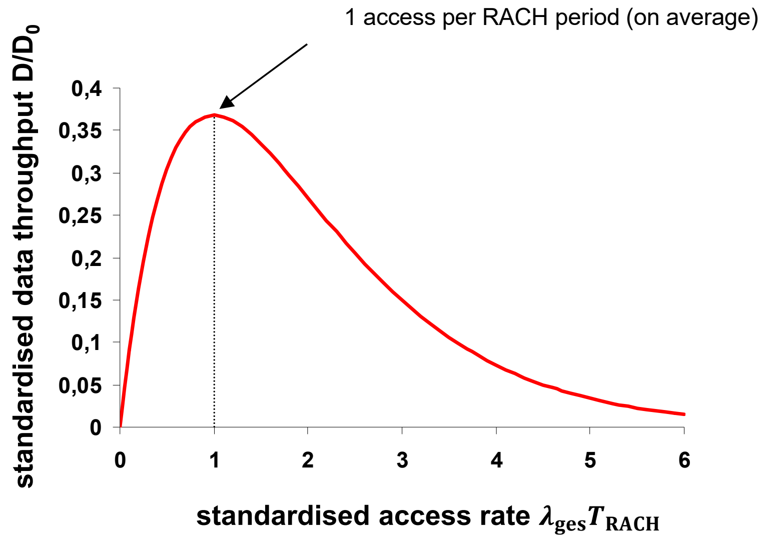
$$D = \lambda_{\text{ges}} \mathrm{e}^{-\lambda_{\text{ges}} T_{\text{RACH}}} \qquad (4.2)$$

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

maximum channel capacity of RACH :

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

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

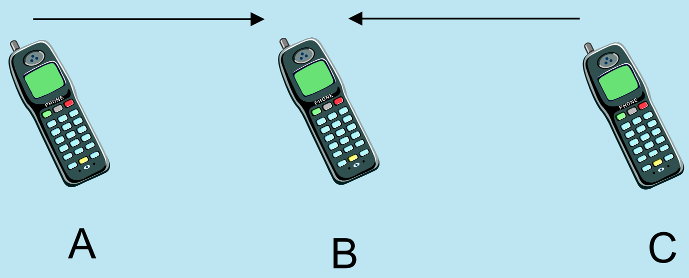


Carrier Sense Multiple Access (CSMA)

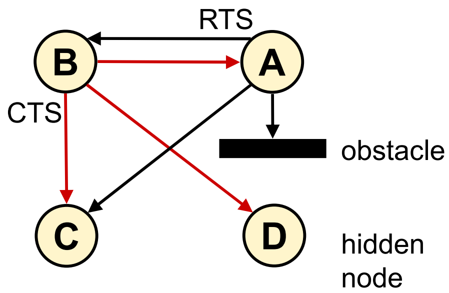
- Extension of the ALOHA method
- Monitoring of the radio channel and access only if the channel is free
- Problem of the hidden terminals (*hidden node*)
- Application with wireless networks

Problem of the hidden terminals (Hidden Node Problem)

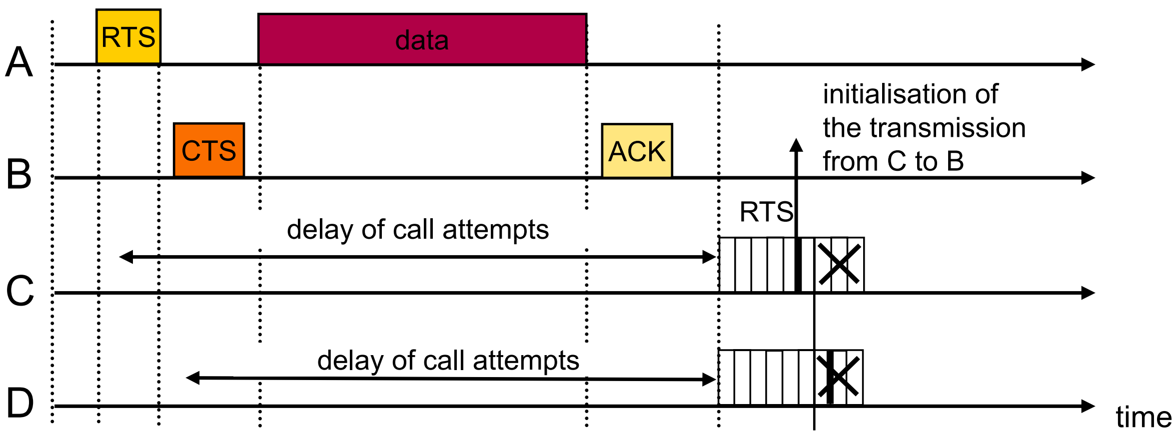
A and C would like to transmit to B at the same time, but cannot see each other because the coverage is too large, i. e. they are “hidden” from each other.



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)

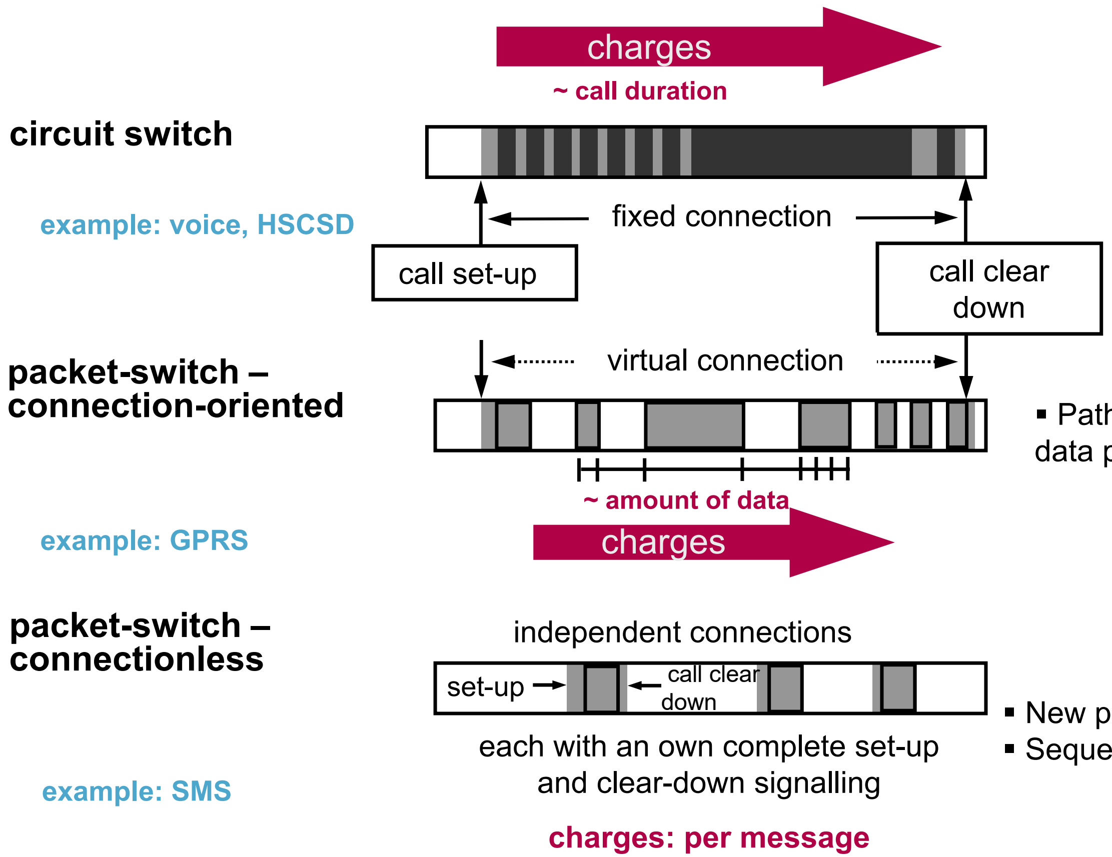
  - Every cell obtains a set of firmly allocated frequencies according to its channel requirements.
  - Assignment can be done according to a fixed regular re-use pattern (not relevant in practice)
  - Assignment within the scope of radio network planning by means of automated frequency assignment methods 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



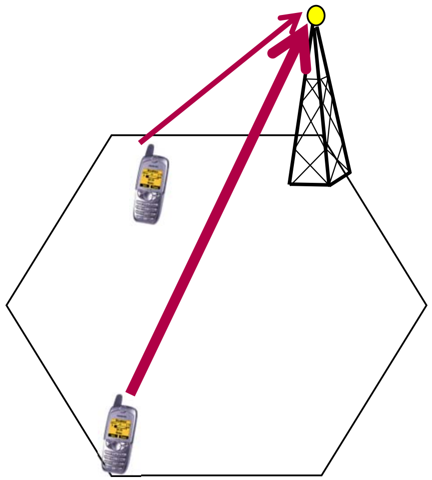
- Path and sequence of the data packets persist

- New path for every packet
- Sequence can change

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