Universität
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Software Defined Radio – State of the Art and Look Ahead

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SDR Forum Technical Conference
Orlando, FL - November 17, 2003

opics

Mobile Radio Communications

SDR Signal Processing

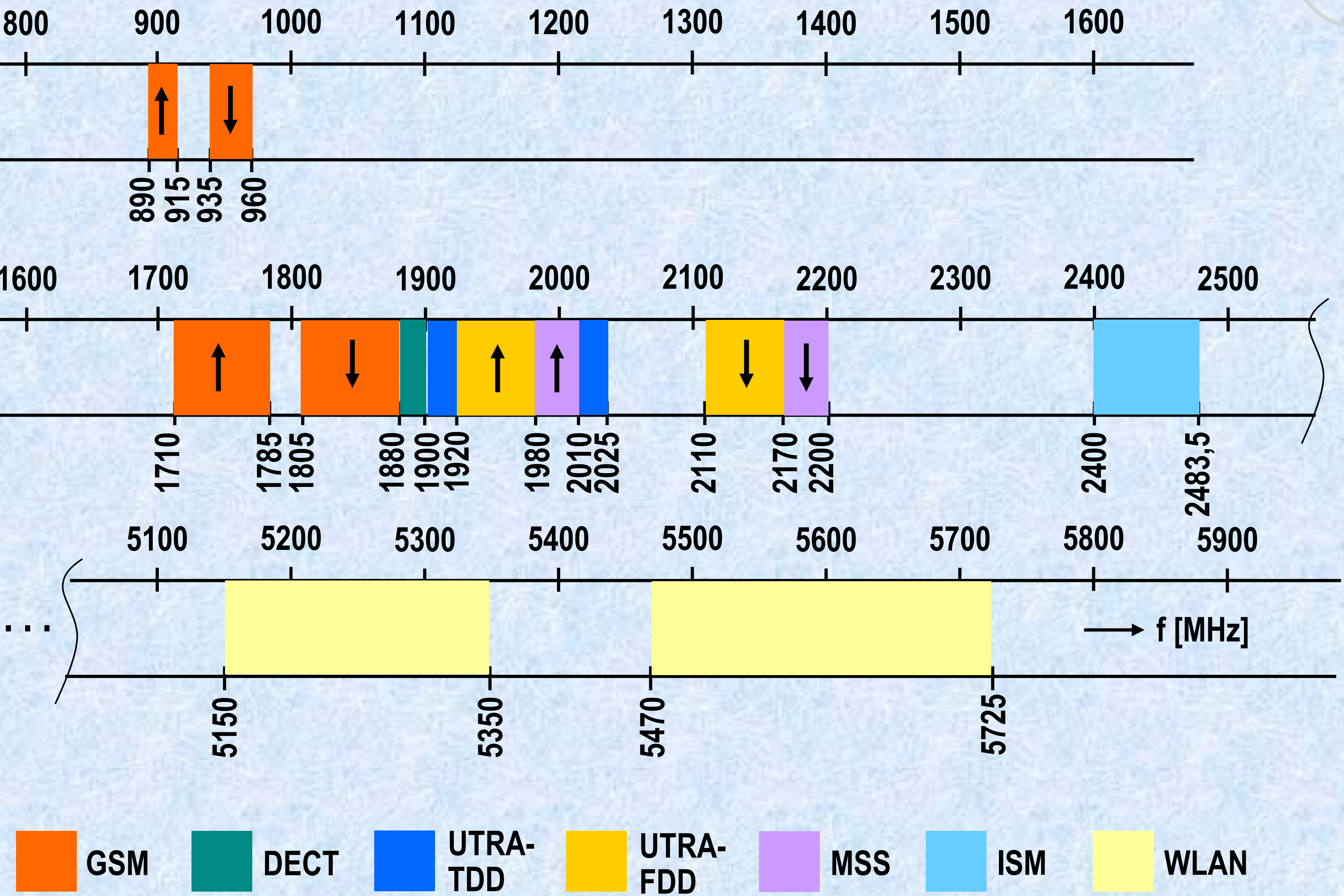
Mobile Communication Channels

Parameter Controlled SDR

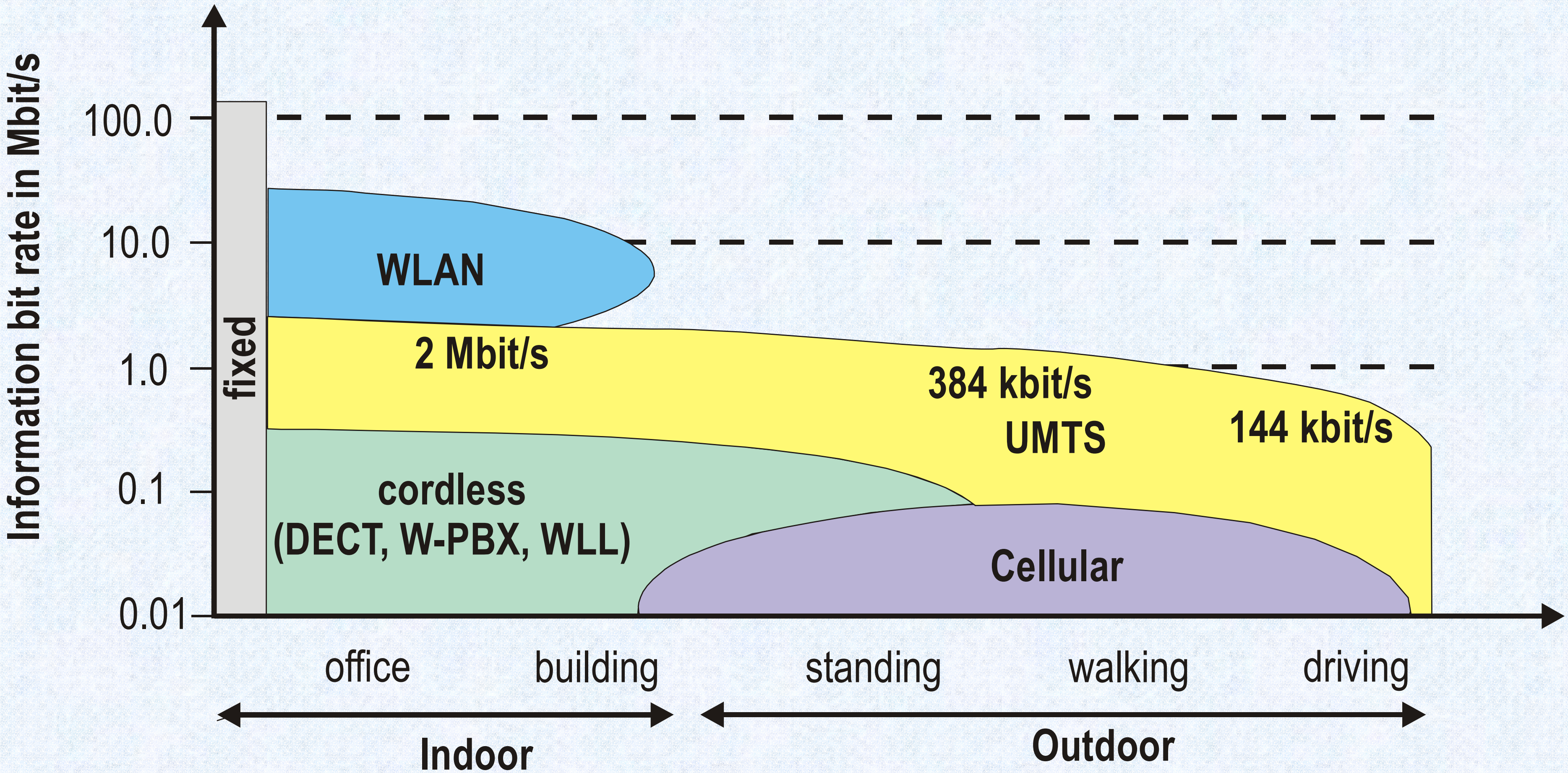
Spectrum Pooling

Modular SDR

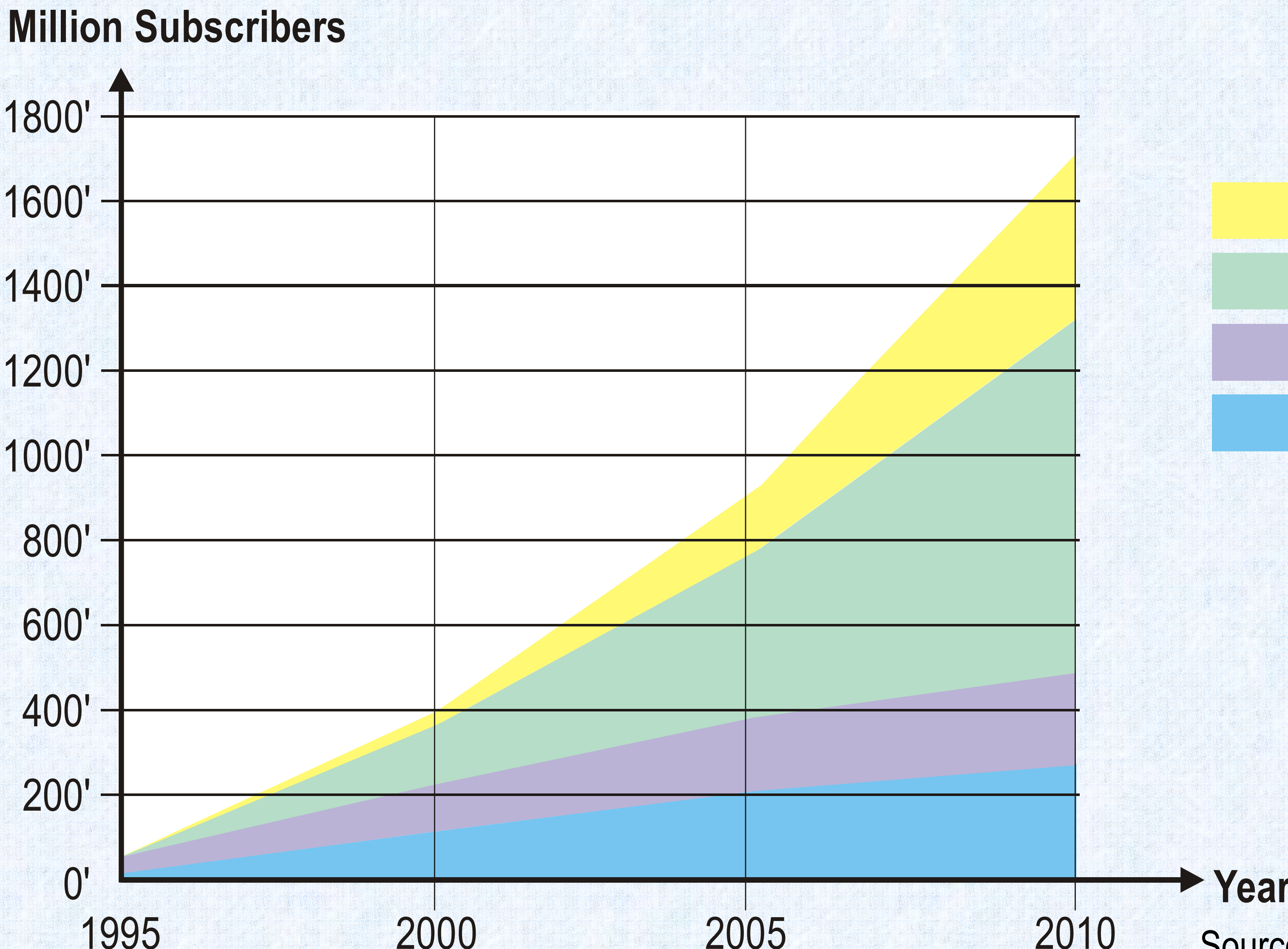
obile Spectrum in Europe



obile Radio Standards

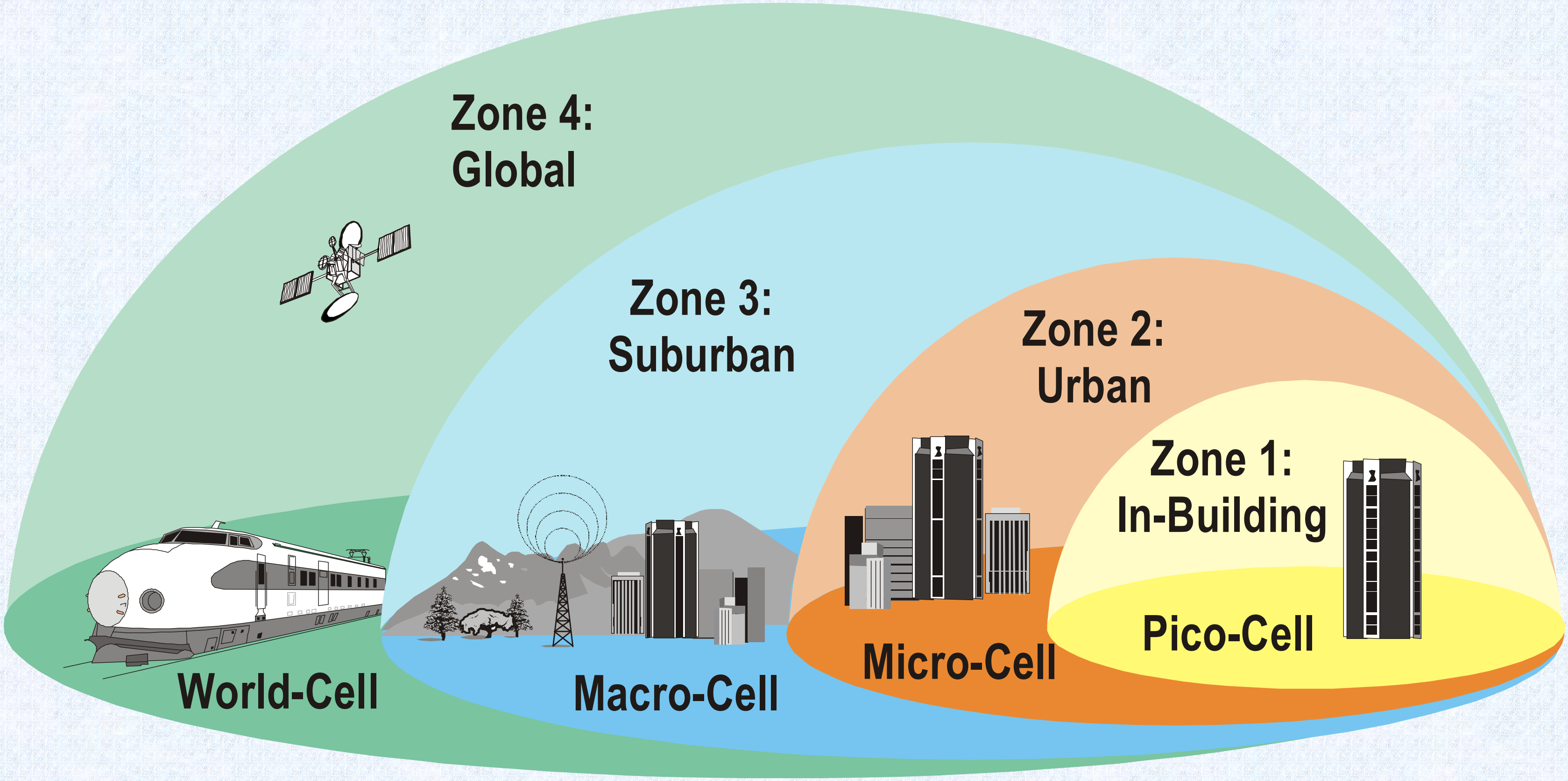


obile Subscribers

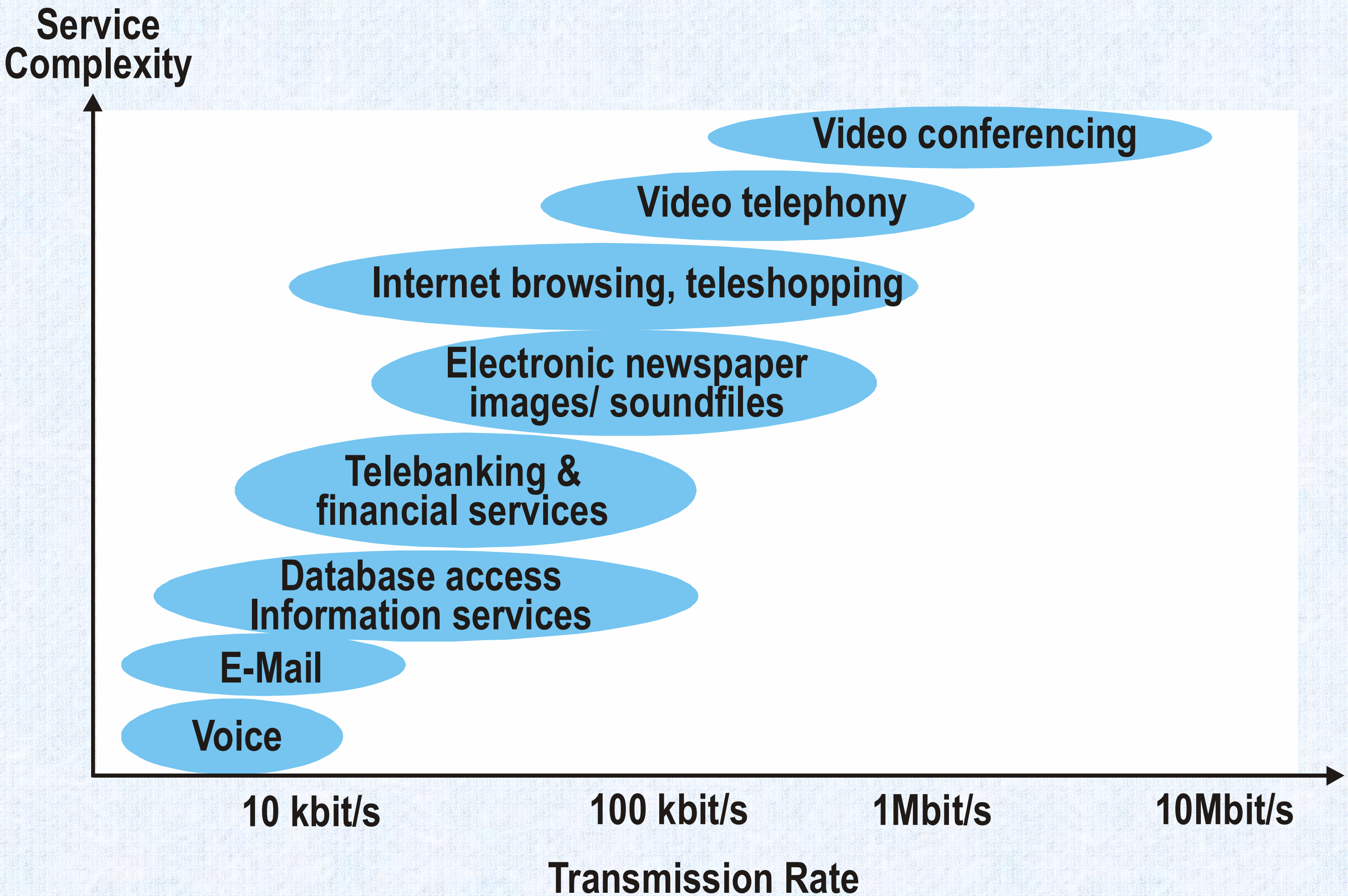


Source: UMTS Forum, 2000

...ierarchical Cells



Source: UMTS Task Force Report


Service
Complexity
Video conferencing
Video telephony
Internet browsing, teleshopping
Electronic newspaper
images/ soundfiles
Telebanking &
financial services
Database access
Information services
E-Mail
Voice
10 kbit/s
100 kbit/s
1Mbit/s
10Mbit/s
Transmission Rate

he Key Question

Pesonal Area Networks	Pico Cells	Voice
Wireless Local Area Networks	Micro Cells	Data
Cordless Phones	Makro Cells	Video
Cellular Networks	Global Cells	Multimedia
Broadcast Networks		Location & Navigation
Satellite Networks		Infotainment

What does a subscriber need:

One specific device for each and every situation or one device that serves all situations?

Definition:

A communications standard is a set of documents that describes the functions of a communication system in such a way that a manufacturer can develop terminals or infrastructure equipment on this basis.

Remarks:

(i) Standardization is one necessary condition for making a communication system successful on the market.

(ii) Today, standardization encompasses all kinds of communication networks.

⇨ Will standards continue to play an outstanding role in future communication systems?

AN: Bluetooth

- **Personal Area (short distance) Network**
- **enables links between mobile computers, mobile phones, portable devices, connectivity to the Internet etc.**

Frequency range	2.4 GHz (ISM band)
Channel bandwith	1 MHz
Access mode	TDMA
Duplex mode	TDD
Users per carrier frequency	8 maximum
Modulation	FH sync. to master station, GFSK with modulation index between 0.28 and 0.35
Error correction code	
Bit (chip) rate	1 Mbit/s
Number of bits (chips) per burst (slot)	625
Frame duration	
Number of bursts (slots) per frame	
Burst (slot) duration	0.625 ms
Maximum cell radius	5 – 10 m (1 mW Tx power)
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	Gauss (BT = 0.5)
Net data rate	1 Mbit/s
Evolutionary concepts	
Comparable systems	

LAN: IEEE 802.11a

- high data rate
- multimedia
- connection to internet
- e-mail
- pedestrian speed
- ad hoc net-working possible

Frequency range	5.5 GHz
Channel bandwith	25 MHz
Access mode	FDMA/TDMA
Duplex mode	Half duplex
Users per carrier frequency	
Modulation	OFDM with subcarrier modulation BPSK /QPSK /16QAM /64QAM
Error correction code	Convolutional
Bit (chip) rate	6/9/12/18/24/36/48/54 Mbit/s
Number of bits (chips) per burst (slot)	52 modulated symbols per OFDM symbol
Frame duration	Packets of several 100 µs
Number of bursts (slots) per frame	variable
Burst (slot) duration	1 OFDM symbol of 3.3 µs + 0.8 µs guard time
Maximum cell radius	Some 10 m
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	
Net data rate	Up to 25 Mbit/s
Evolutionary concepts	IEEE802.11n, WIGWAM
Comparable systems	HiperLAN/2

ORDLESS: DECT

- **voice and low data rate**
- **pedestrian speed**
- **cordless connection to ISDN**
- **well suited for home and office applications**

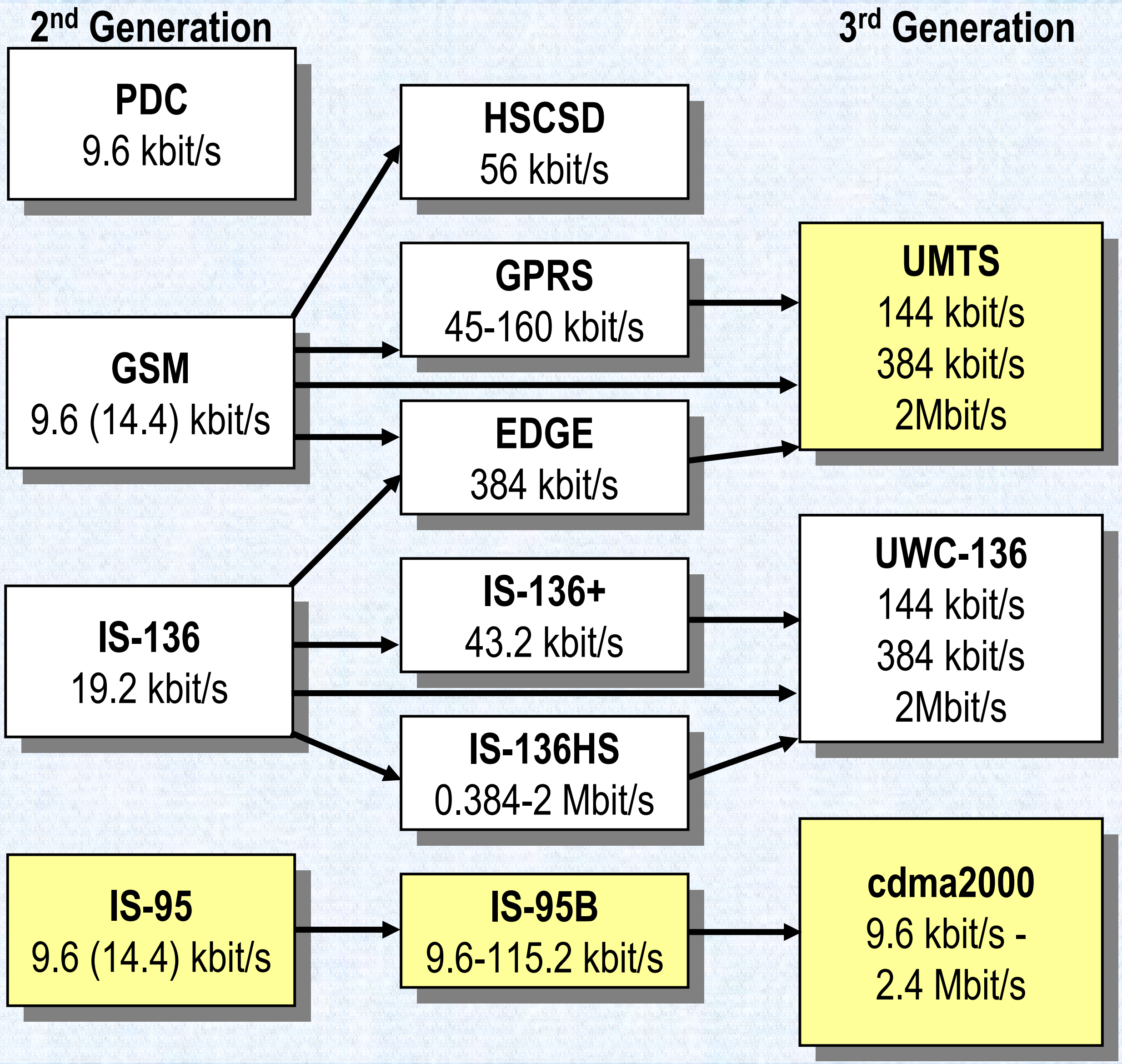
Frequency range	1900 MHz
Channel bandwith	1728 kHz
Access mode	FDMA/TDMA
Duplex mode	FDD
Users per carrier frequency	12
Modulation	GMSK
Error correction code	No (CRC)
Bit (chip) rate	1152 kbit/s
Number of bits (chips) per burst (slot)	480 (DECT P32)
Frame duration	10 ms
Number of bursts (slots) per frame	24
Burst (slot) duration	0.417 ms
Maximum cell radius	300 m
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	Gauss (BT = 0.5)
Net data rate	36 kbit/s
Evolutionary concepts	
Comparable systems	PHS, PACS, WACS

ELLULAR 2G: GSM

- voice and low data rate
- car speed
- seamless handoff
- national and international roaming
- wireless connection to ISDN

Frequency range	900, 1800 or 1900 MHz
Channel bandwith	200 kHz
Access mode	FDMA/TDMA
Duplex mode	FDD
Users per carrier frequency	8
Modulation	GMSK
Error correction code	CRC, convolutional
Bit (chip) rate	270.833 kbit/s
Number of bits (chips) per burst (slot)	156.25
Frame duration	4.615 ms
Number of bursts (slots) per frame	8
Burst (slot) duration	0.577 ms
Maximum cell radius	35 km (10 km)
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	Gauss (BT = 0.3)
Net data rate	13 kbit/s
Evolutionary concepts	GPRS, HSCSD, EDGE
Comparable systems	IS-136, PDC

volution in Mobile (DATA) Communication



EDGE
Enhanced Data for GSM Evolution

GPRS
General Packet Radio Services

HSCSD
High Speed Circuit Switched Data

UWC
Universal Wideband Communication

CDMA

ELLULAR 3G: UMTS-FDD

- **wireless multimedia**
- **car speed**
- **seamless (soft) handoff**
- **national and inter-national roaming**
- **wireless connection to ISDN and Internet**

Frequency range	2 GHz
Channel bandwith	5 MHz
Access mode	Direct Sequence (DS) CDMA
Duplex mode	FDD
Users per carrier frequency	
Modulation	QPSK
Error correction code	Convolutional, turbo, CRC
Bit (chip) rate	3.840 Mchip/s
Number of bits (chips) per burst (slot)	2560
Frame duration	10 ms
Number of bursts (slots) per frame	15
Burst (slot) duration	0.667 ms
Maximum cell radius	Few km
Spreading sequences	User specific OVSF codes, cell specific scrambling
Spreading factor	2^k (k= 2, 3, ..., 8) 512 for downlink only
Bit (chip) pulse shaping filter	Root raised cosine, rolloff factor 0.22
Net data rate	8 kbit/s to 2 Mbit/s
Evolutionary concepts	HSDPA
Comparable systems	cdma2000, UMTS-TDD

MR: TETRA

- **Professional Mobile Radio**
- **voice and low data rate**
- **well suited for police and fire department services**
- **mobile to mobile connection possible**

Frequency range	400 MHz
Channel bandwith	25 kHz
Access mode	TDMA
Duplex mode	FDD/TDD
Users per carrier frequency	4
Modulation	π/4-DQPSK
Error correction code	CRC, Reed-Muller, RCPC codes
Bit (chip) rate	36 kbit/s
Number of bits (chips) per burst (slot)	510 (255 symbols)
Frame duration	56.67 ms
Number of bursts (slots) per frame	4
Burst (slot) duration	14.167 ms
Maximum cell radius	
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	Root raised cosine, roll-off factor 0.35
Net data rate	Up to 28.8 kbit/s
Evolutionary concepts	
Comparable systems	TETRAPOL

ocation & Navigation: GPS

- **self location of (mobile) users**
- **navigation**
- **high speed**
- **direct Sequence Spread Spectrum modulation**

Frequency range	1200, 1500 MHz
Channel bandwith	
Access mode	
Duplex mode	
Users per carrier frequency	
Modulation	Direct Sequence Spread Spectrum: BPSK
Error correction code	
Bit (chip) rate	50 bit/s
Number of bits (chips) per burst (slot)	
Frame duration	15 s (7500 bit)
Number of bursts (slots) per frame	5 subframes
Burst (slot) duration	30 s
Maximum cell radius	
Spreading sequences	Gold or PRN code
Spreading factor	1023 or 10230
Bit (chip) pulse shaping filter	
Net data rate	
Evolutionary concepts	Galileo
Comparable systems	GLONASS

/ Broadcast: DVB-T

- **broadcast service**
- **mobile reception possible, even at high speeds**
- **OFDM modulation**

Frequency range	VHF, UHF
Channel bandwith	7 (VHF) or 8 MHz (UHF)
Access mode	FDMA
Duplex mode	
Users per carrier frequency	
Modulation	OFDM with subcarrier modulation QPSK/16QAM/64QAM
Error correction code	Reed-Solomon, convolutional
Bit (chip) rate	9.143 Msamples/s for a 8 MHz channel
Number of bits (chips) per burst (slot)	2k-mode: 2048 + guard interval 8k-mode: 8192 + guard interval
Frame duration	68 OFDM symbols
Number of bursts (slots) per frame	68
Burst (slot) duration	2k-mode: 224 μs + guard time 8k-mode: 896 μs + guard time
Maximum cell radius	
Spreading sequences	
Spreading factor	
Bit (chip) pulse shaping filter	Rectangular, other filtering possible
Net data rate	49.8 to n31.67 Mbit/s
Evolutionary concepts	
Comparable systems	DAB

tandards Summary

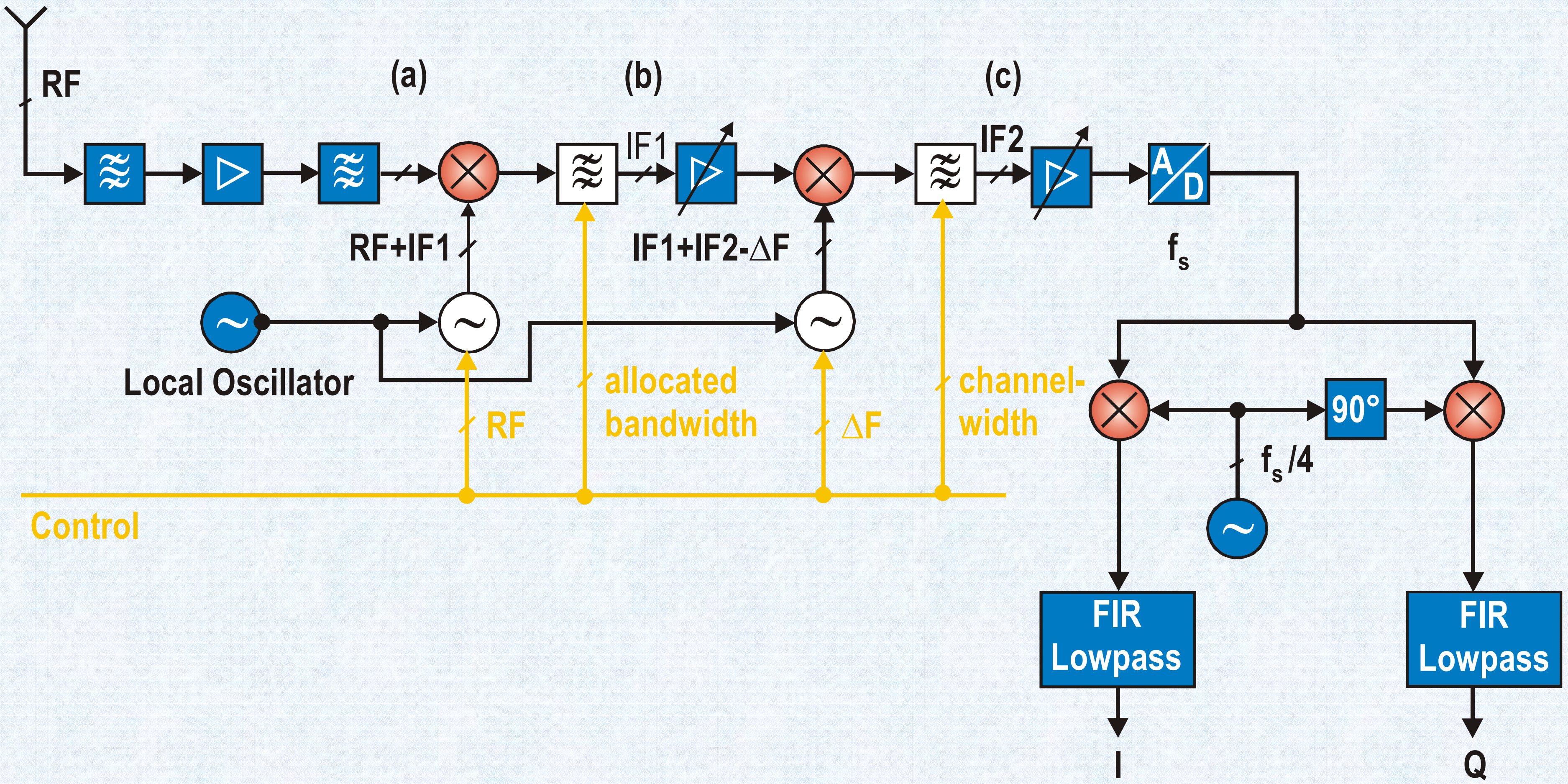
A radio communication standard defines transmission systems w.r.t. specific services like voice, video, data, multimedia, broadcast, location, navigation etc.

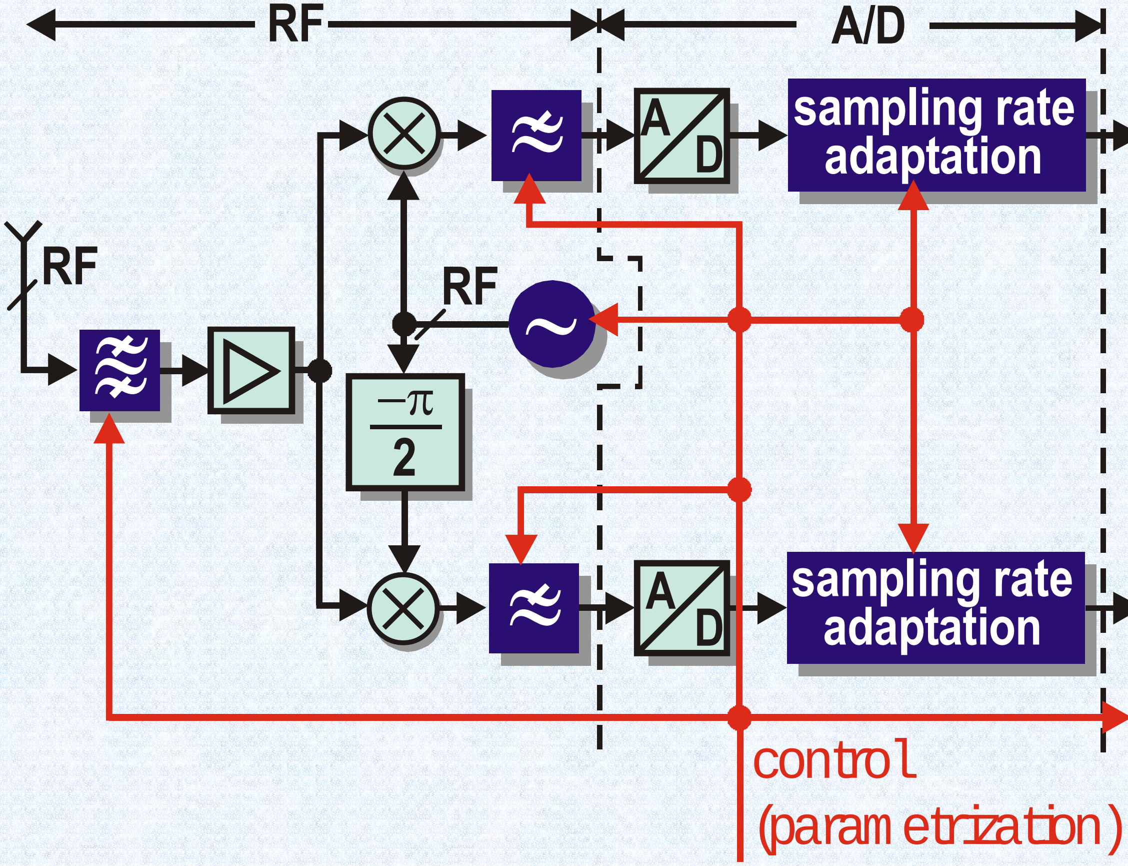
The accompanying transmission modes and protocols depend on data rate bandwidth, velocity, type of service etc.

⇨ Mobile radio communication starts with the channel properties.

- Mobile Radio Communications
- **SDR Signal Processing**
- Mobile Communication Channels
- Parameter Controlled SDR
- Spectrum Pooling
- Modular SDR

uperhet Receiver

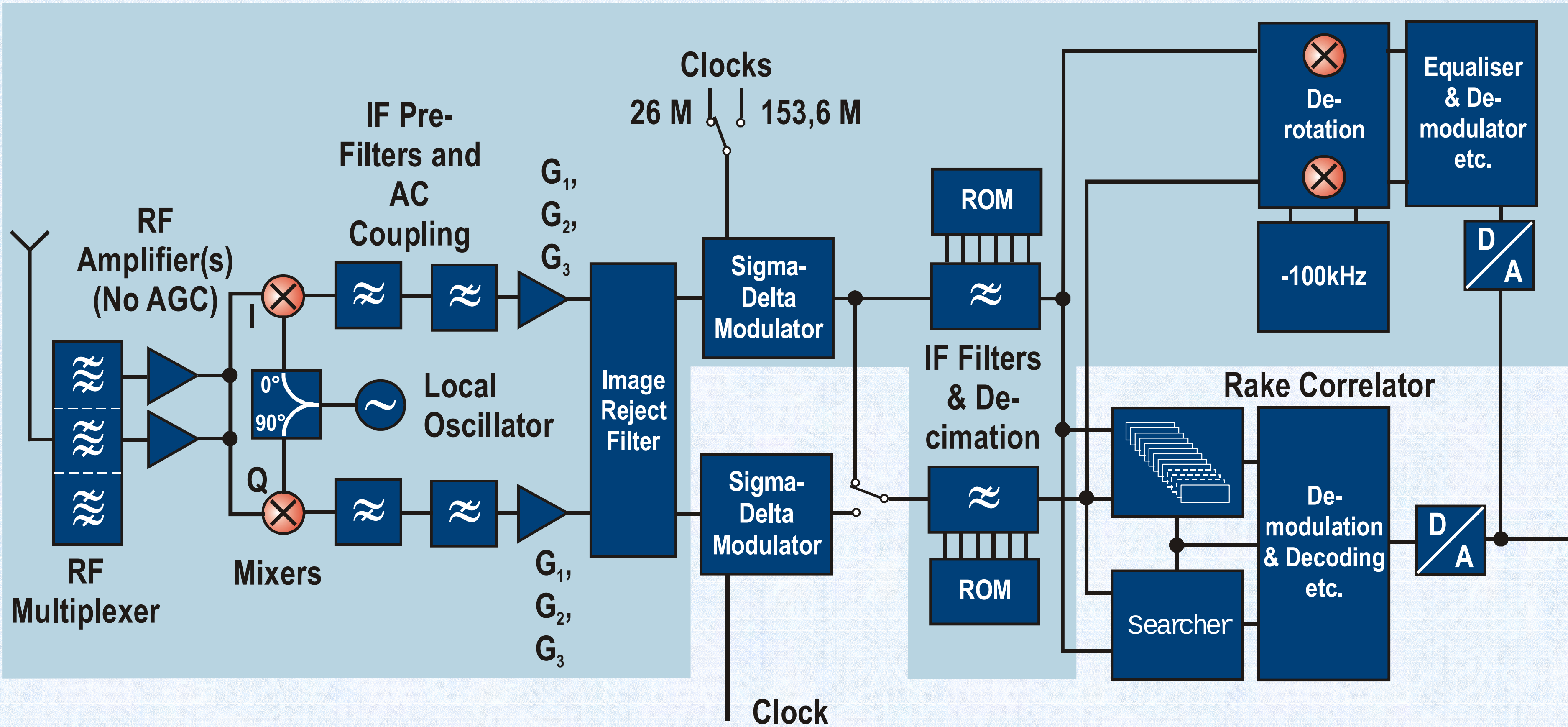




Conversion of the antenna signal to the complex baseband in one step

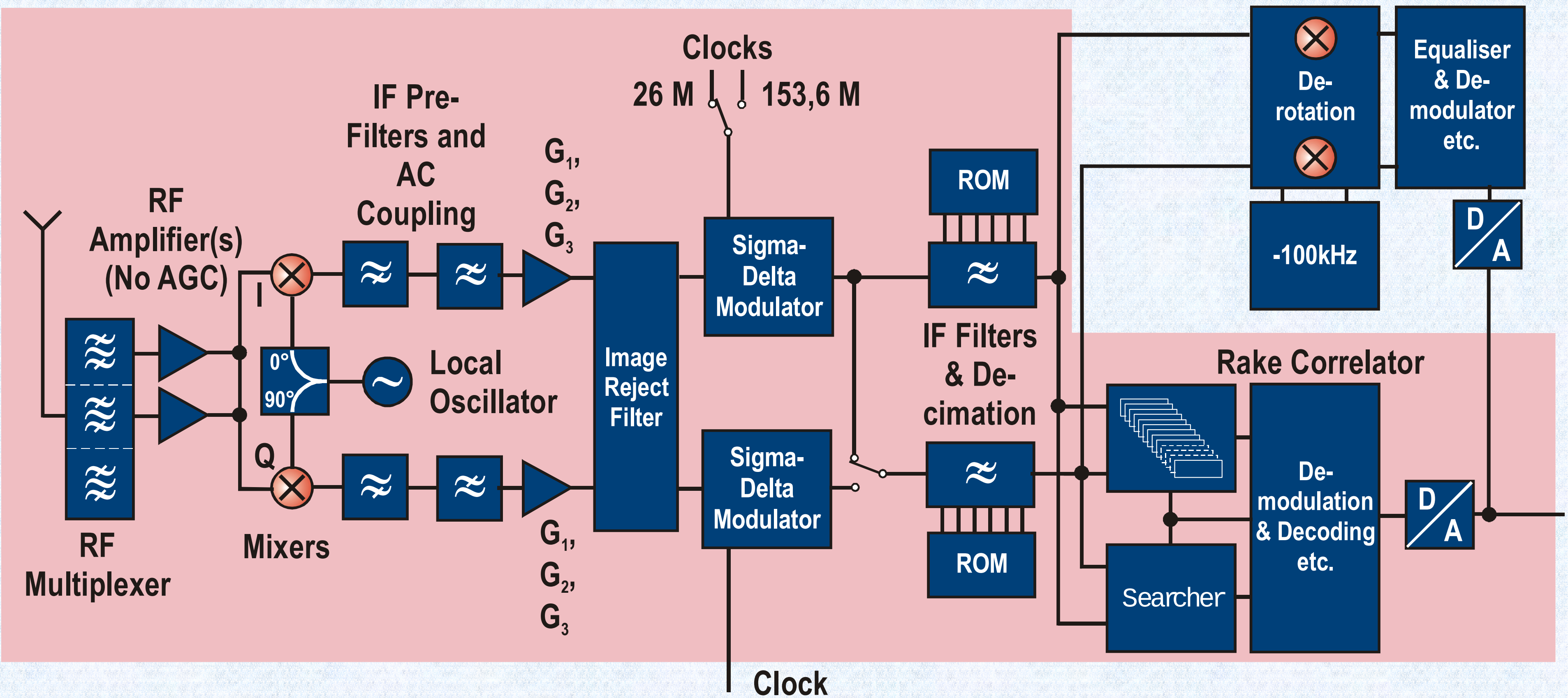
Zero IF receiver : RF and A/D units

MTS/GSM Multimode receiver: GSM Mode



from: Brian J. Minnis, Paul A. Moore: A Highly Digitized Multimode Receiver Architecture for 3G Mobiles, IEEE Transactions on Vehicular Technology, Vol. 52, 2003, pp. 637-653

MTS/GSM Multimode Receiver: UMTS Mode



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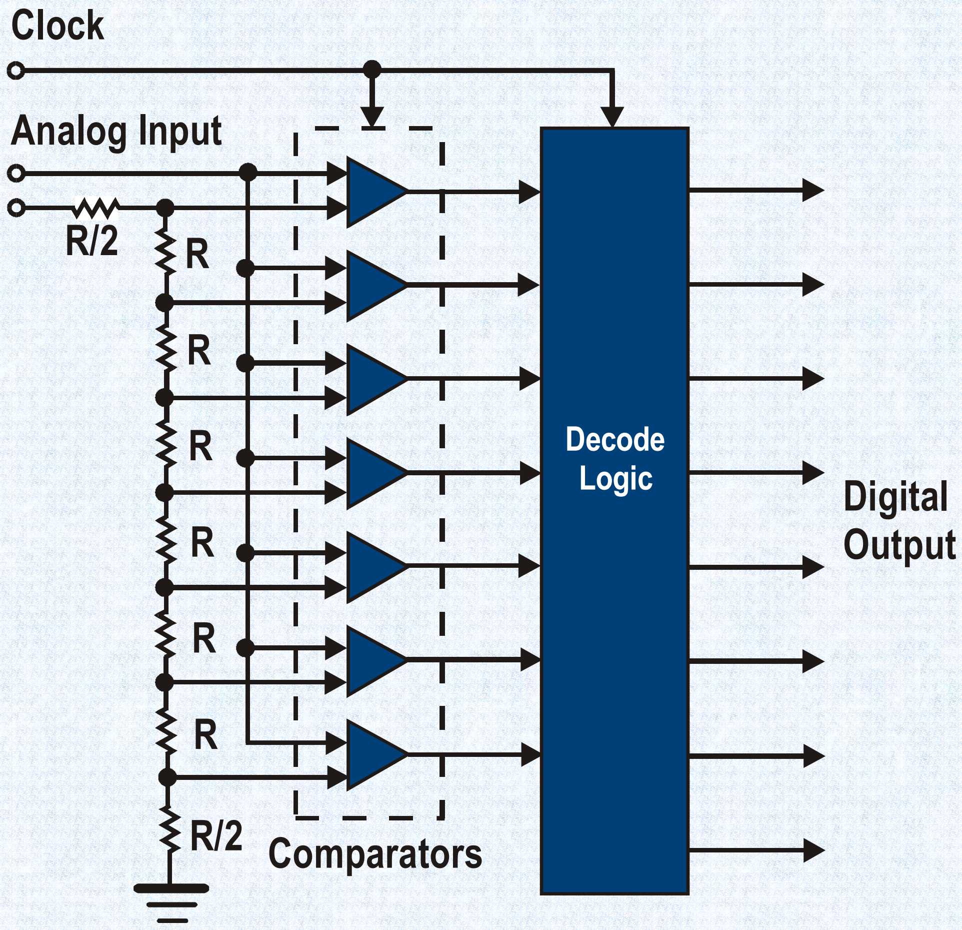
uperhet vs. Direct Conversion

	Pros	Cons	preferred for SDR
Superhet Receiver	- high sensitivity - high selectivity - no I/Q mismatch, if bandpass sub-sampling is applied	- monolithic integration is difficult - tradeoff between gain, noise figure, stability and power dissipation in the amplifier is necessary - ADC: high resolution at high sampling rate, aperture jitter	no
Direct Conversion Receiver	- no IF processing - no mirror frequencies - LNA simple to realize - monolithic integra-tion possible	- DC offset - LO leakage - I/Q matching necessary	yes

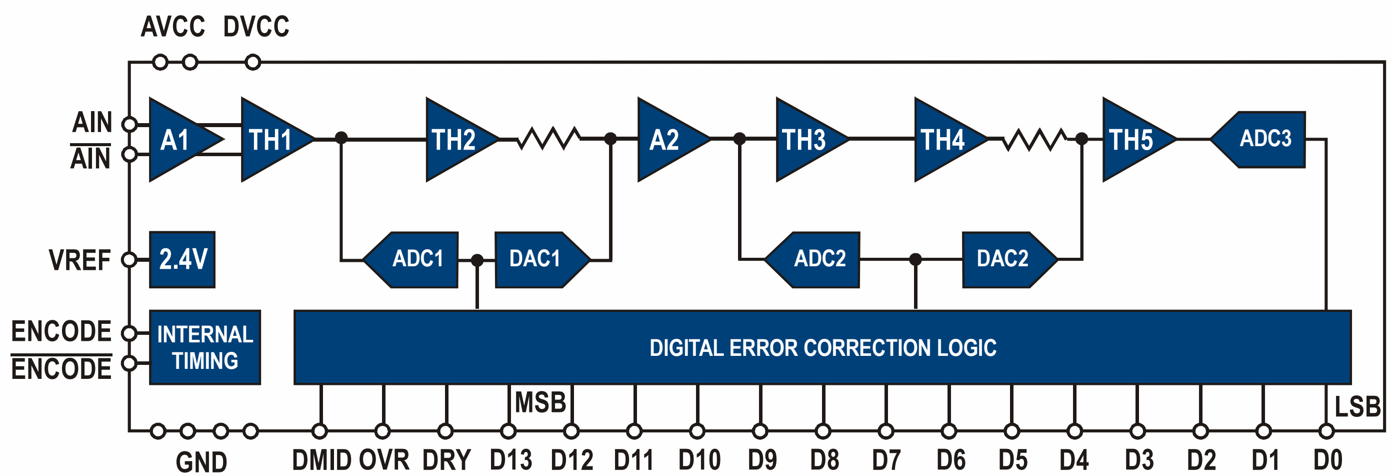
DCs: FLASH

- fast
- easy to implement
- chip area, costs and complexity increase with 2^N (N resolution in bit)
- resolution ≤ 10 bit



from: J.Reed.: *Software Radio*, Prentice Hall, Upper Saddle River, NJ, 2002

- less chip area, lower power consumption, lower cost than FLASH
- small latency
- resolution $\geq$ 16 bit possible

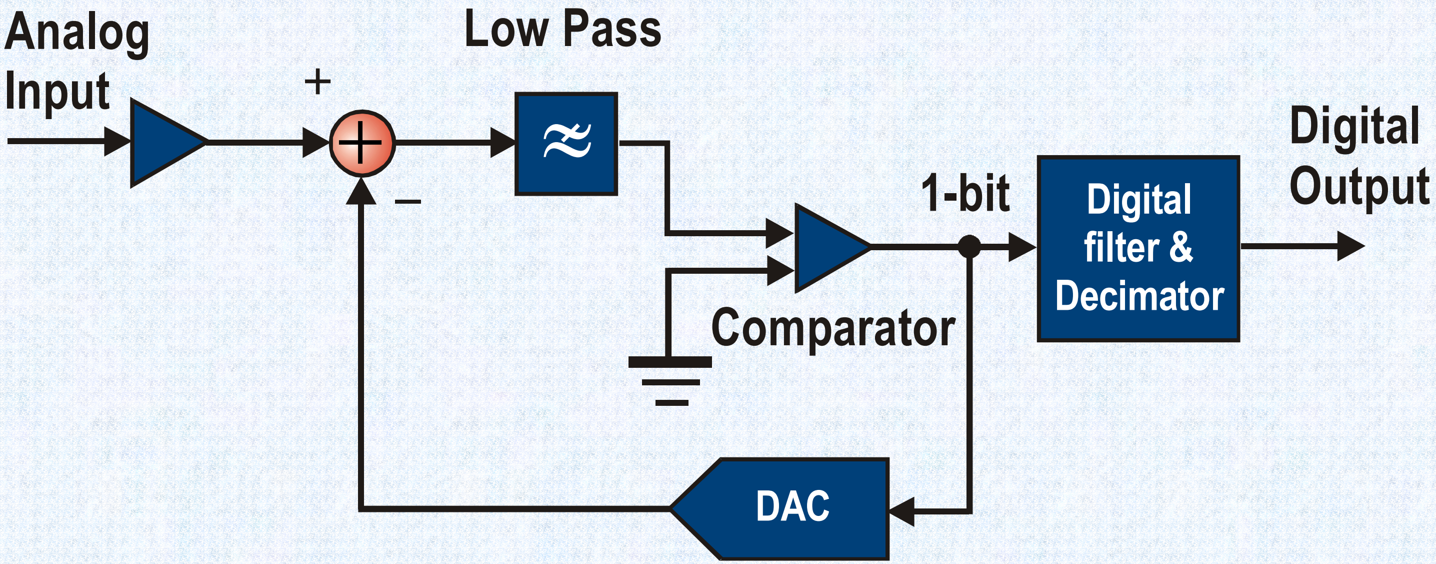


from: B.Brannon et al.: *Data Conversion in Software Defined Radios*, in W. Tuttlebee (ed.): Software Defined Radio-Enabling Technologies, Wiley, Chichester, UK, 2002

⇨ “a popular architecture used in many SDR applications“

DCs: ΣΔ

- "ΣΔ modulators offer an attractive approach to realizing high performance analog-to-digital conversion without relying on the use of high precision and accurately trimmed analog components."



from: B.Brannon et al.: *Data Conversion in Software Defined Radios*, in W. Tuttlebee (ed.): Software Defined Radio-Enabling Technologies, Wiley, Chichester, UK, 2002

"ΣΔ ADCs are well suited for use in SDR"

ample Rate Conversion

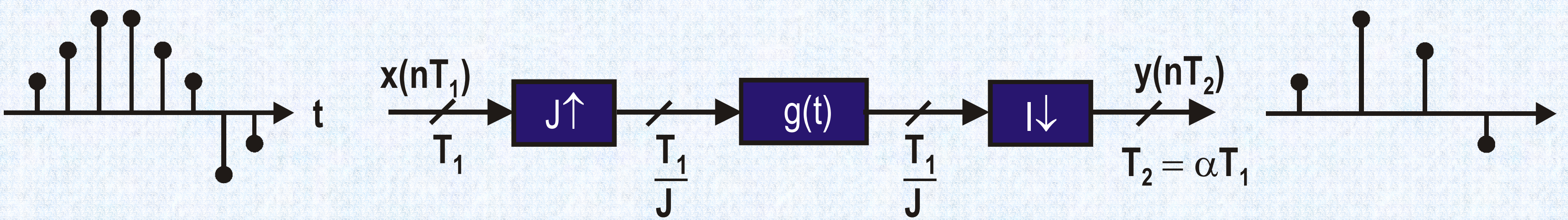
The anlog frontend of an SDR is usually implemented as a direct conversion receiver. The sample rate of the ADCs in the I and Q branches is fixed:

- The ADCs always work at maximum speed.

The tasks of the sample rate conversion are:

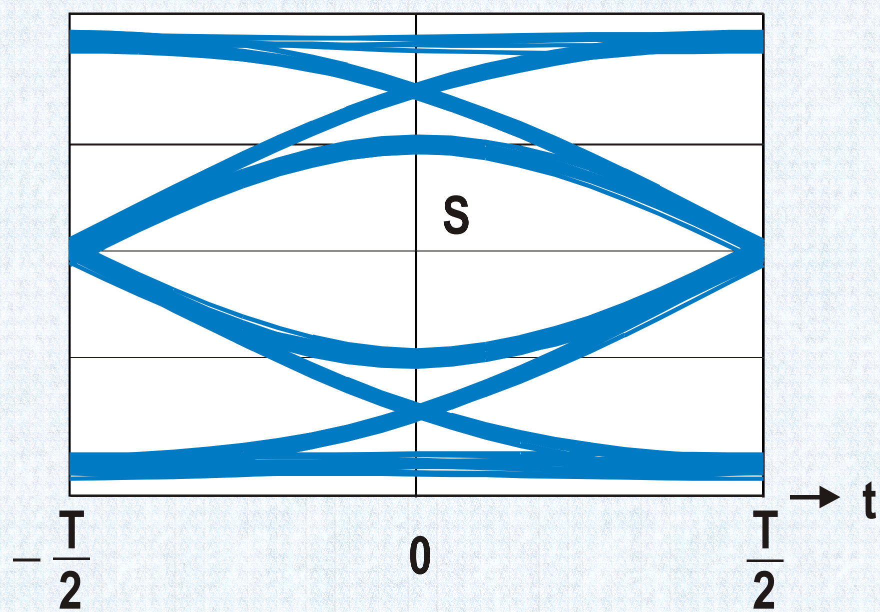
- Adjustment of the sample rate according to the standard of the received signal.
- Sampling at the symbols‘ eye pattern maximum.

Sample rate conversion by a rational factor $\alpha = \frac{I}{J}$:



Pay attention to aliasing! The implementation of g(t) is important.

Eye pattern:

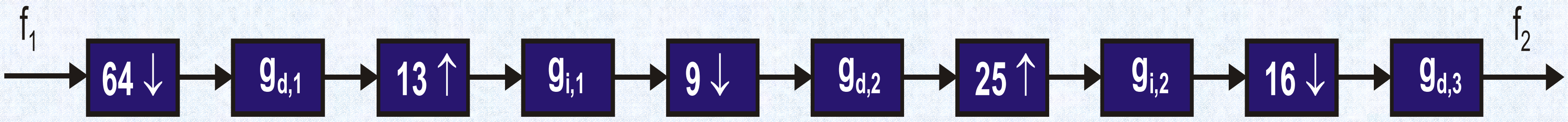


ample Rate Conversion

Example:

From $f_1 = \frac{1}{T_1} = 30.720$ MHz (8 x UMTS chip rate)

to $f_2 = \frac{1}{T_2} = 1.08333$ MHz (4 x GSM bit rate)

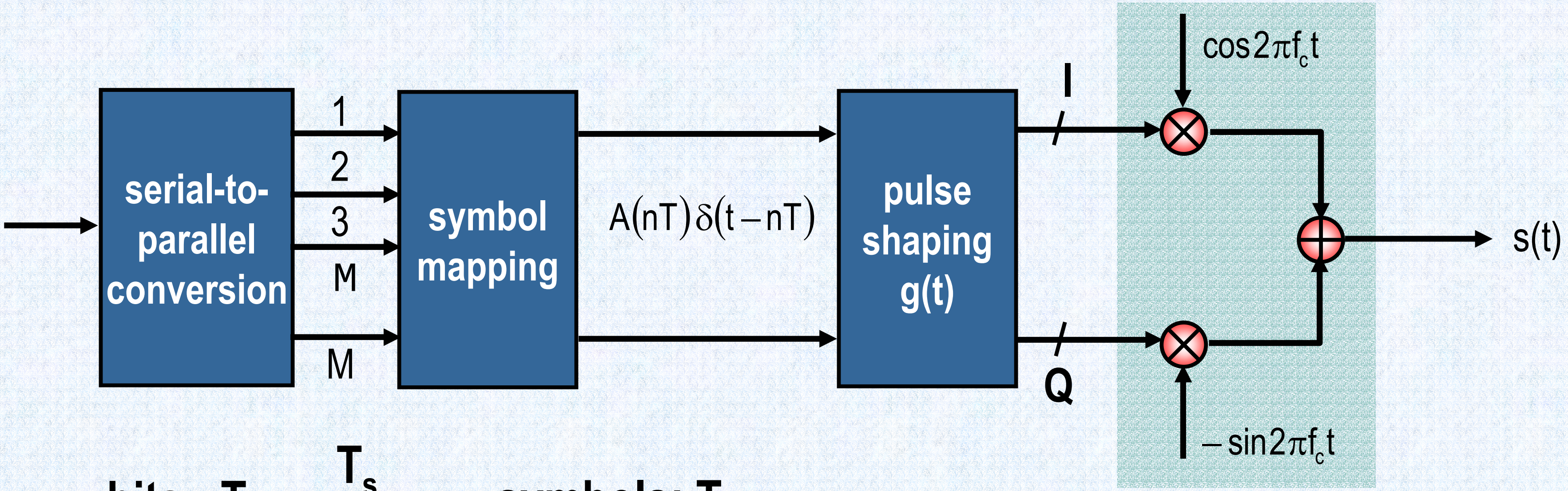


$$f_1 = 8 \cdot 3840 \text{ kHz} = 2^{11} \cdot 3 \cdot 5 \text{ kHz}$$

$$f_2 = 4 \cdot 270.833 \text{ kHz} = \frac{2 \cdot 5^3 \cdot 13}{3} \text{ kHz}$$

$$\frac{f_2}{f_1} = \frac{2 \cdot 5^3 \cdot 13}{3 \cdot 2^{11} \cdot 3 \cdot 5} = \frac{1}{64} \cdot 13 \cdot \frac{1}{9} \cdot 25 \cdot \frac{1}{16}$$

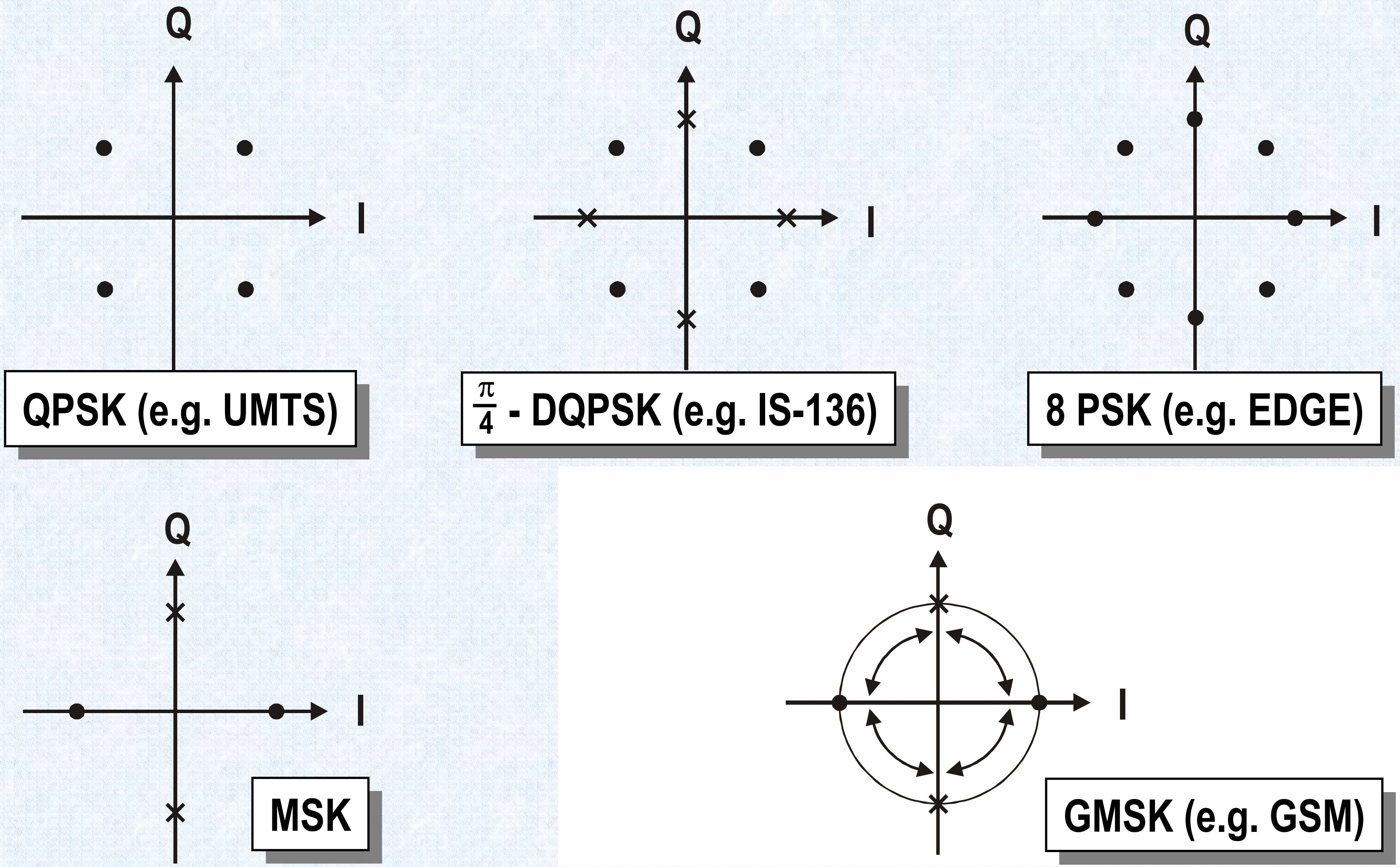
Modulation is the mapping of information bits to symbols, the pulse shaping and the up-conversion of the signal to the radio frequency.



bits : $T_b = \frac{T_s}{M}$ **symbols:** T_s

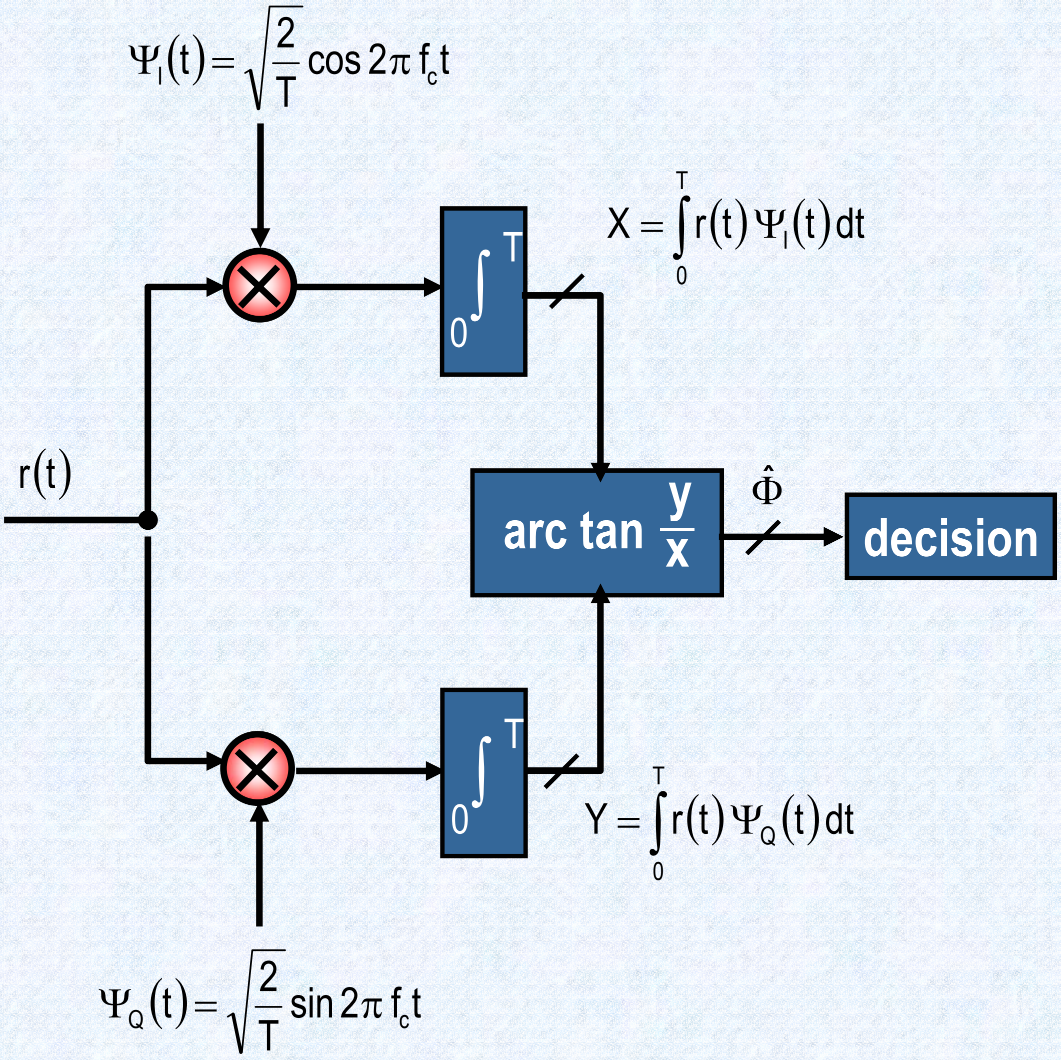
for linear modulators: $s(t) = \mathrm{Re}\{u(t)e^{j2\pi f_c t}\}$, **where** $u(t) = \sum_{n=0}^{\infty} A(nT)g(t-nT)$,

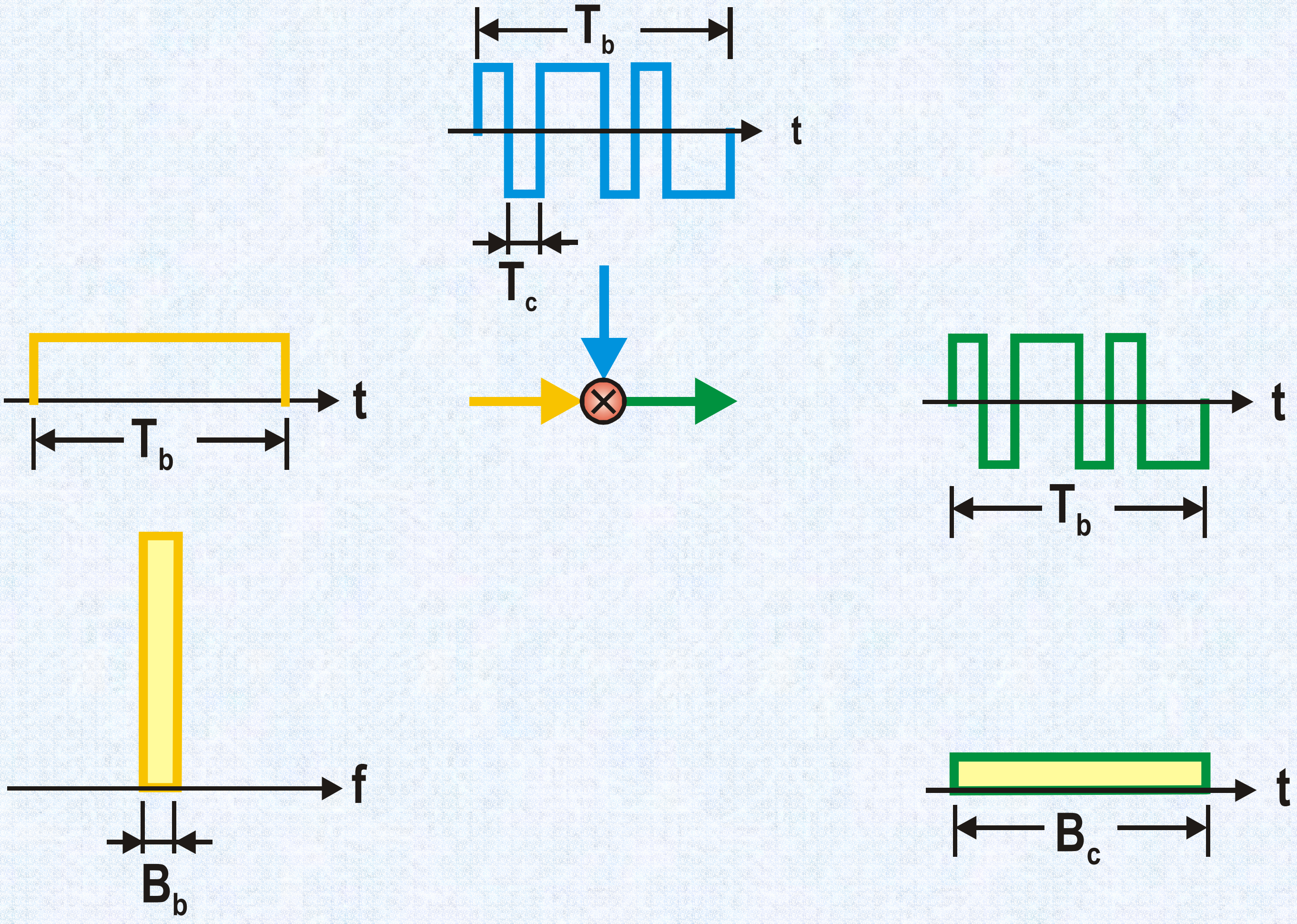
$$A(nT) \in \mathbf{C}$$


Q
I
QPSK (e.g. UMTS)
Q
I
$\frac{\pi}{4}$ - DQPSK (e.g. IS-136)
Q
I
8 PSK (e.g. EDGE)
Q
I
MSK
Q
I
GMSK (e.g. GSM)

All linearily modulated signals can be demodulated with the same demodulator structure (here coherent demodulation)

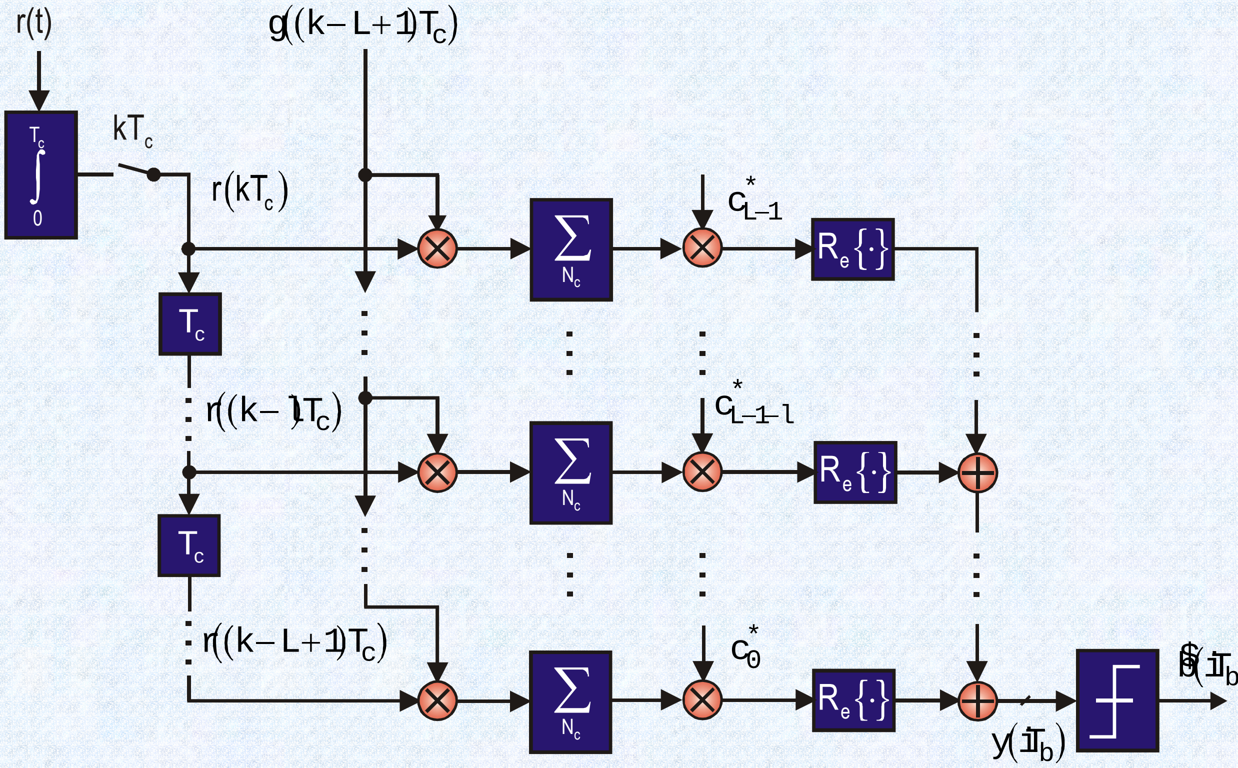
- **project the signal onto the I- and Q-components**
- **compute the angle between the positive I-axis and the signal**
- **decide for the symbol**





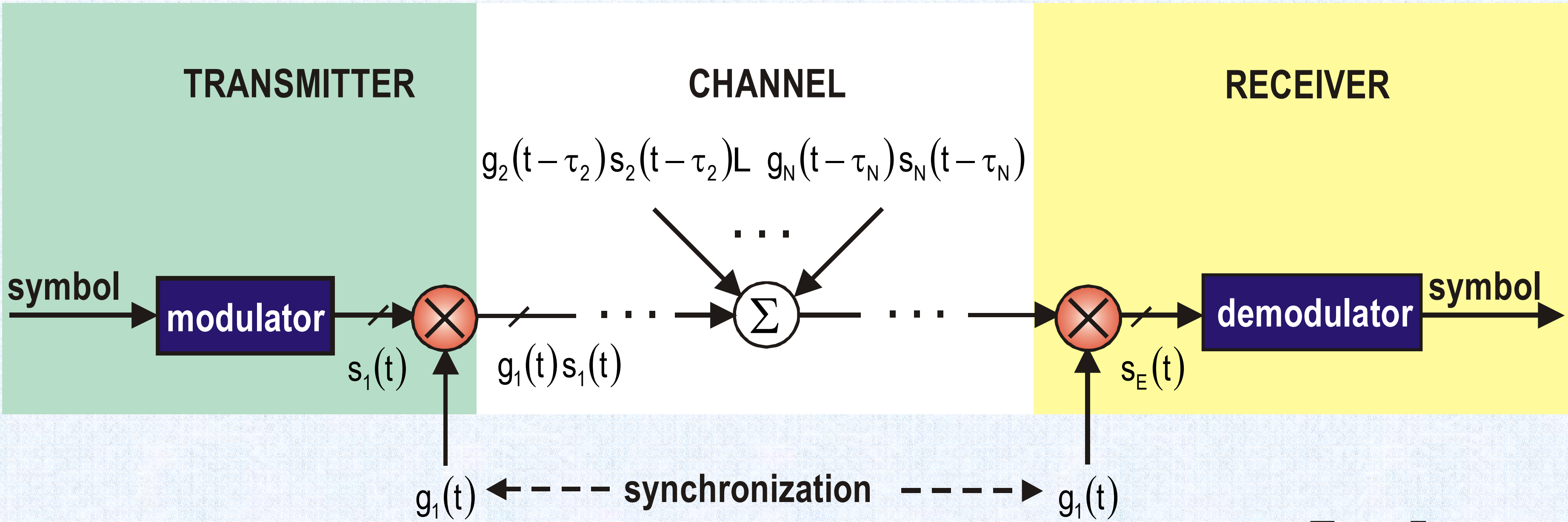
A direct sequence spread spectrum (DSSS) signal is twice modulated.

- Ideally, the rake fully compensates the mobile radio channel's spectral selectivity.
- At the RAKE's output the signal-to-interference ratio equals $E_b/(2N_0)$.
- The RAKE is <u>not</u> a measure against MAI.



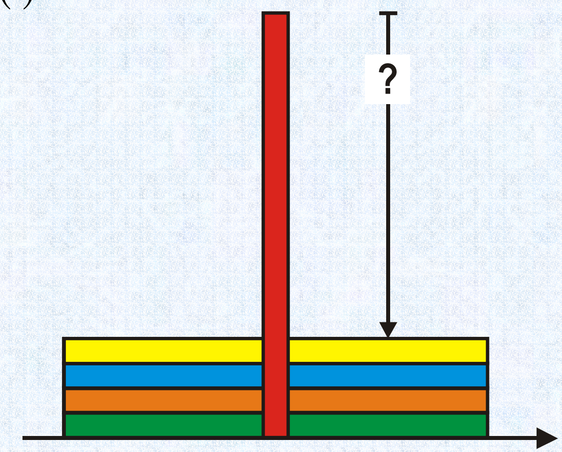
RAKE (e.g. for antipodal signaling)

ultiple Access Interference (MAI)



$$s_E(t) = s_1(t) + \sum_{n=2}^{N} \int_0^{T_b} g_1(t)\, g_n(t-\tau_n)\, s_n(t-\tau_n)\, dt$$

MAI

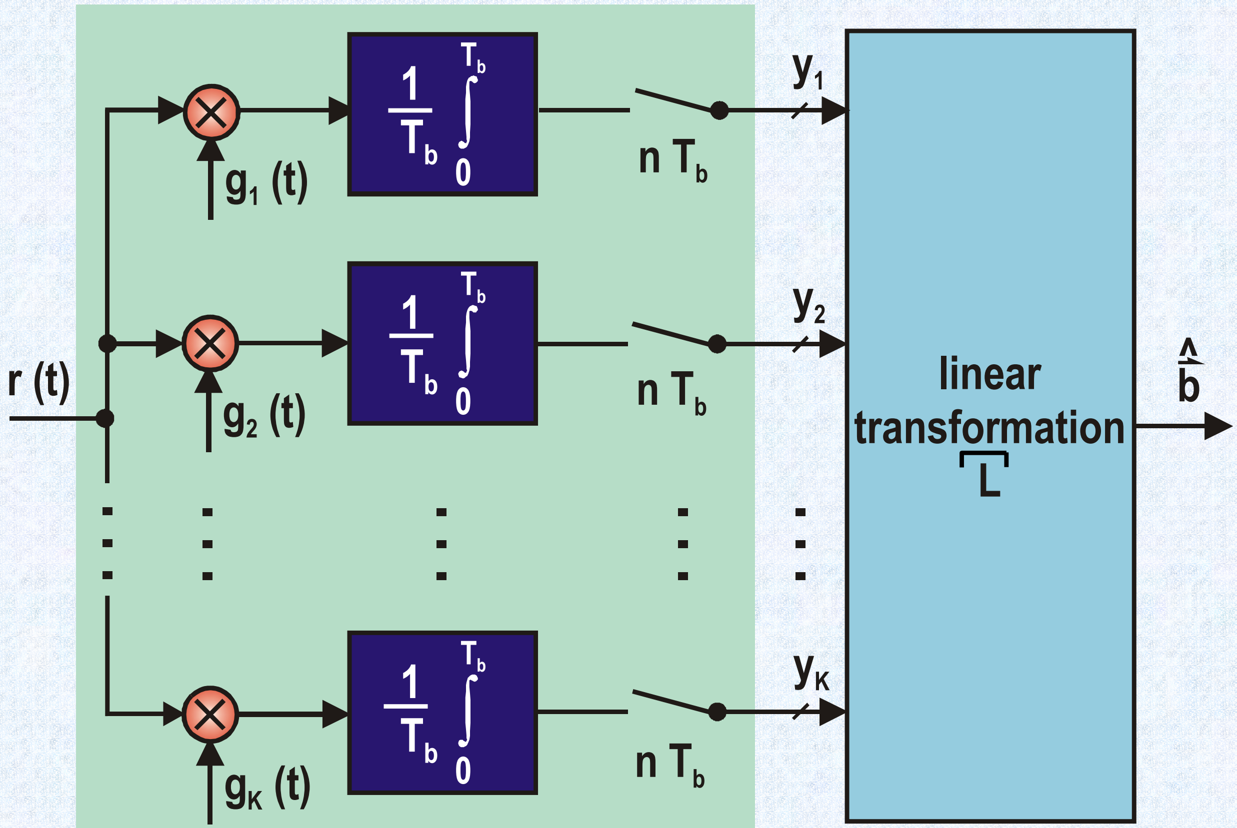


MUDs

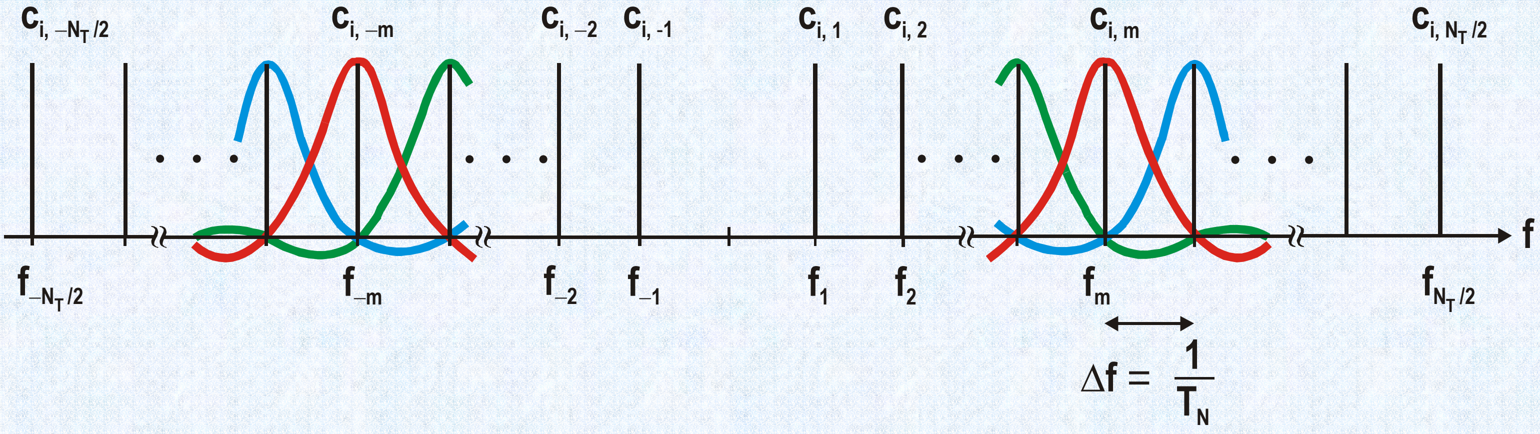
- suppress MAI
- are complex
- (i.e. expensive)

Optimum MUDs like the Maximum A Posteriori Detector (MAPD) or the Maximum Likelihood Sequence Detector (MLSD) are too complex for a realization.

➡ Linear MUDs and iterative solutions are investigated.

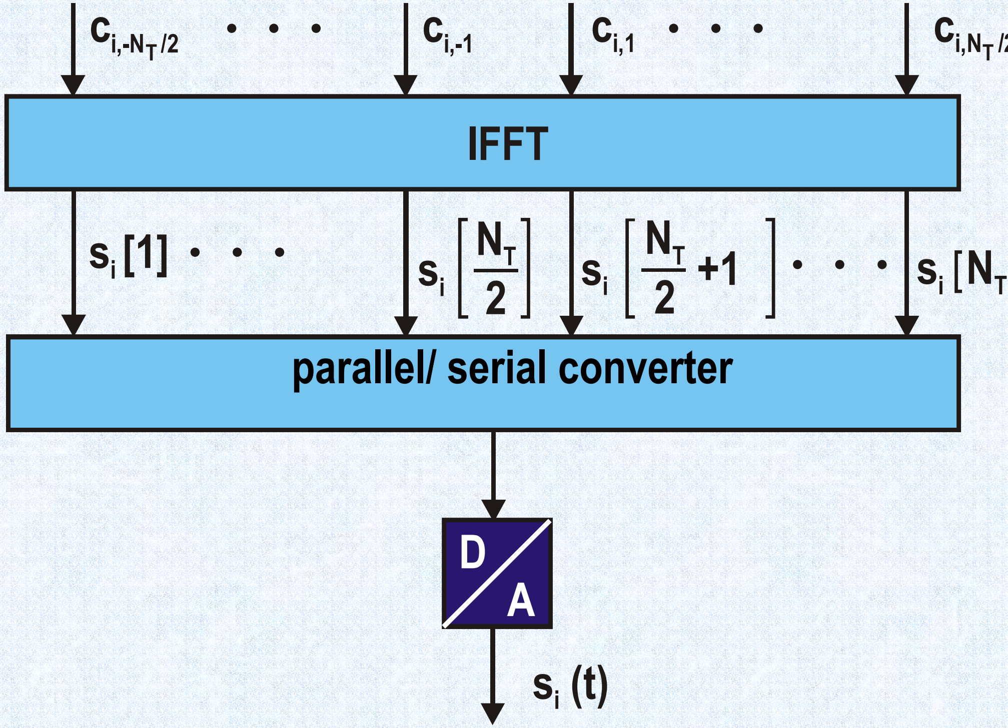


FDM



An Orthogonal Frequency Division Multiplex (OFDM) system transmits information on several orthogonal subcarriers in parallel.

E.g. for IEEE 802.11a the modulation mode can be BPSK, QPSK, 8PSK, 16QAM or 64QAM.



By coding we mean forward error correction (FEC) coding.

All codes schemes in mobile communications (CRC, block, convolutional, turbo) are binary.

I.e. all encoders are built up of linear (recursive) shift registers (and interleavers).

All coding schemes can be realized from the same parameter controlled structure.

addition

+	0	1
0	0	1
1	1	0

multiplication

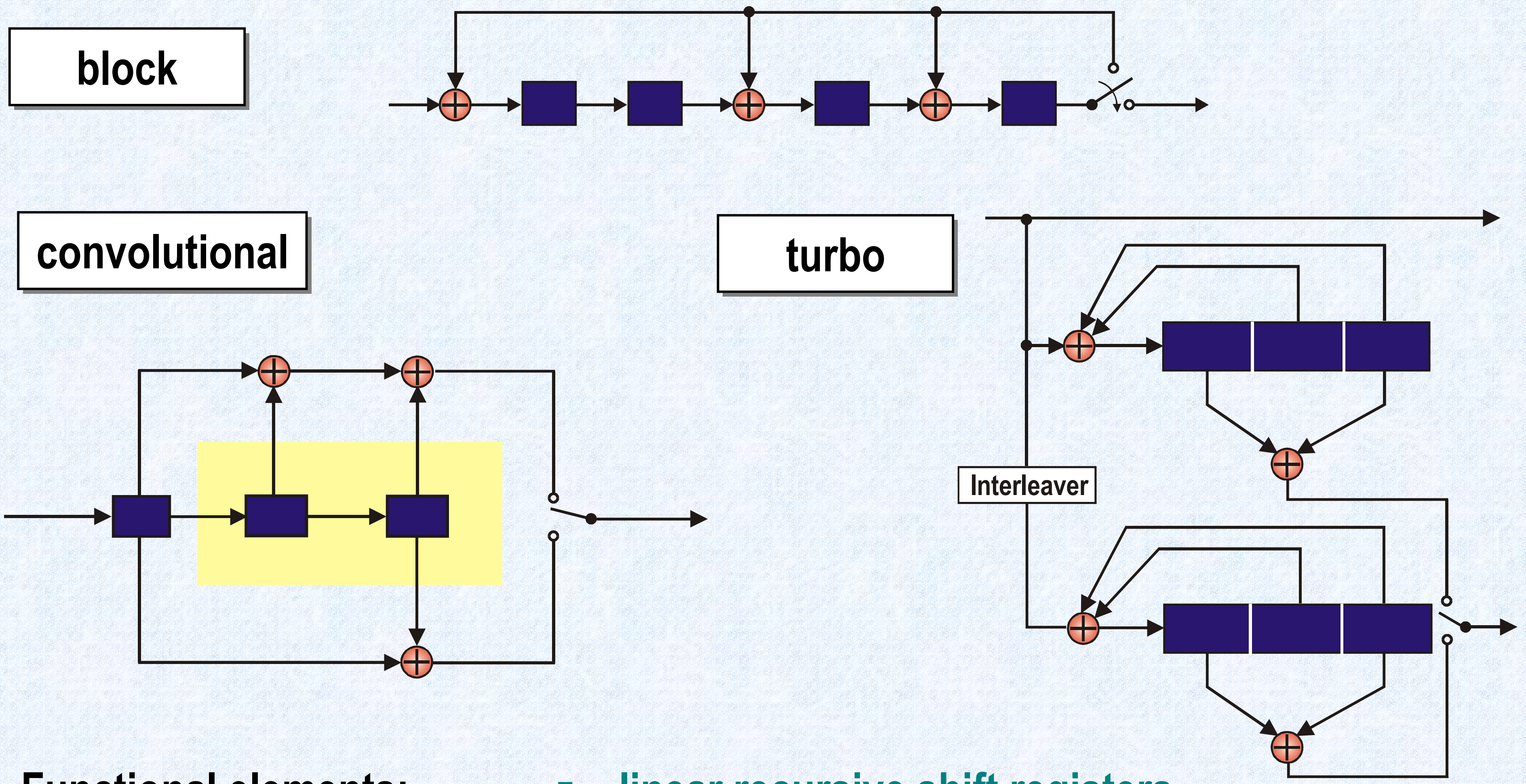
•	0	1
0	0	0
1	0	1

With the addition + and the multiplication • GF(2) = {0; 1} forms are a field.

Most coding schemes are bit oriented, i. e. GF(2) algebra is used.

Generalizations: $GF(2^k)$

ncoders



Functional elements:

- linear recursive shift registers
- interleavers

- **Soft decision TURBO decoder:**

  MAP (log-MAP, MAX-log) Algorithm

- **Soft decision convolutional decoder:**

  Viterbi Algorithm

- **Block decoder**

- **CRC**

pper Layers

Parameter control for SDRs has to be extended to upper layer protocols.

- **Many protocol functions for ISDN subscriber signaling are included in different air interfaces (e.g. DECT, GSM/GPRS, UMTS, HiperLAN/2).**
- **Protocols for user data transport are to a great extent identical and independent of the specific radio standard (c.f. HDLC protocol family).**

Solution:

Development of an adaptive protocol stack utilizing generic layer protocols and standard specific supplements thereof.

pper Layers

- The protocols are formally specified in SDL (Specification and Description Language)
- Realisation of generic C++ classes (as part of the specification) and standard specific classes derived from them (e.g. for GSM, DECT, UMTS etc.)
- Combination of the realized air interfaces, realized by generic protocols, for parameter controlled SDR
- Activation of a specific protocol stack by loading the appertaining parameter set from the local ROM or by download over an air interface

- Mobile Radio Communications
- SDR Signal Processing
- **Mobile Communication Channels**
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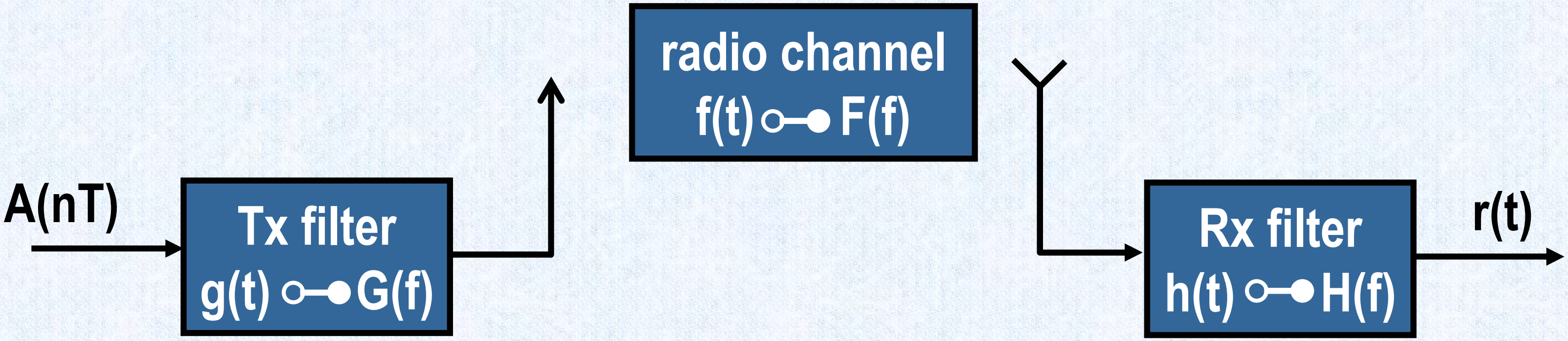
The most important topic in mobile communications is knowledge about the transmission channel.



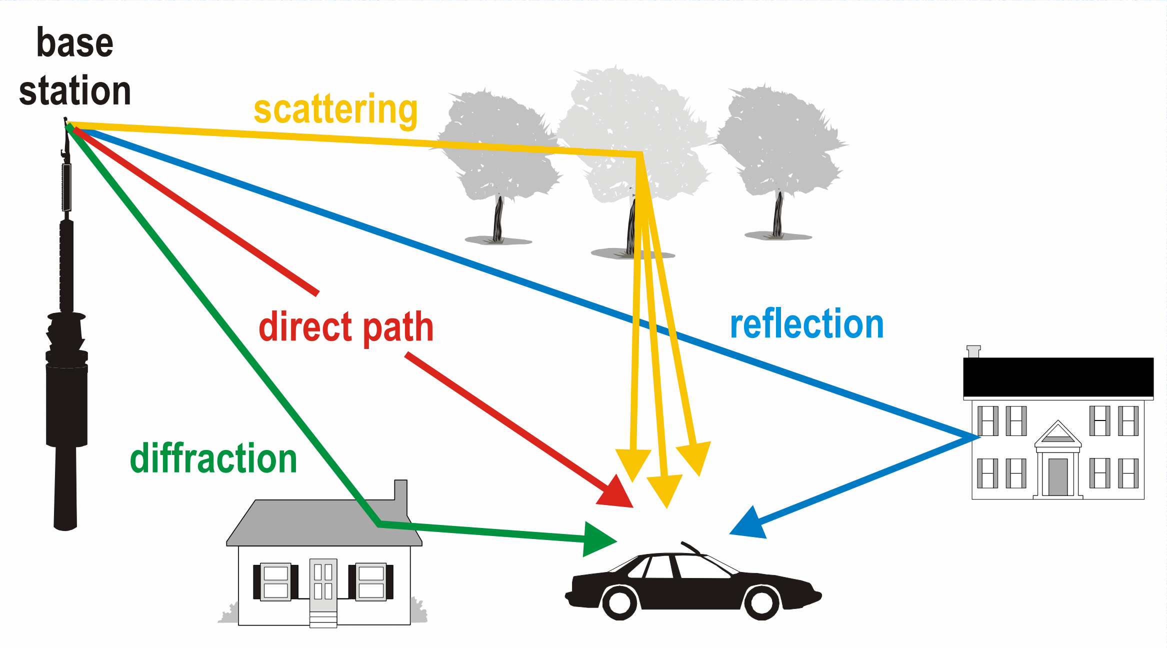
$$k(t) = g(t) * f(t) * h(t) \quad \circ\!\!-\!\!\bullet \quad K(f) = G(f) \cdot F(f) \cdot H(f)$$

$$r(mT) = A(mT) + \underbrace{\sum_{n \neq m} A(nT)\, k((m-n)T)}$$

Inter Symbol Interference (ISI)

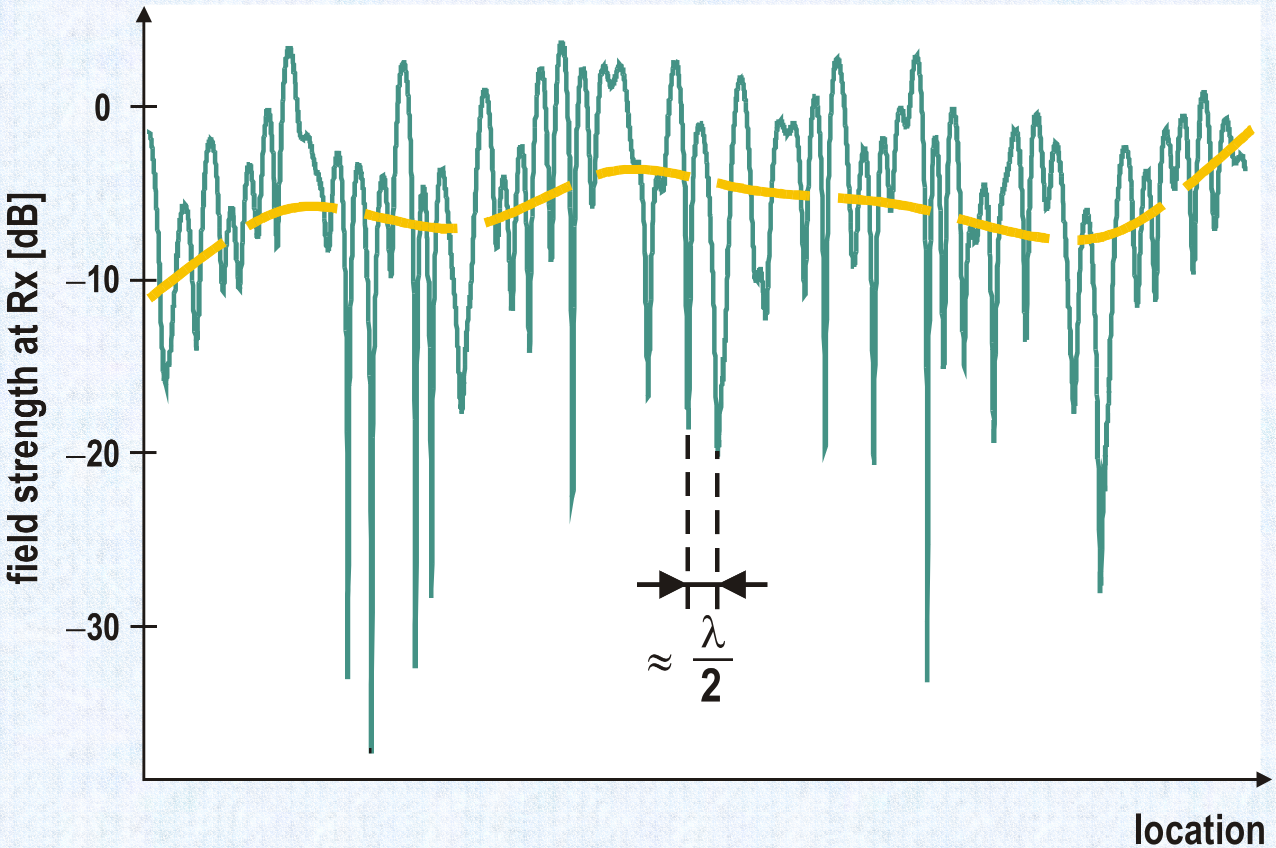
In addition to free space attenuation $L = \left[\frac{4\pi Rf}{c}\right]^2$ several effects have to be considered for mobile communication channels:

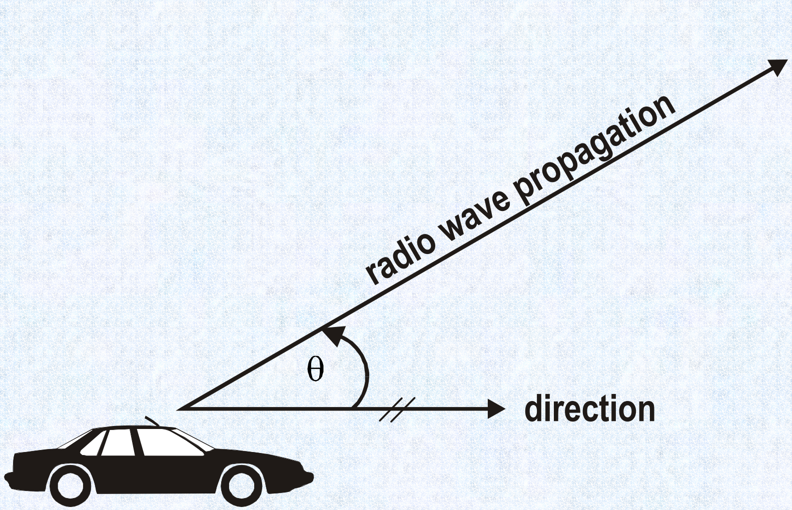
- multipath with diffraction, reflection and scattering
- slow and fast fading
- Doppler shift and Doppler spread
- random noise



Summing up the signal of different paths leads strong variations of the field strength at the receiver, the minima of the field strength are at a distance of about half the wavelength. This effect is called fast fading.

The underlying variation of the field strength's mean value is called slow fading.

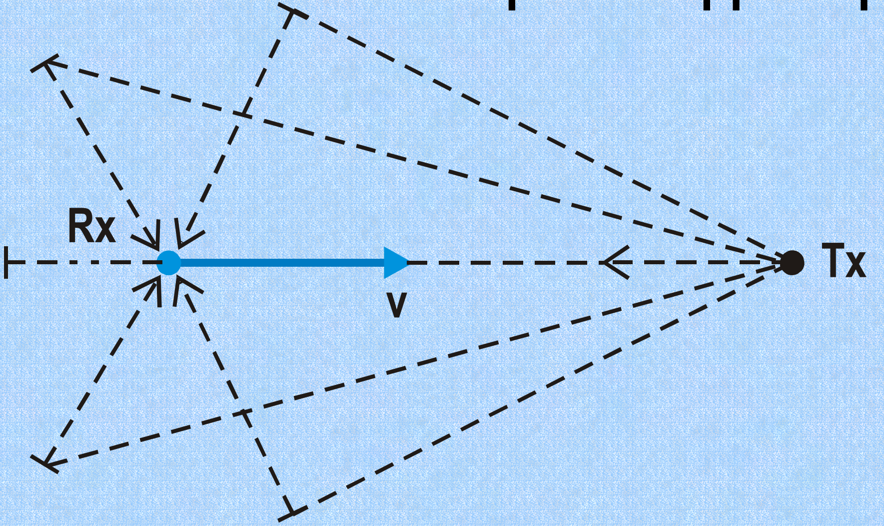




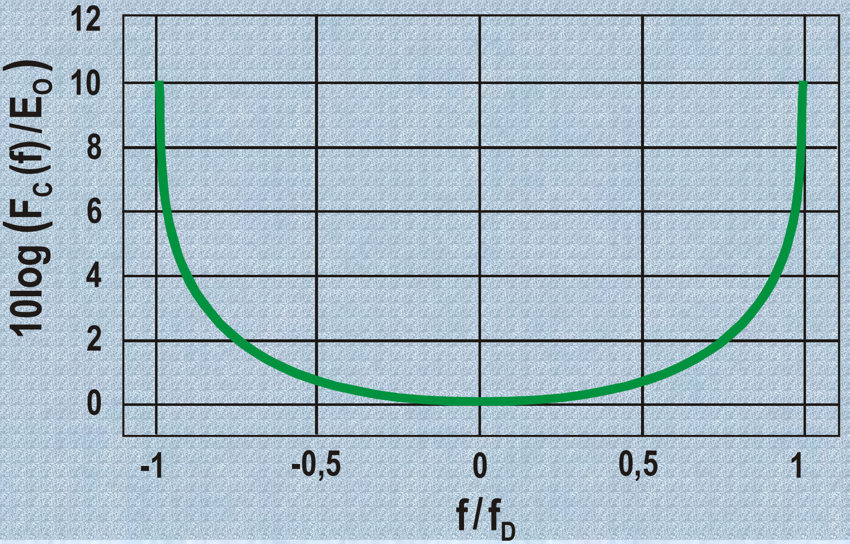
single path: Doppler shift

$$\Delta f_D = \frac{v}{\lambda} \cos \theta$$

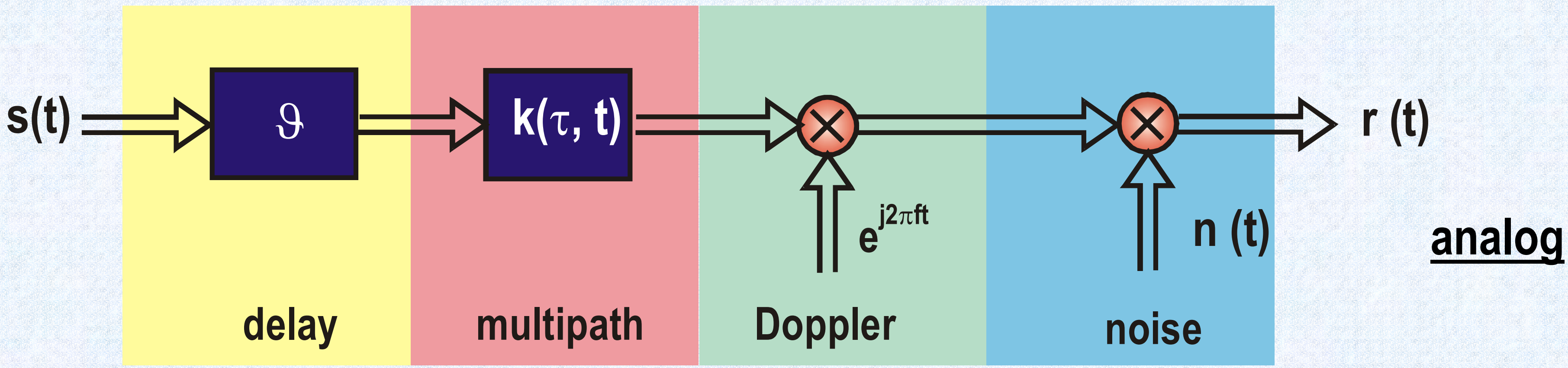
multipath: Doppler spread

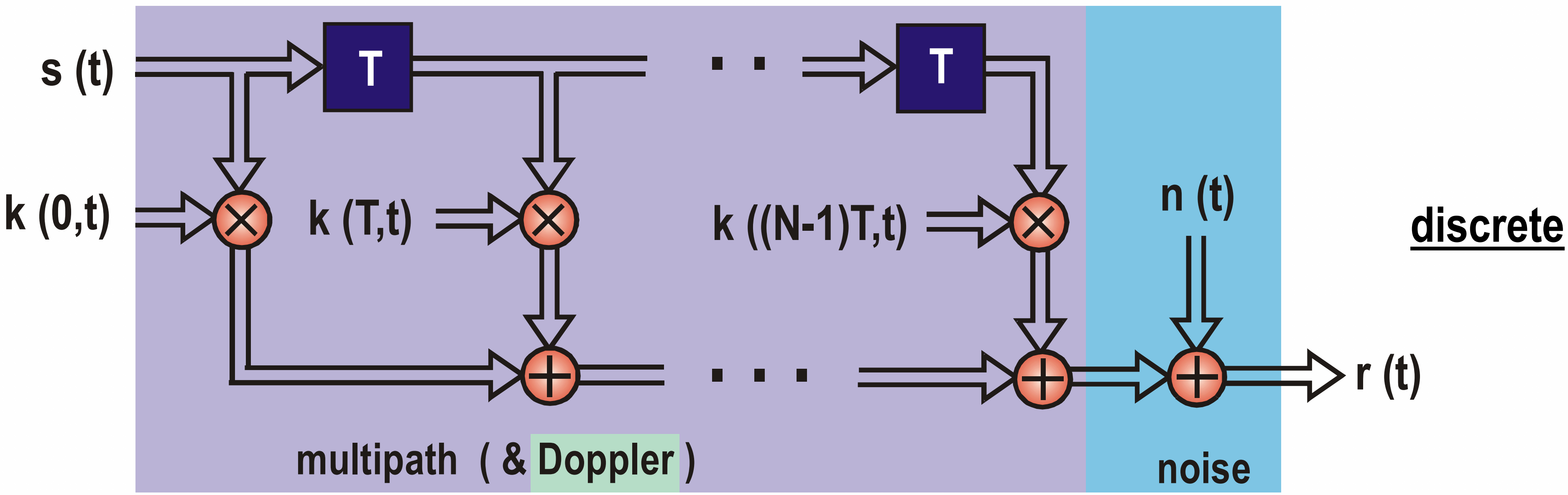


Clarke (Jakes) Spectrum

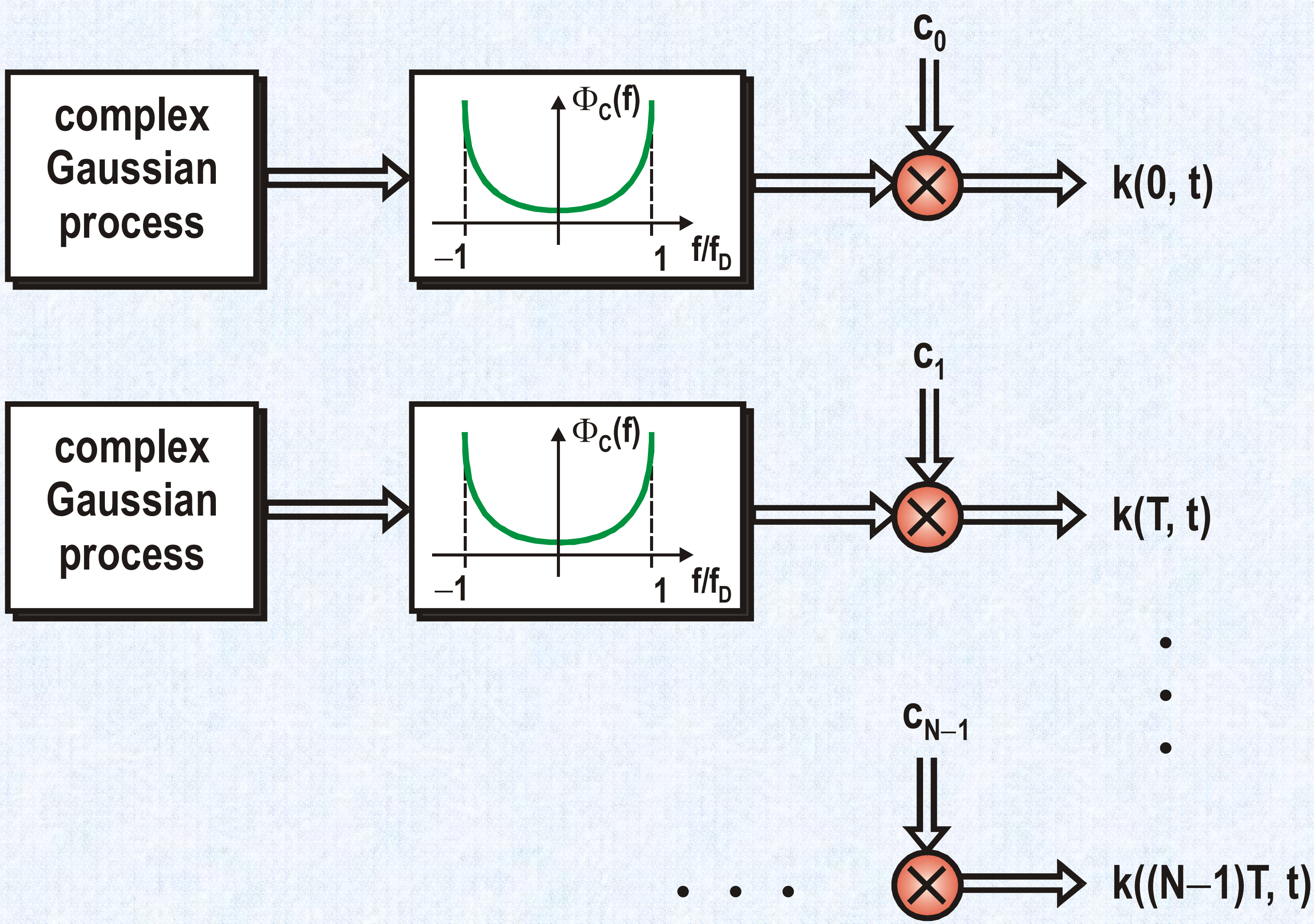


hannel Models



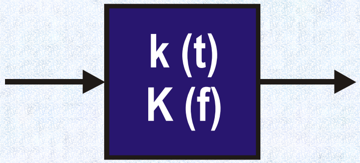


ultipath Coefficients



The principle of channel measurement

white noise: $X(t)$
ACF: $(N_0/2)\, d(t)$
power spectral density: $N_0/2$



output process: $Y(t)$
ACF: $j_{YY}(t)$
power spectral density: $F_{YY}(f)$

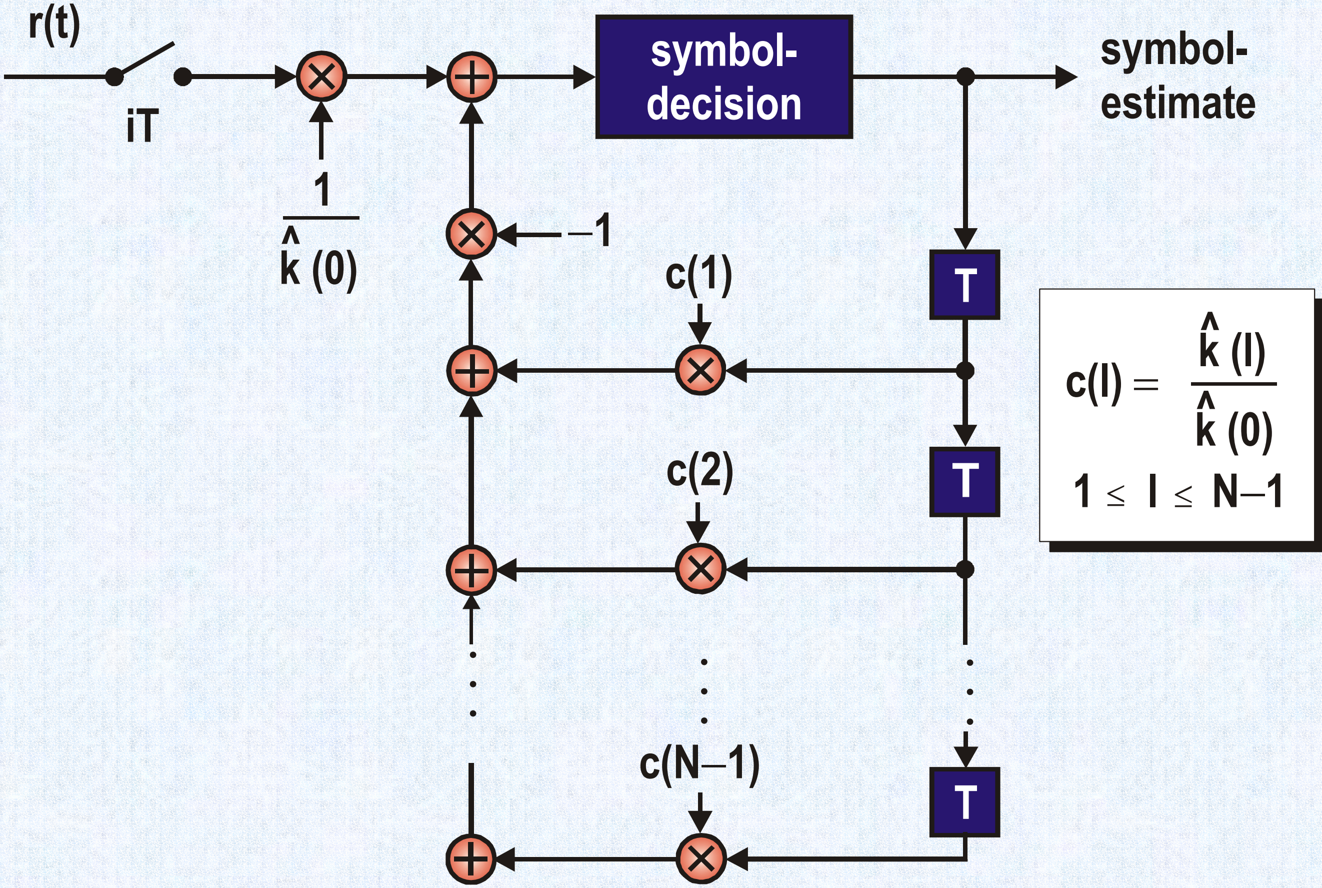
estimation of the cross power spectral density: $\hat{F}_{xy}(f) = \hat{F}_{xx}(f)\, K(f) = \frac{N_0}{2} K(f) \Rightarrow K(f) = \frac{2\hat{F}_{xy}(f)}{N_0}$

The cross correlation function (ccf) is estimated by transmission/reception of a pseudo noise signal:

$$\frac{2}{N_0}\hat{F}_{xy}(f) = \hat{K}(f) \bullet\!\!-\!\!\circ\ \hat{k}(t) = \frac{2}{N_0}\hat{j}_{xy}(t)$$

assum ption : stationarity

The fact that the mobile communication channel is non stationary is taken into account by blockwise transmission and using midambles.



The decision feedback equalizer tries to remove the effects of multi-paths on the received signal r(t).

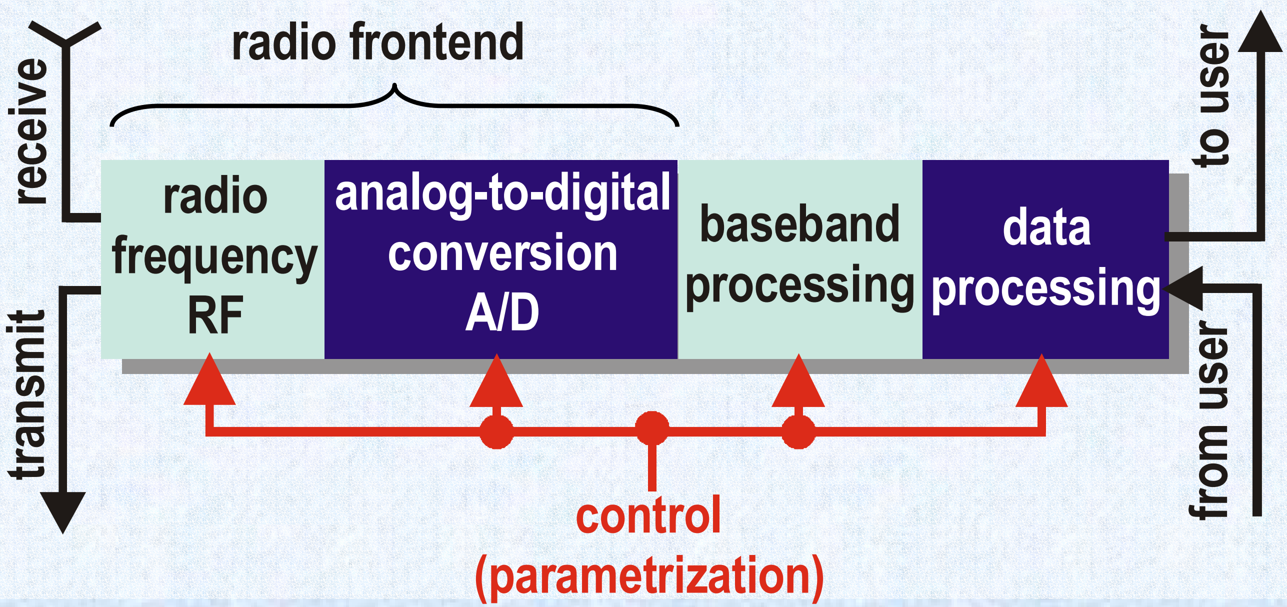
- Mobile Radio Communications
- SDR Signal Processing
- Mobile Communication Channels
- **Parameter Controlled SDR**
- Spectrum Pooling
- Modular SDR

Digital Radio (DR): The baseband signal processing is invariably implemented on a DSP.

Software Radio (SR): An ideal SR directly samples the antenna output.

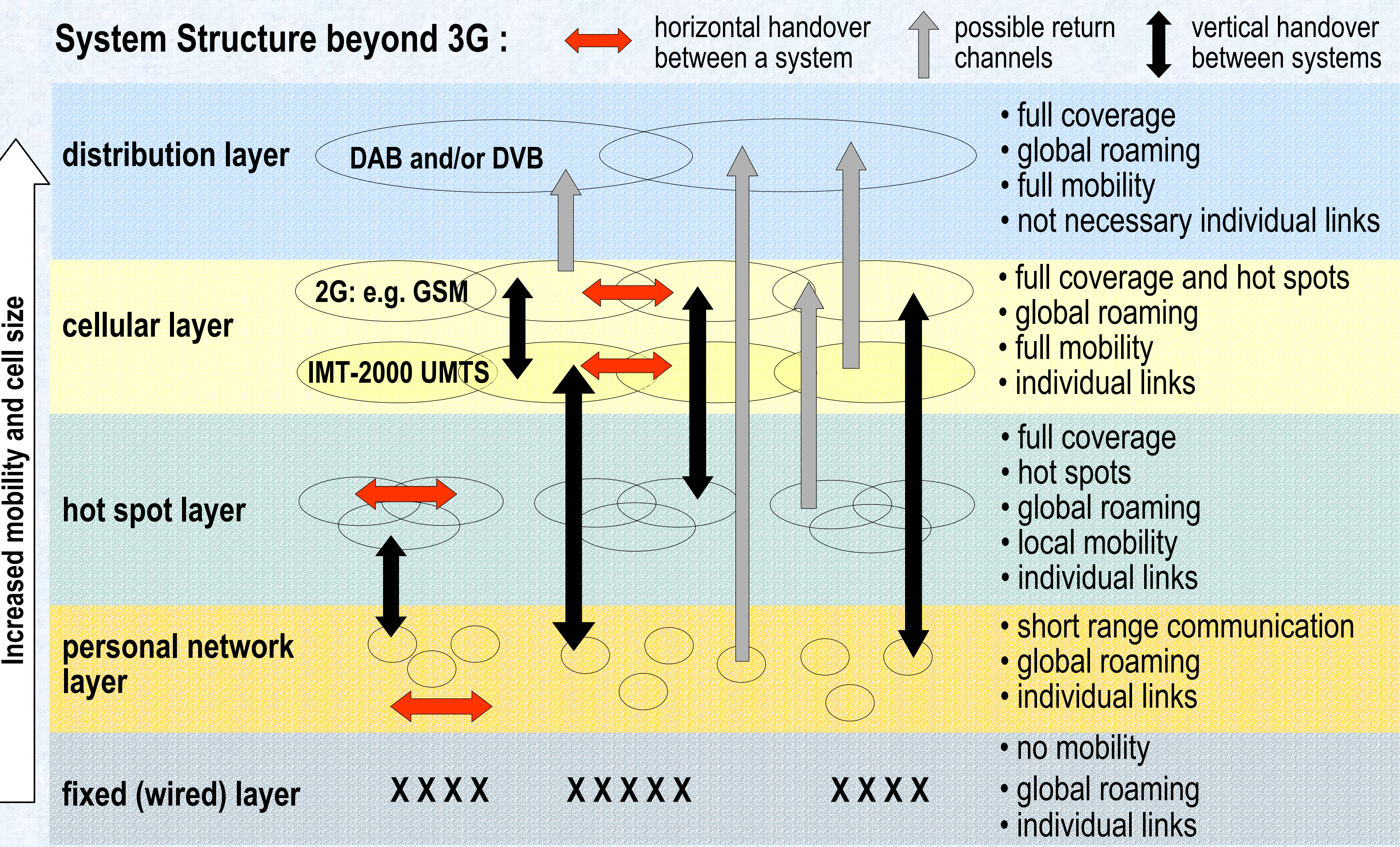
Software Defined Radio (SDR): An SDR is a presently realizable version of an SR: Signals are sampled after a suitable band selection filter.

Cognitive Radio (CR): A CR combines an SR with a PDA and connects its owner to INs.



1) According to J. Mitola, 200

ʰ Generation Network?



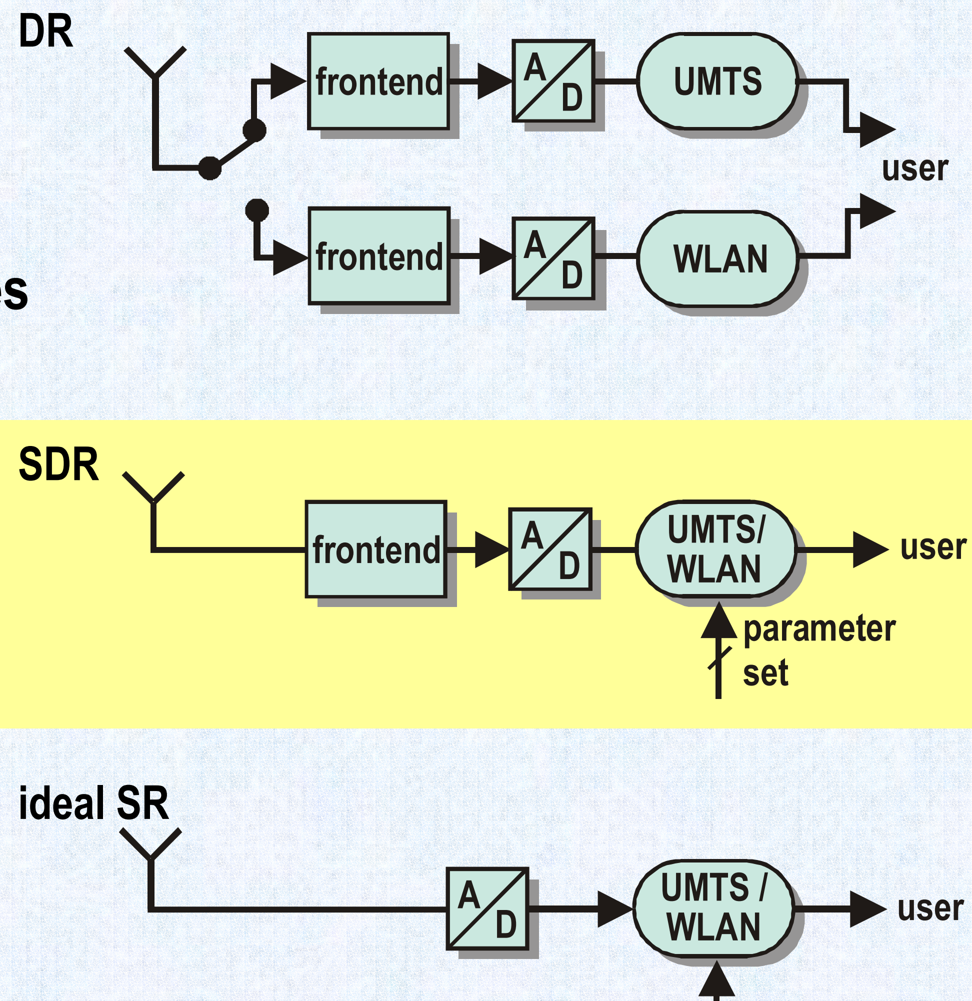
G / WLAN Multi Mode Receivers

UMTS:

- ➡ licensed frequency band
- ➡ third generation standard
- ➡ suited for outdoor and higher velocities
- ➡ moderate data rates

WLAN (e.g. HiperLAN/2, IEEE 802.11a):

- ➡ ISM band
- ➡ small providers
- ➡ mainly developed for indoor
- ➡ well suited for hot spot coverage
- ➡ stationary terminals
- ➡ high data rates



UMTS / WLAN multi mode receivers

LAN/UMTS Application

INT

Notebook University Karlsruhe (TH) (NUKATH)

With their notebook computers students use a IEEE 802.11a connection to the university's while being present at the campus, in busses, streetcars, or at home they are connected via UTRA-FDD.

- **The project is funded by the German Ministry of Research and Technology and sponsored by industry**
- **The Departments of Computer Science, of Electrical Engineering and Information Technology, of Architecture, and of Social Sciences are carrying out the project**
- **The Communications Engineering Lab is responsible for the transmission technology that is based on a UMTS/WLAN PaC-SDR**
- **A "field trial" with 20 students took place during the summer 2003**

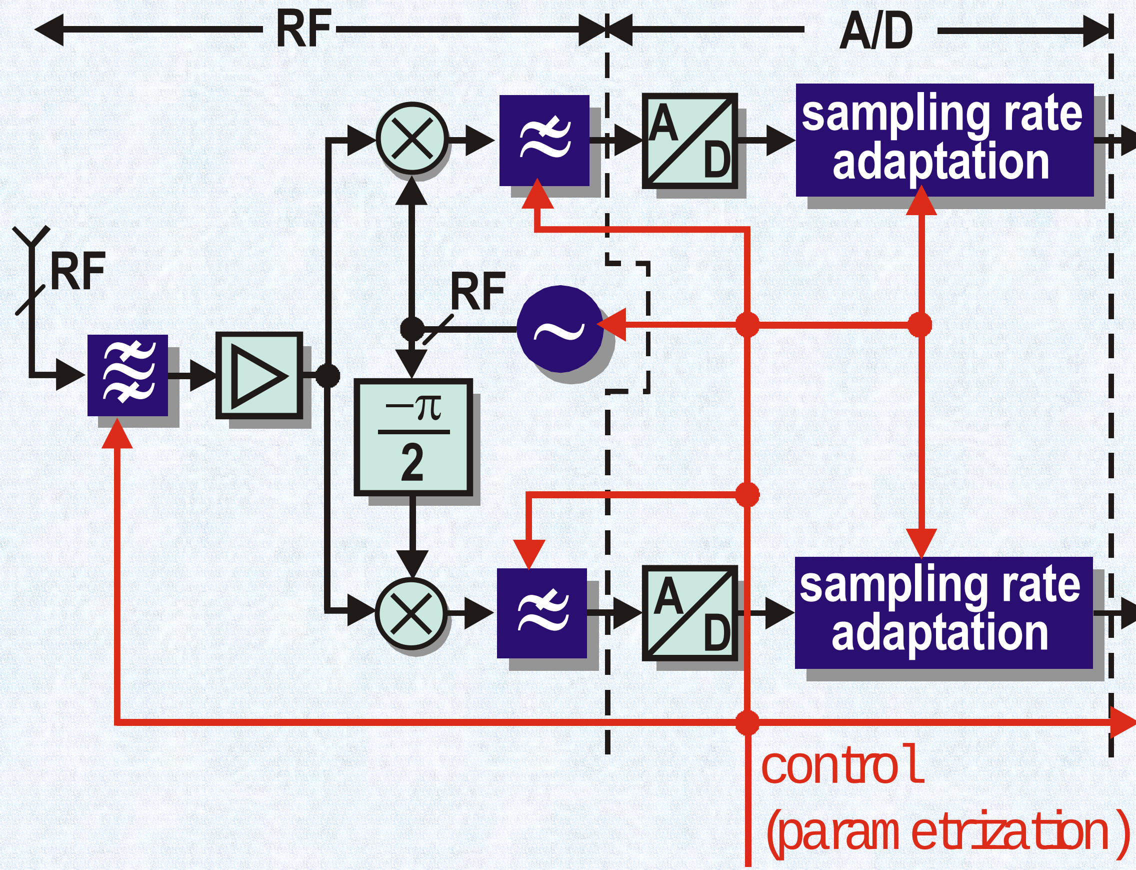
ellular Air Interfaces

	GSM	IS-136	UTRA-FDD
channel spacing	200 kHz	30 kHz	5 MHz
access mode	FDMA/TDMA	FDMA/TDMA	Direct Sequence (DS), CDMA
duplex mode	FDD/TDD	FDD/TDD	FDD
users per carrier frequency	8	3	depends on the situation
net data rate	13 kbit/s	7.95 kbit/s	8 kbit/s to 2 Mbit/s
modulation mode	GMSK	π/ 4 - DQPSK	QPSK
channel coding	CRC, convolutional	CRC, convolutional	convolutional, turbo, CRC with interleaving
symbol duration	3.692 μs	41.14 μs	depends on the spreading factor
bits per burst (slot)	156.25	324	depends on the spreading factor
burst (slot) duration	0.577 ms	6.67 ms	0.677 ms
frame duration	4.62 ms	40 ms	10 ms
channel bit rate	270.833 kbit/s	48.6 kbit/s	depends on the situation
maximum cell radius	35 km	20 km	few kilometers
user specific signatures	-	-	OVFS codes
spreading factor	1	1	2^k; k=2, 3, ... 8; 512 downlink only
chip rate	-	-	3.84 Mchip/s

Conversion of the antenna signal to the complex baseband

Candidates:

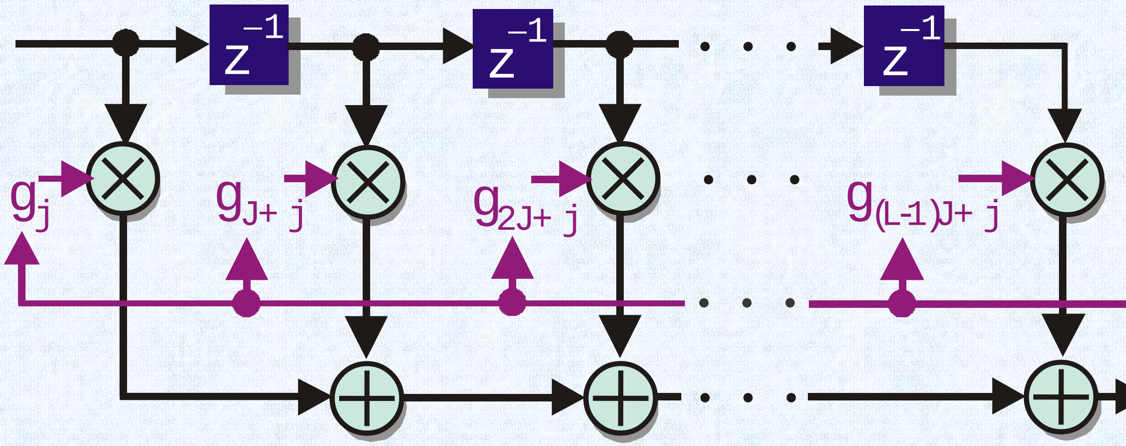
- ➡ superhet
- ➡ superhet combined with bandpass subsampling
- ➡ low IF
- ➡ zero IF



Zero IF receiver : RF and A/D units

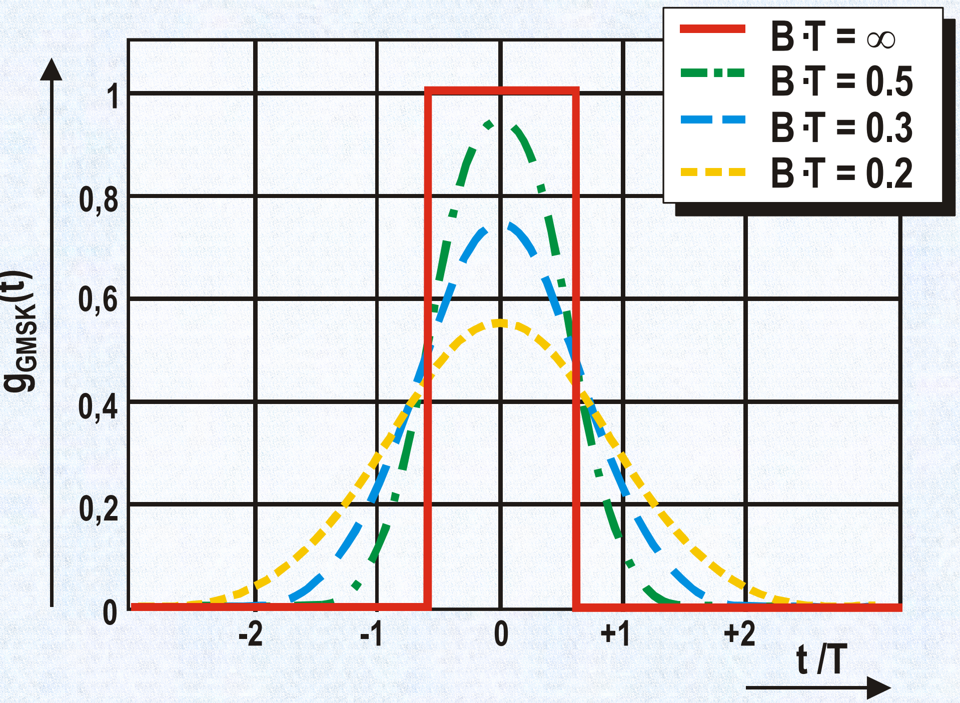
INT

- The signal processor should work at the minimum possible rate.
  - ➡ Samples must be taken at the instant of the eye pattern maximum

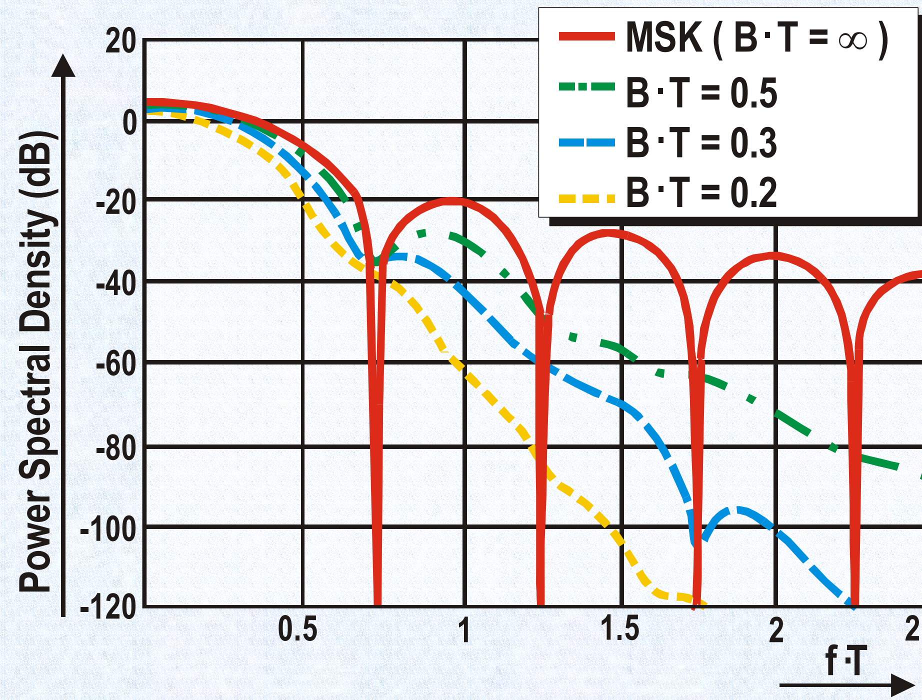


- Sampling rate adaptation can be implemented by a polyphase filter. Its coefficients may be stored or computed „just in time“ (Hentschel, Fettweis 2000).

Gaussian impuls formers



PSDs of GMSK signals



Decreasing B•T leads to longer pulses (increased ISI) and narrower spectra.

MBIT2Symbol:

Modulation Mode	*ModulationNumber*
GMSK	1
$\pi/4$-DQPSK	2
QPSK	3
dual QPSK	4

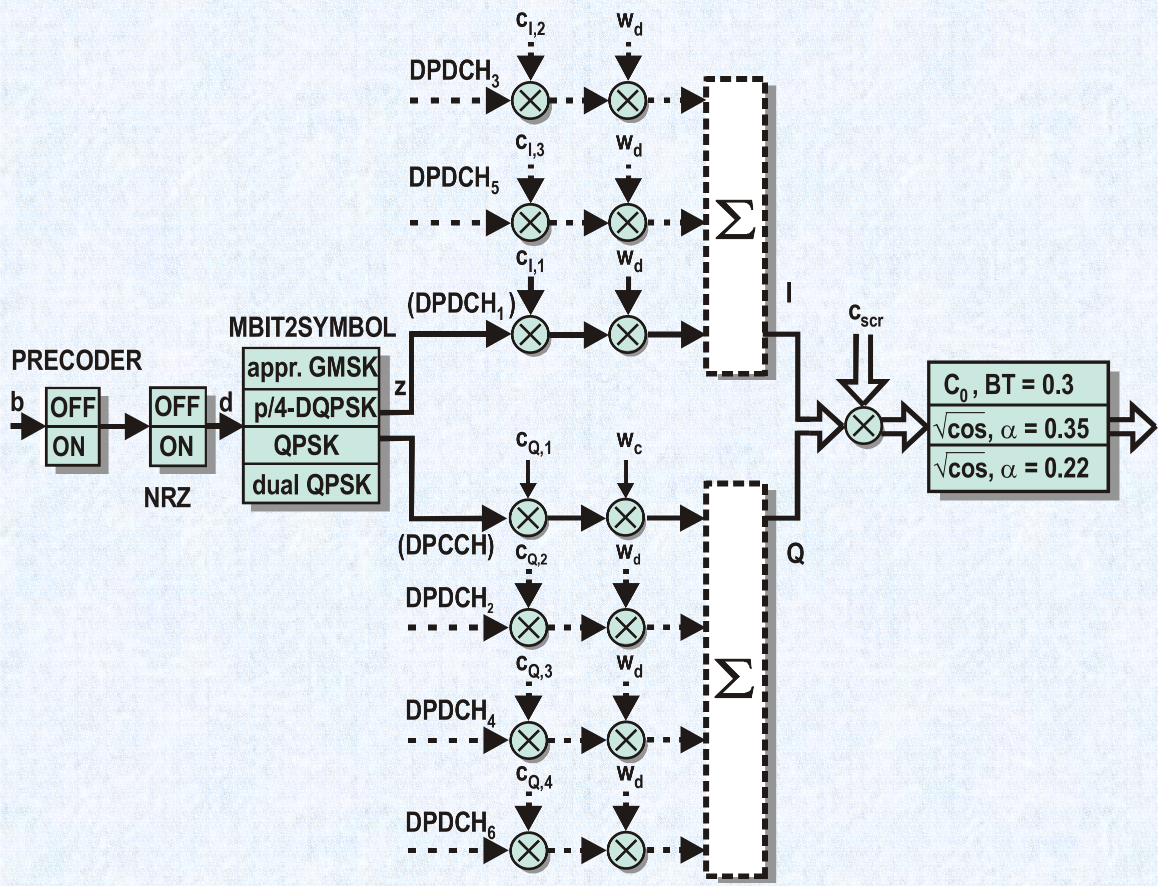
Impulse formers:

Filter	*Filter-Number*
main impuls $C_o(t)$ of linearized GMSK with BT = 0.3	1
root raised cosine roll-off filter with roll-off factor α = 0.35	2
root raised cosine roll-off filter with roll-off factor α = 0.22	3

Parametrization

Parameter	GSM	IS-136	UTRA-FDD
Burst Length	148	312	330
Precoder_On_Off	1	0	0
NRZ_On_Off	1	1	-1
ModulationNumber	1	2	4
Spreadingfactor_I	1	1	8
Spreadingfactor_Q	1	1	256
Filter_Number	1	2	3
I_Length	-	-	320
Q_Length	-	-	10

Structure



GMSK signal

$$S_{GMSK}(t) = A \exp\left\{ j\,2\pi h \sum_{n=0}^{\infty} \int_{-\infty}^{t} d(nT)\, g(\tau - nT)\, d\tau \right\}$$

Laurent 1986

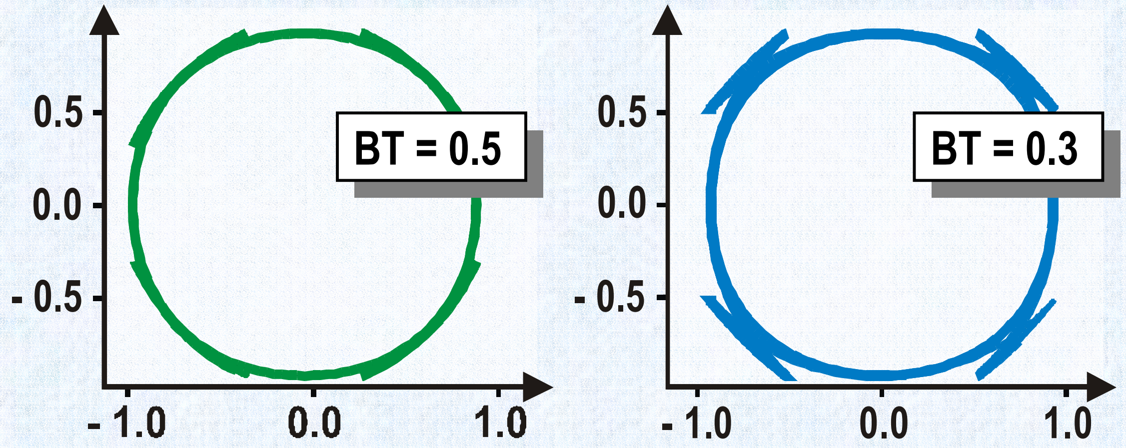
$$S_{GMSK}(t) = A \sum_{n=0}^{\infty} \sum_{k=0}^{N-1} \exp\left\{ j\pi h B_{k,n} \right\} C_k(t - nT)$$

Linearization

$$S_{GMSK}(t) \approx A \sum_{n=0}^{\infty} \exp\left\{ j\pi h \sum_{i=0}^{n} d(iT) \right\} C_0(t - nT)$$

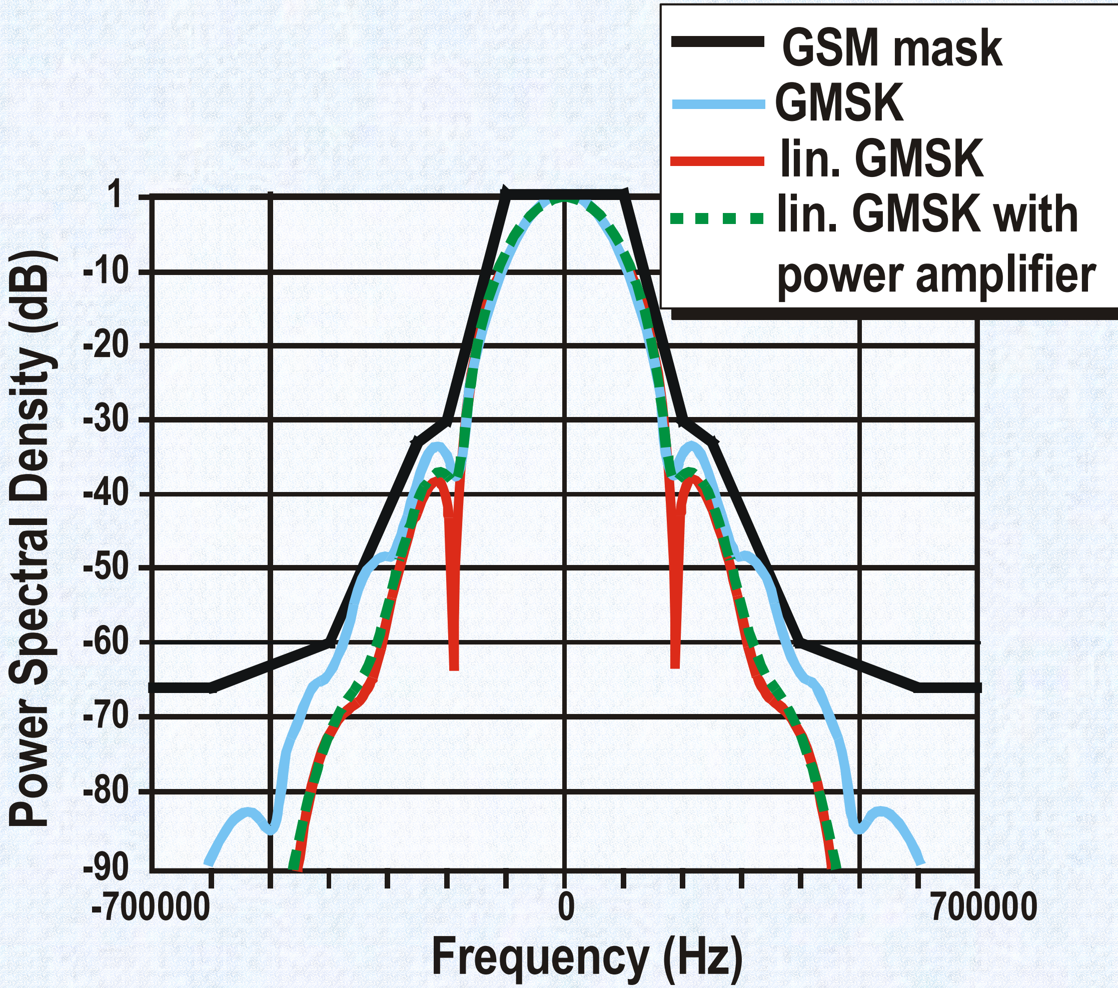
$$= A \sum_{n=0}^{\infty} z(nT)\, C_0(t - nT)$$

Complex envelope of linearized GMSK signals



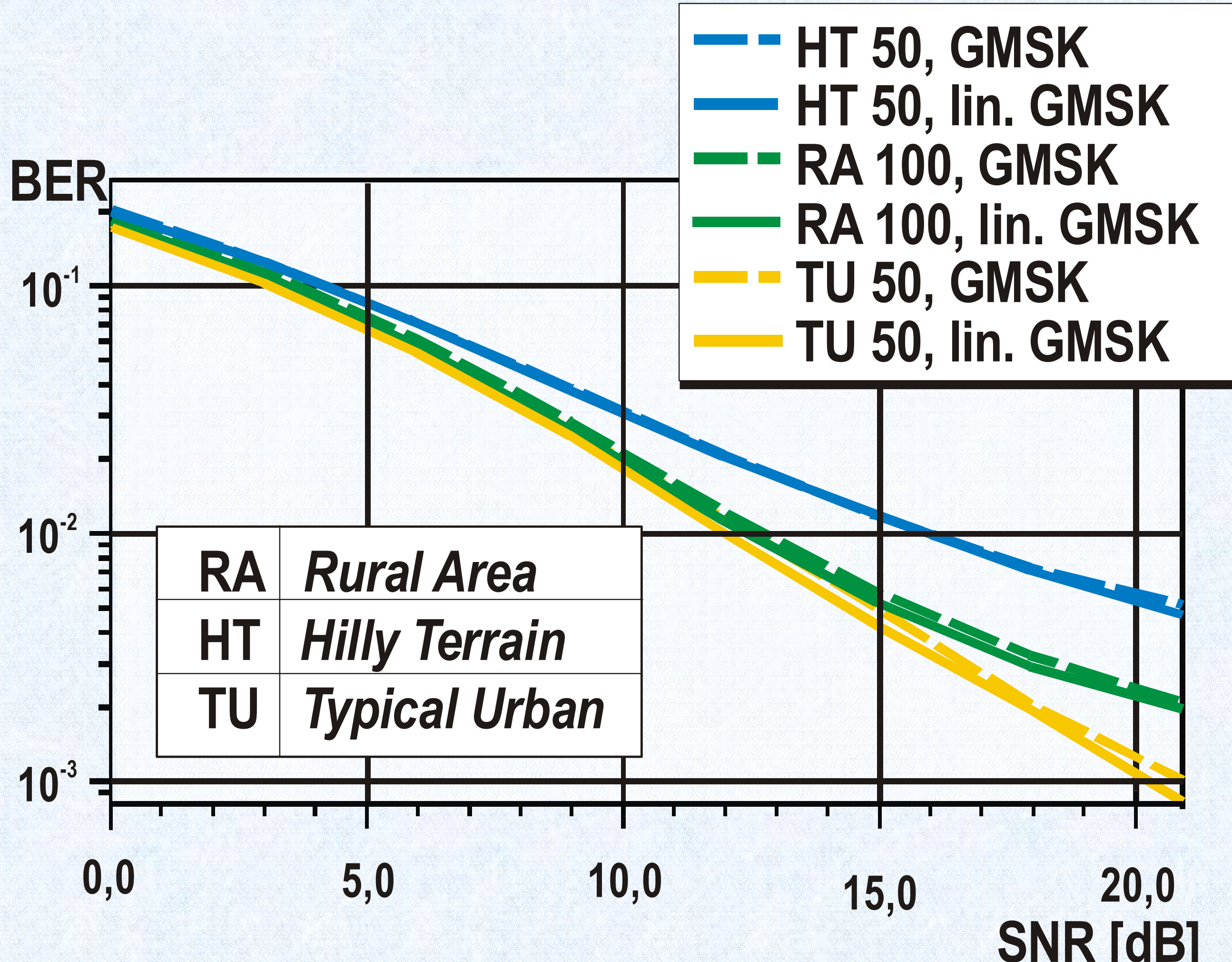
...ower Spectral Densities

The PSD of a linearized GMSK signal still meets the GSM spectrum mask, even if it is power amplified.

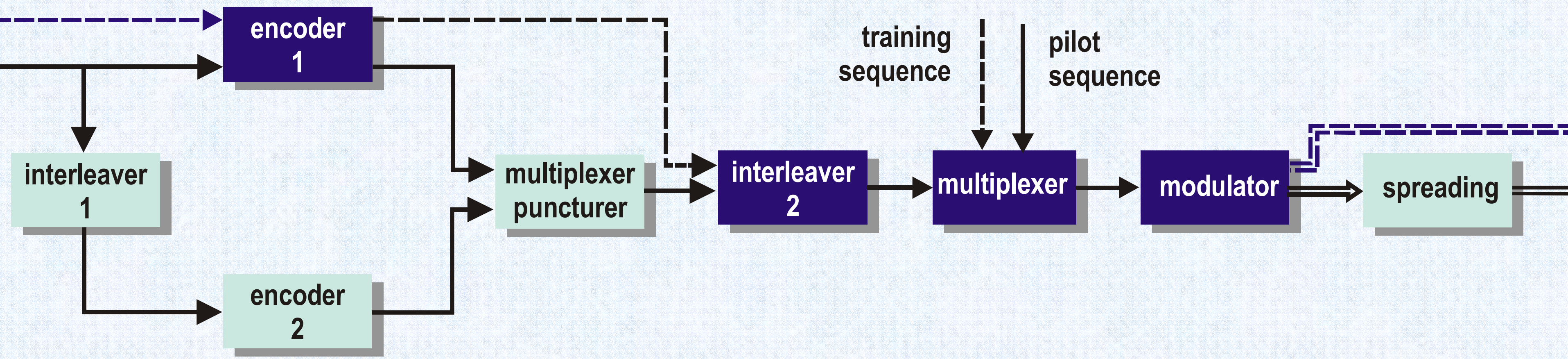


PSDs, linearized vs. „pure“ GMSK

GMSK linearization does not affect the bit error rate (compared to „pure“ GMSK) in simulations.

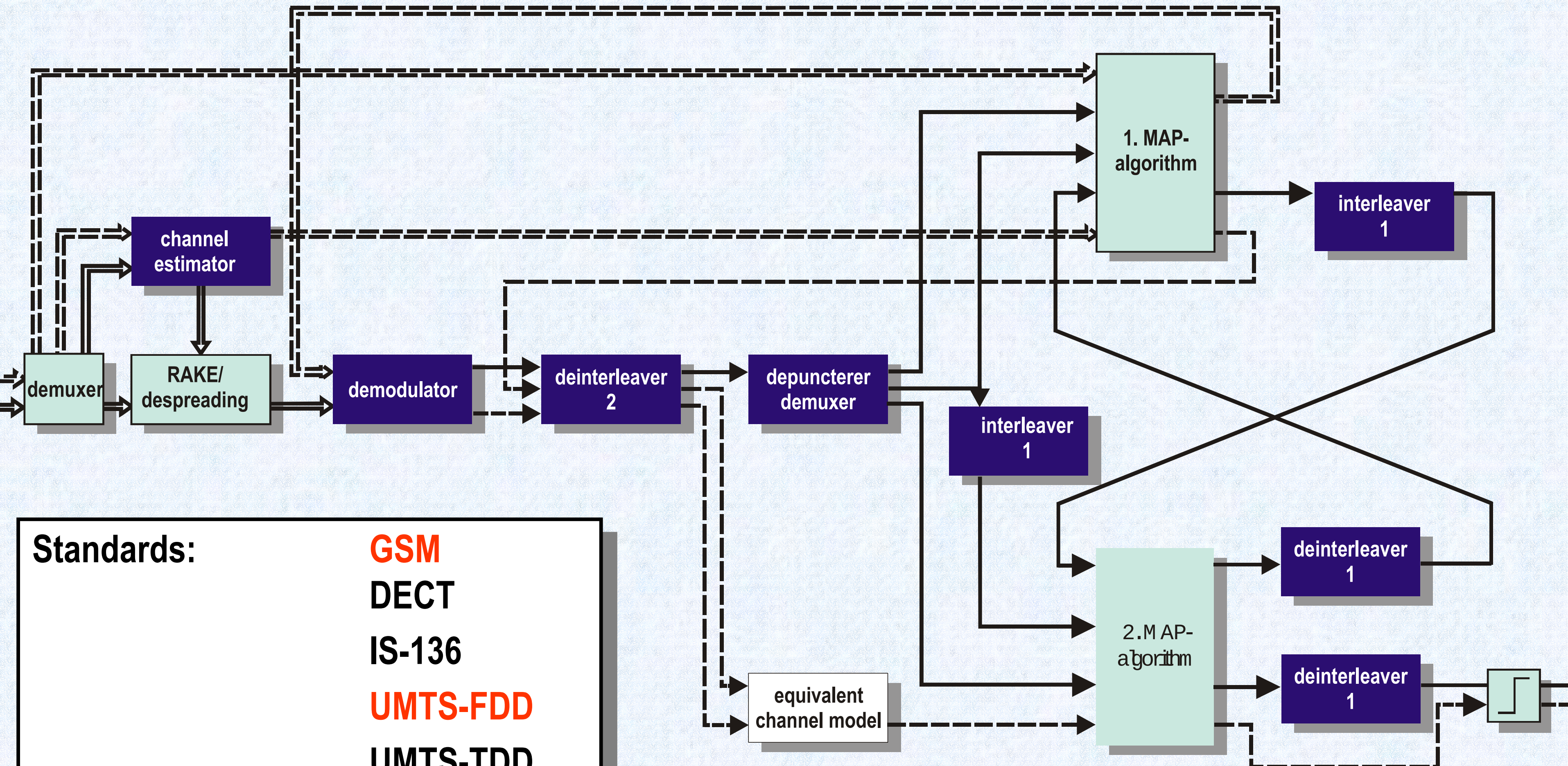


eneral Transmitter Structure



Standards: GSM
DECT
IS-136
UMTS-FDD
UMTS-TDD
cdma2000

eneral Receiver Structure



Standards:

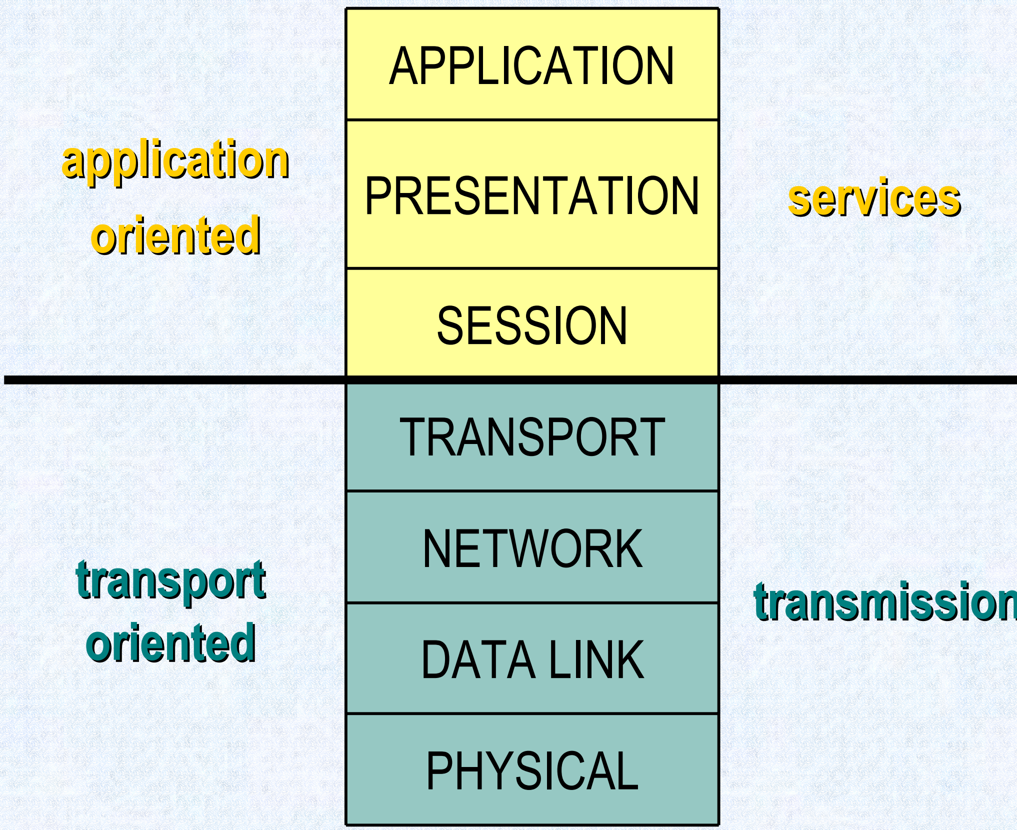
- GSM
- DECT
- IS-136
- UMTS-FDD
- UMTS-TDD
- cdma2000

IT Software Radio Projects

	Parameter Controlled Software Radios	*Adaptive Terminal*	*UMTSPlus*	*MMR-ADM*	*RMS*
DECT					
GSM					
GPRS					
EDGE					
IS-54 / IS-136					
PDC					
IS-95					
TETRA					
TETRAPOL					
DVB-T					
cdma2000					
UMTS					
IEEE 802.11a					

onclusions

- SDR shows a plethora of facets
- Many research projects are under way
- First SDR products seem to appear on the market
- SDR leads to completely new solutions in mobile communications
- The 6. EU framework program supports several SDR projects
- SDR projects, that pick up the view over all transmission layers, are needed

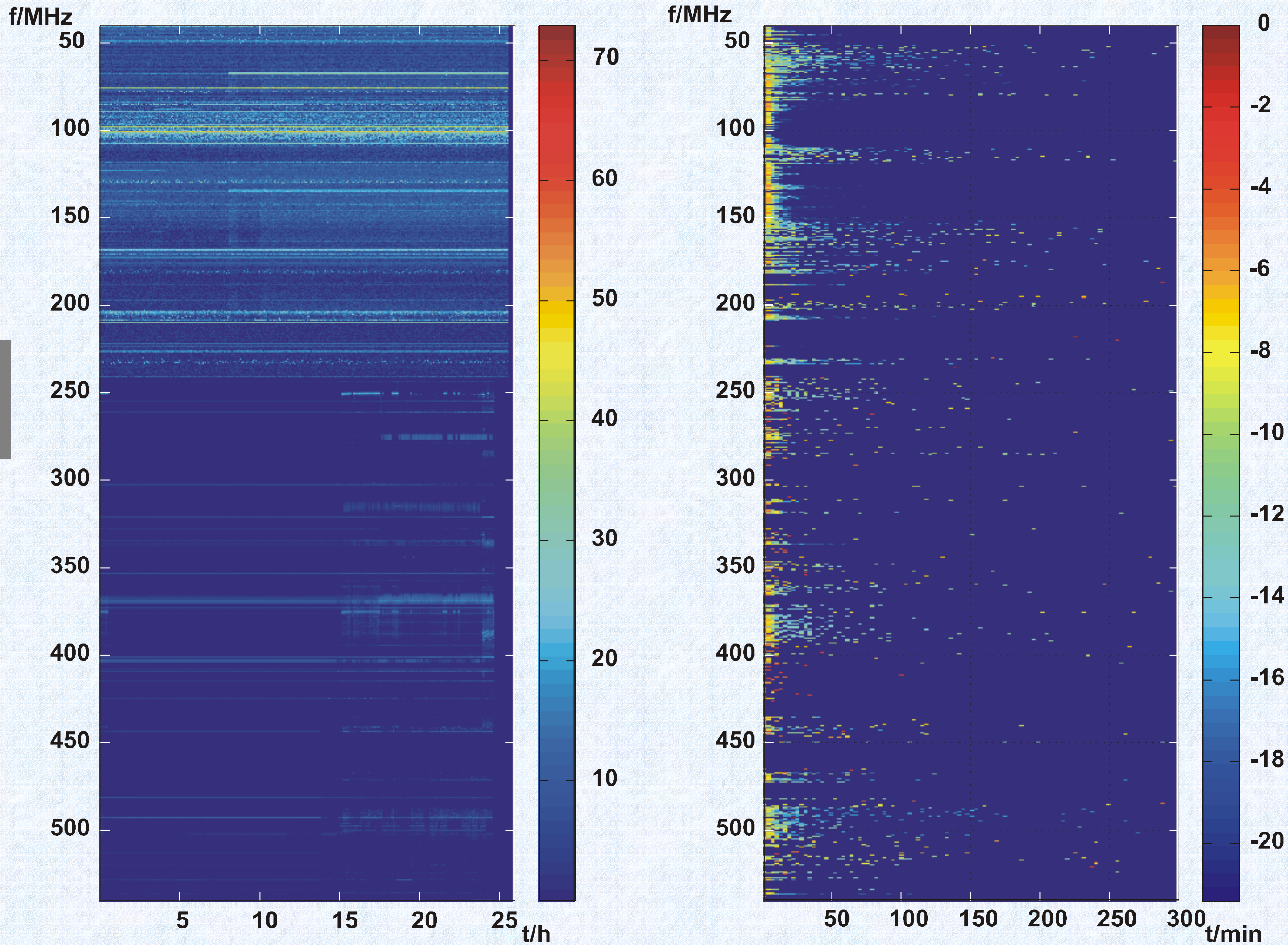


opics

- Mobile Radio Communications
- SDR Signal Processing
- Mobile Communication Channels
- Parameter Controlled SDR
- **Spectrum Pooling**
- Modular SDR

pectrum Utilization Measurements (50-550 MHz)

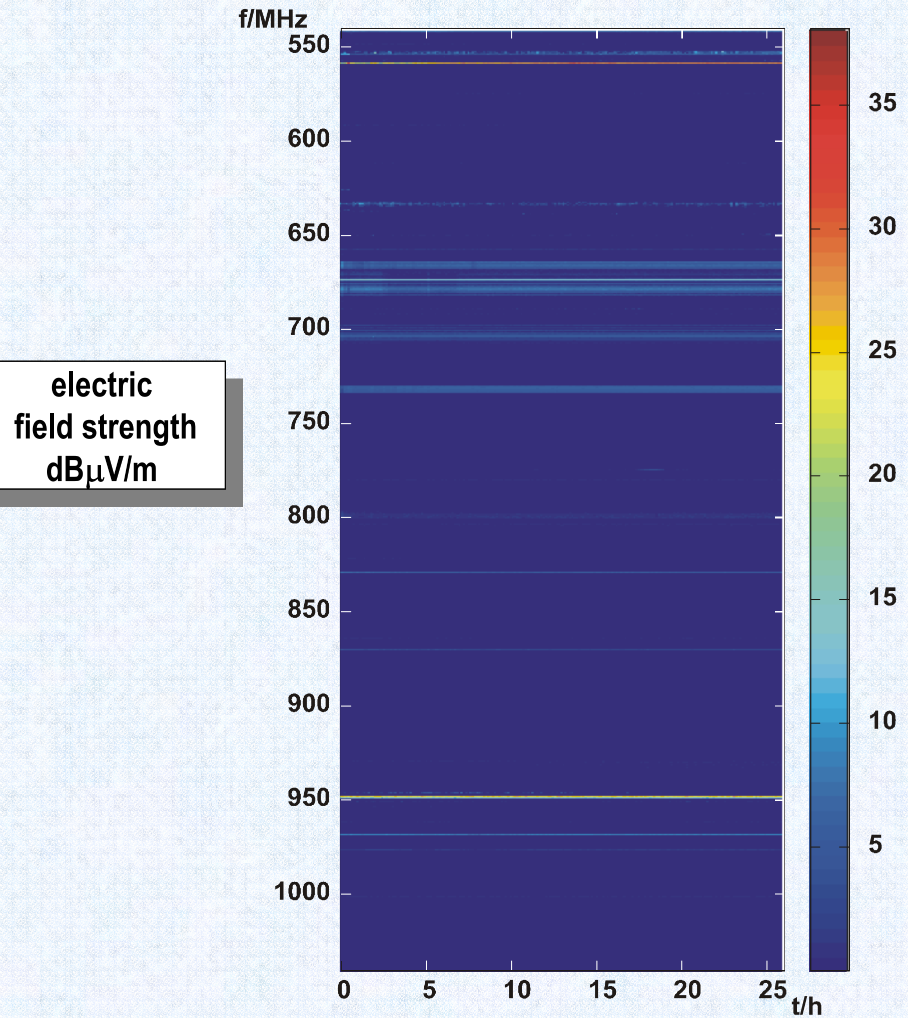
electric field strength dBμV/m

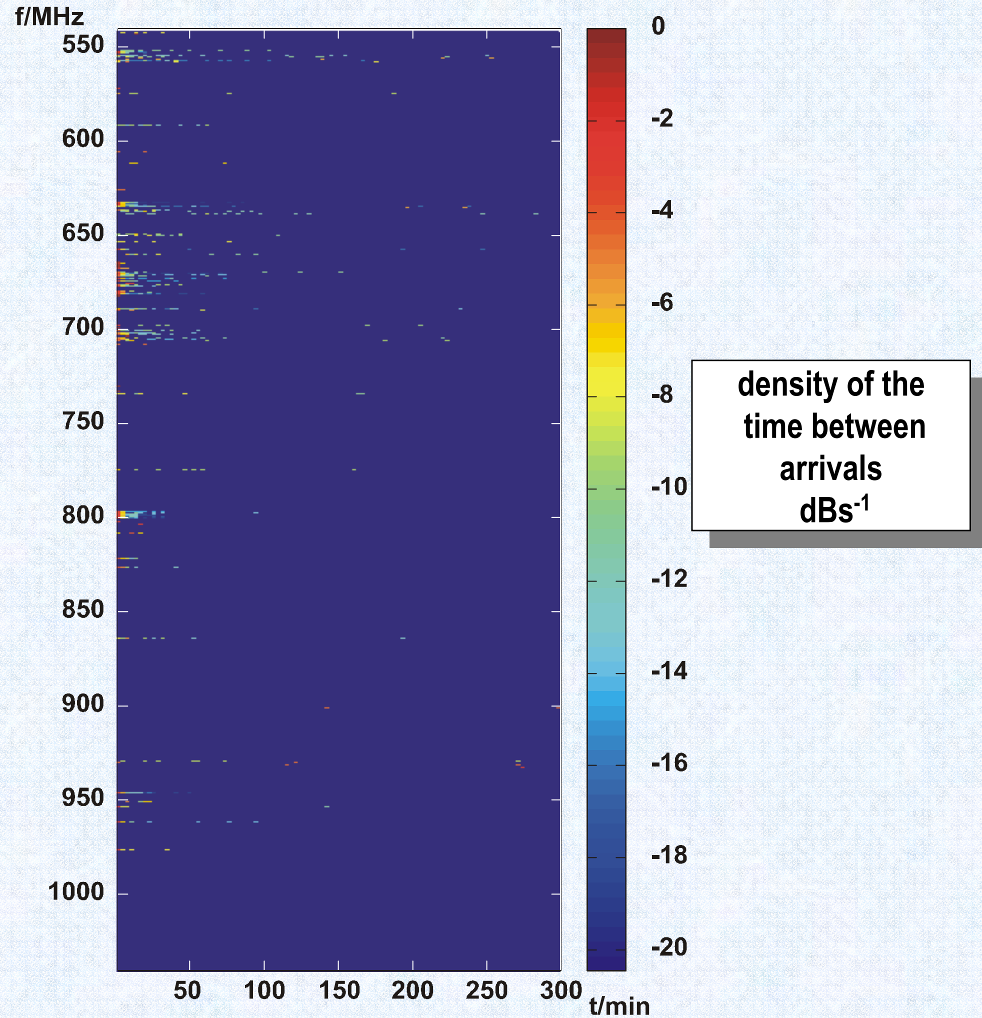


density of the time between arrivals dBs^{-1}

Lichtenau (Germany), September 2001

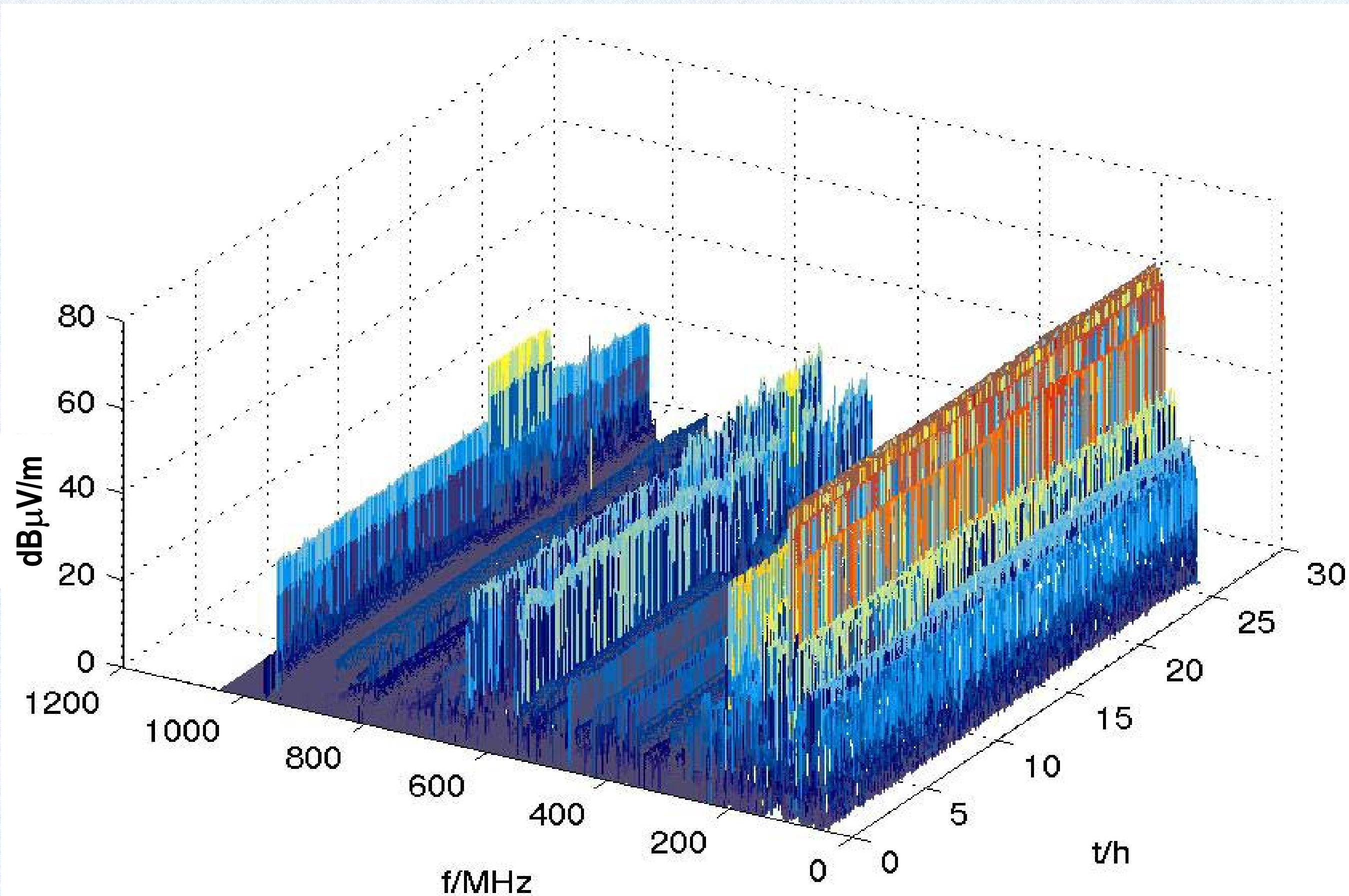
pectrum Utilization Measurements (550-1000MHz)





Lichtenau (Germany), September 2001

pectrum Utilization (50 MHz-1GHz)



Lichtenau (Germany), September 2001

ynopsis

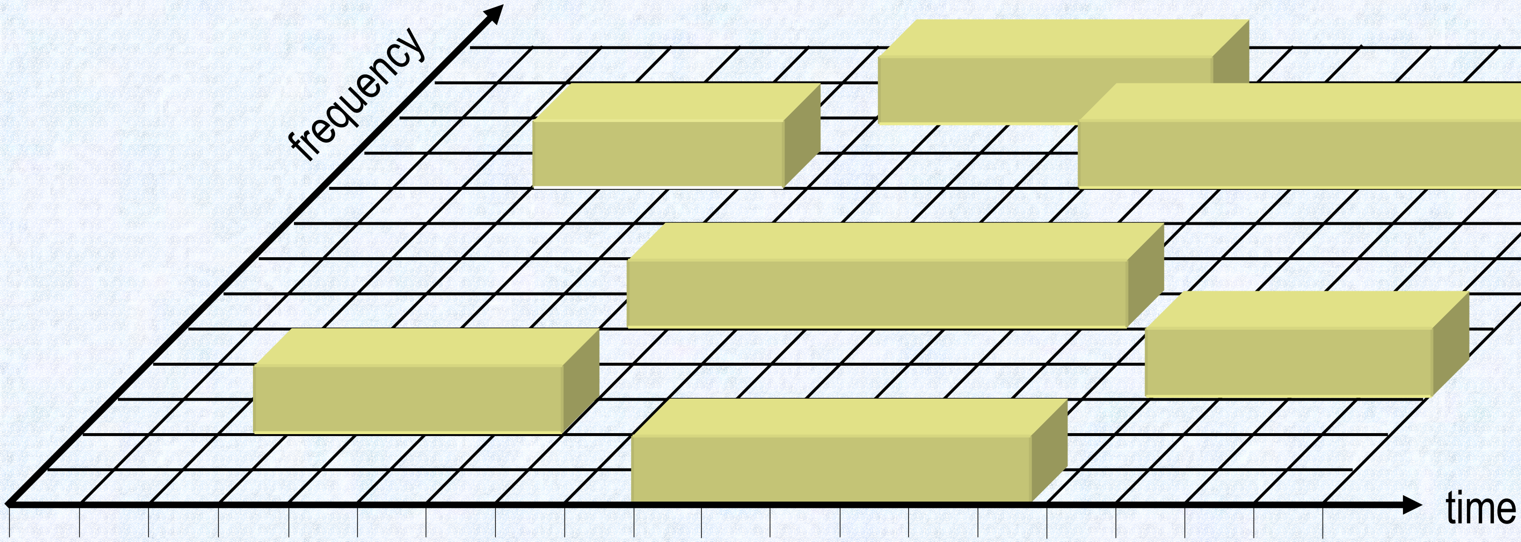
- Spectrum Pooling
- HIPERLAN/2 System Overview
- The Licensed User (LU) System
- Physical Layer Issues
- Detection and Signaling
- Summary and Outlook

Spectrum Pooling

Vision:

Usage of free capacities in licensed frequency bands:

Licensed Users **(LUs) lease out spectrum to** ***Rental Users*** **(RUs)**

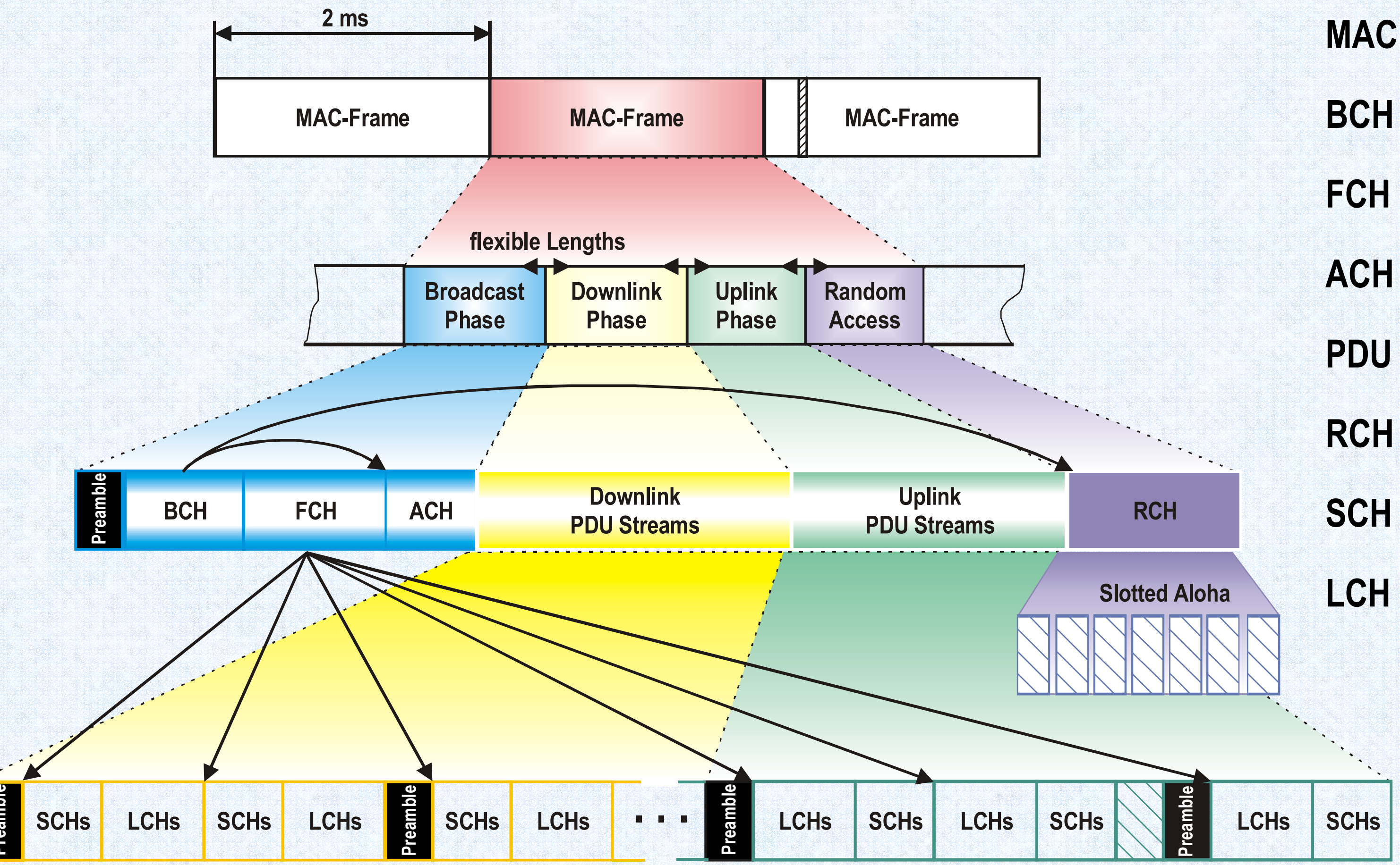


FDMA / TDMA LU system and HIPERLAN/2 RU system:

Two different radio systems → Coexistence in the same frequency region ?!

IPERLAN/2 System Overview

- European Wireless Local Area Network Standard



MAC *Medium Access Control*

BCH *Broadcast CHannel*

FCH *Frame CHannel*

ACH *Access feedback CHannel*

PDU *Protocol Data Unit*

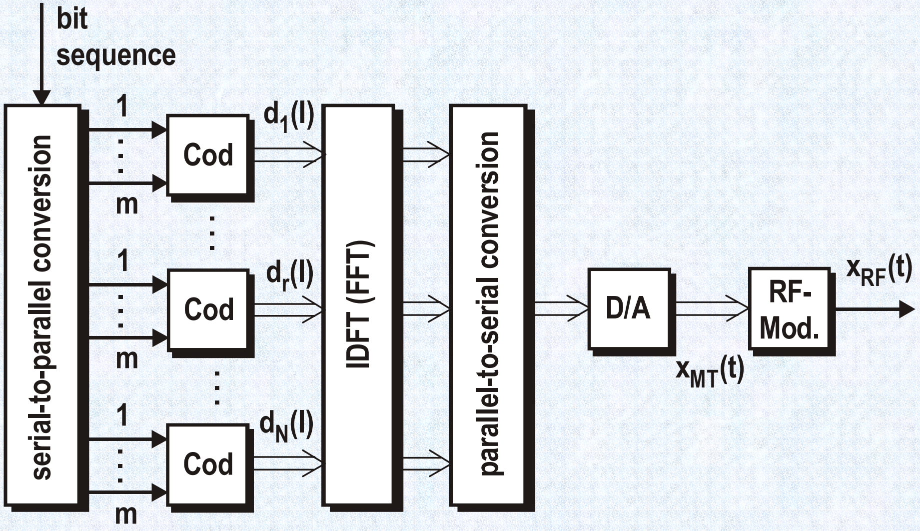
RCH *Random CHannel*

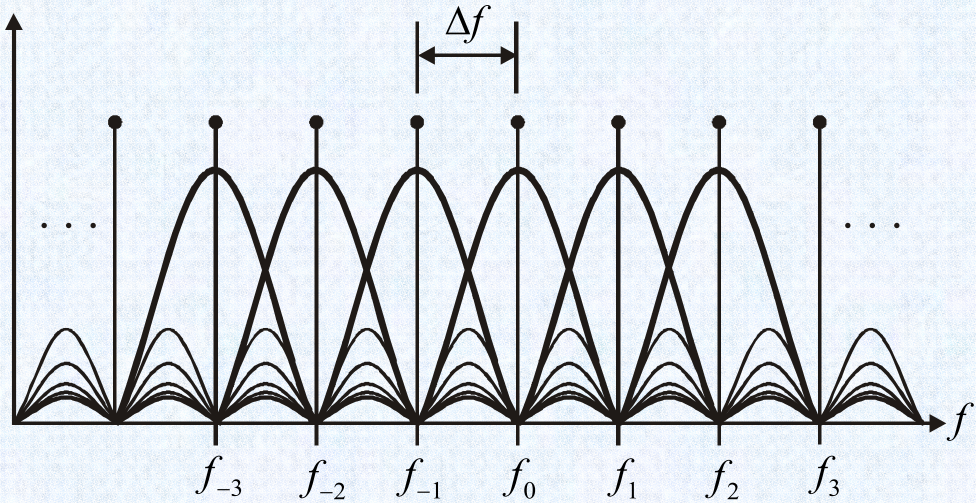
SCH *Short transport CHannel*

LCH *Long transport CHannel*

HIPERLAN/2 System Overview

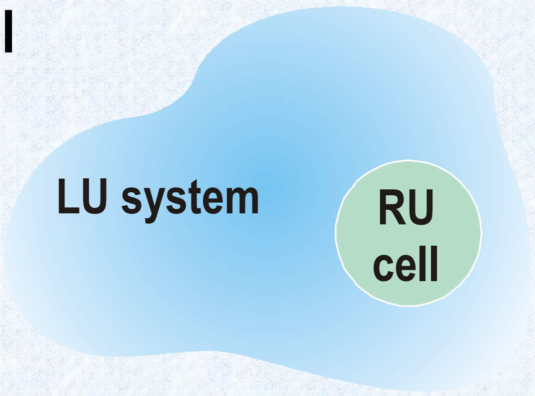
- **Physical Layer: OFDM**
  Transmitter structure and spectrum



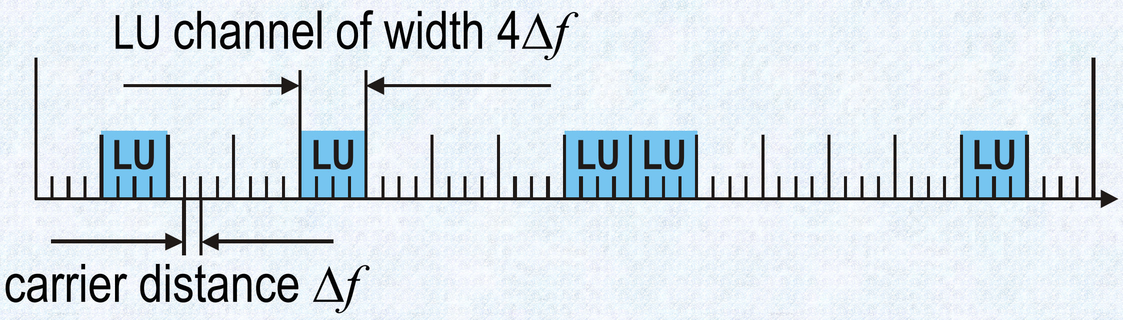


The Licensed User System

1. **Embedding a RU cell into a LU cell (Hot Spot Scenario)**



2. **Channel pattern and Occupancy Vector (OV)**

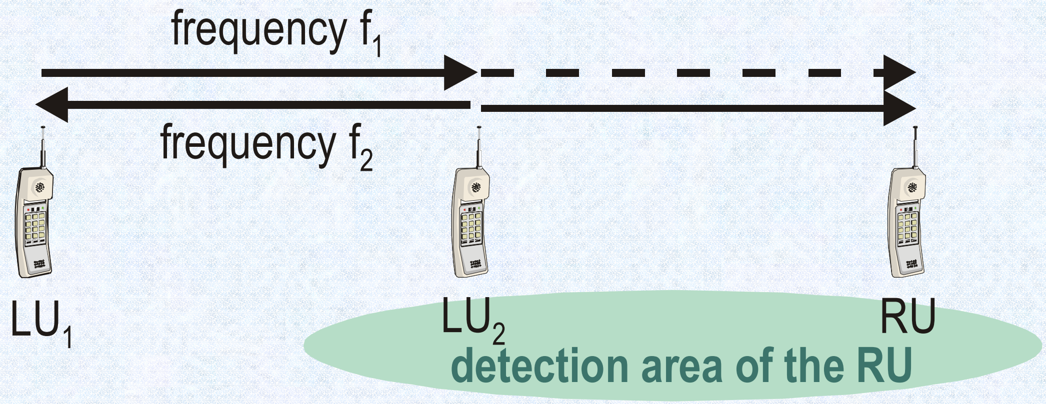


OV = (0 1 0 0 1 0 0 0 1 1 0 0 0 0 1 0)

The Licensed User System

3. No LU signaling channel → LU detection necessary for the RU system

   - hidden / exposed station problem



➔ The detection has to cover the whole sphere of influence of the RU cell

➔ Access delay for the LUs

   ➨ Waiting period

4. No Carrier Sense Medium Access (CSMA) in the LU system.

RU Physical Layer Issues

- LU detection and signaling
  - Optimum detection?
  - Quality of detection necessary for coexistence?
  - OV transmission calls for a new protocol

- RU system synchronization
  - Necessity of a new preambel concept
  - Optimum positioning of pilots?

- Interference reducing measures
  - Disturbances to the LU system caused by the *sin(x)/x*-shaped OFDM spectrum
  - Disturbances to the RU system by FFT leakage caused by the non orthogonality of the LU signals

The engaged / idle decision has to be done by the RU system for each LU channel within the pool

➡ The frequency resolution is realized by the anyhow existing FFT:

1. Sampling of the signal $s(k)$ band limited to the pool width

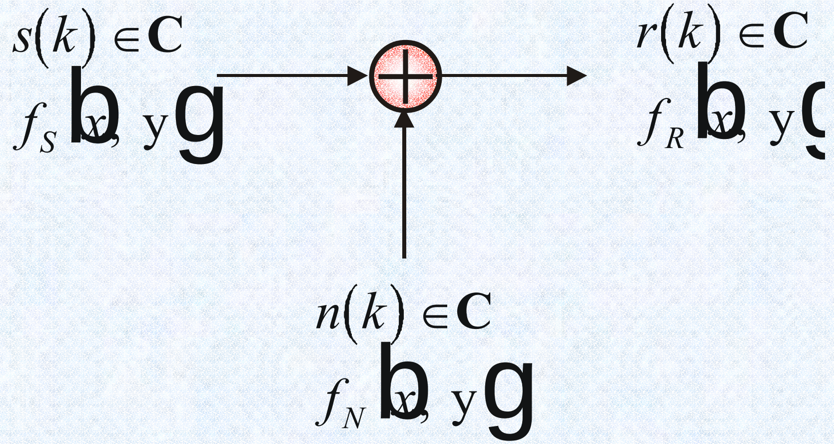
2. FFT for 64 samples at a time. The process is repeated n times.

3. The spectrum values belonging to one LU channel are integrated into a vector z .

4. Decision based on z and on an optimality criterion.

J Transmission Model

- **Signal model**



- **Transition to n FFT repetitions**

$$f_S(x, y) \Rightarrow f_s(\mathbf{x}, \mathbf{y}) : \quad \mathbf{R}^2 \to \mathbf{R}^{2n}$$

$$f_S(\mathbf{x}, \mathbf{y}) = f_S(\underbrace{x_1, x_2, \ldots, x_n}_{n \text{ real parts}}, \underbrace{y_1, y_2, \ldots, y_n}_{n \text{ imaginary parts}}) = f_S(\mathbf{z}) \quad \text{where } \mathbf{z} = (\mathbf{x}, \mathbf{y})^T$$

Multidimensional Gaussian Density

- There is No Line of Sight (NLOS) from the LU to be detected to the measuring RU

$$f_S(\mathbf{z}) = \frac{1}{\sqrt{(2\pi)^{2n} \det \mathbf{C}_{SS}}} \exp\left(-\frac{1}{2}\mathbf{z}^T \mathbf{C}_{SS}^{-1}\mathbf{z}\right)$$

$$\mathbf{C}_{SS} = \mathbf{C}_{\mathbf{ZZ}} = \begin{pmatrix} \mathbf{C}_{\mathbf{XX}} & \mathbf{C}_{\mathbf{XY}} \\ \mathbf{C}_{\mathbf{YX}} & \mathbf{C}_{\mathbf{YY}} \end{pmatrix} = \begin{pmatrix} \mathbf{C}_{\mathbf{XX}} & \mathbf{C}_{\mathbf{XY}} \\ \mathbf{C}_{\mathbf{XY}} & \mathbf{C}_{\mathbf{XX}} \end{pmatrix}$$

$$\mathbf{C}_{XX} = \begin{pmatrix} \sigma_{x_1}^2 & \sigma_{x_1x_2} & \sigma_{x_1x_3} & \cdots & \sigma_{x_1x_n} \\ \sigma_{x_1x_2} & \sigma_{x_1}^2 & \sigma_{x_1x_2} & \cdots & \sigma_{x_2x_n} \\ \sigma_{x_1x_3} & \sigma_{x_1x_2} & \sigma_{x_1}^2 & \cdots & \sigma_{x_3x_n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sigma_{x_1x_n} & \sigma_{x_2x_n} & \sigma_{x_3x_n} & \cdots & \sigma_{x_1}^2 \end{pmatrix}$$

otal Density

- **Noise component density** **(AWGN)**

$$f_N(\mathbf{z}) = \frac{1}{\left(2\pi\sigma_N^2\right)^{n}} \exp\left(-\frac{\mathbf{z}^T\mathbf{z}}{2\sigma_N^2}\right)$$

- **Resulting density**
  - **Convolution of the single densities**

$$f_{R|\,\text{no LU}}(\mathbf{z}|\,\text{no LU}) = f_N(\mathbf{z})$$

$$f_{R|\,\text{LU}}(\mathbf{z}|\,\text{LU}) = \frac{1}{\sqrt{(2\pi)^n \det\left(\mathbf{C}_{SS} + \sigma_N^2\mathbf{E}\right)}} \exp\left(-\frac{1}{2}\mathbf{z}^{\mathrm{T}}\left(\mathbf{C}_{SS} + \sigma_N^2\mathbf{E}\right)^{-1}\mathbf{z}\right)$$

  - **Derivation of an optimal estimator**

stimator

- **Neyman-Pearson criterion:** **Maximization of the detection probability P_D for a given false alarm probability P_F**

$$P_F = \int_{\mathbf{R}_1} f_{R|\text{no LU}}(\mathbf{z}|\text{no LU})\,d\mathbf{z}$$

$$P_D = \int_{\mathbf{R}_1} f_{R|\text{LU}}(\mathbf{z}|\text{LU})\,d\mathbf{z}$$

Likelihood ratio:

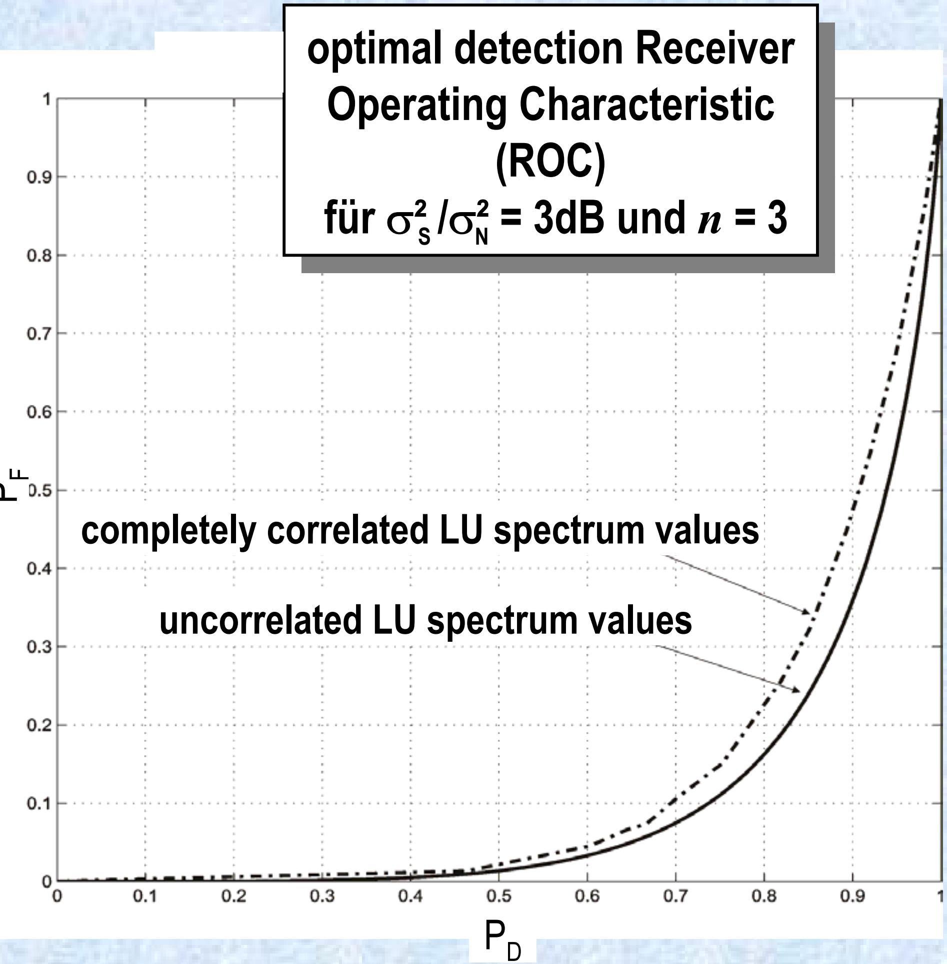
$$\frac{f_{R|\text{LU}}(\mathbf{z}|\text{LU})}{f_{R|\text{no LU}}(\mathbf{z}|\text{no LU})} \overset{\text{LU}}{>} \lambda_0$$

Optimal estimator:

$$\mathbf{z}^T\left(\left(\mathbf{C}_{SS}+\sigma_N^2\mathbf{E}\right)^{-1}-\left(\sigma_N^2\mathbf{E}\right)^{-1}\right)\mathbf{z} \overset{\text{LU}}{<} -2\ln\left(\lambda_0\frac{\sqrt{\det\left(\mathbf{C}_{SS}+\sigma_N^2\mathbf{E}\right)}}{\left(\sigma_N^2\right)^n}\right)$$

Unknown Covariance Matrix

- **Problem: For the optimal estimator C_{SS} must be known**



$\rightarrow$ **mismatched estimator!**

- **Uncorrelated spectrum values for the LU receiving process:**

$$\mathbf{z}^T\mathbf{z} = |\mathbf{z}|^2 \overset{\text{SN}}{>} 2\,\frac{\sigma_S^2+\sigma_N^2}{\sigma_S^2/\sigma_N^2}\left(\ln(\lambda_0) + n\ln\left(\frac{\sigma_S^2}{\sigma_N^2}+1\right)\right)$$

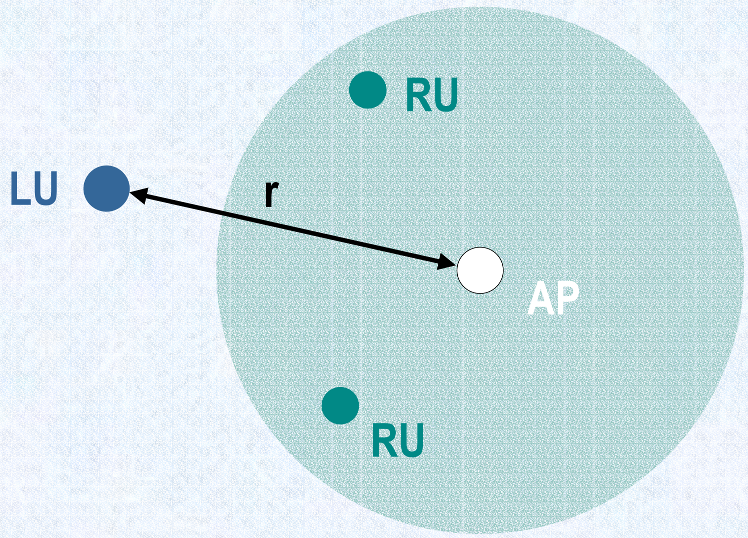
- **Completely correlated real parts and imaginary parts of the spectrum values:**

$$\left(\sum_{i=1}^{n} x_i\right)^2 + \left(\sum_{i=1}^{n} y_i\right)^2 \overset{\text{SN}}{>} 2\,\frac{n\,\sigma_S^2+\sigma_N^2}{\sigma_S^2/\sigma_S^2}\,\ln\left(\lambda_0\left(n\frac{\sigma_S^2}{\sigma_N^2}+1\right)\right)$$

SNR_D Estimation

- **For which average power of a received LU signal must the LU channel be classified as used?**

→ depends on the permissible interferences on the LUs



AP *Access Point*

$$SNR_D\,[\text{dB}] \quad \overset{!}{\leq} \quad 10\log\left(10^{\frac{\Delta SNR\,[\text{dB}]}{10}} - 1\right) + \Delta P\,[\text{dB}]$$

etermination of SNR_D

ΔP [dB]	ΔSNR [dB]	SNR_D [dB]
0	1	−5.8
0	2	−2.3
0	3	0.0
0	4	1.8
0	5	3.3
3	1	−2.8
3	2	0.7
3	3	3.0
3	4	4.8
3	5	6.3

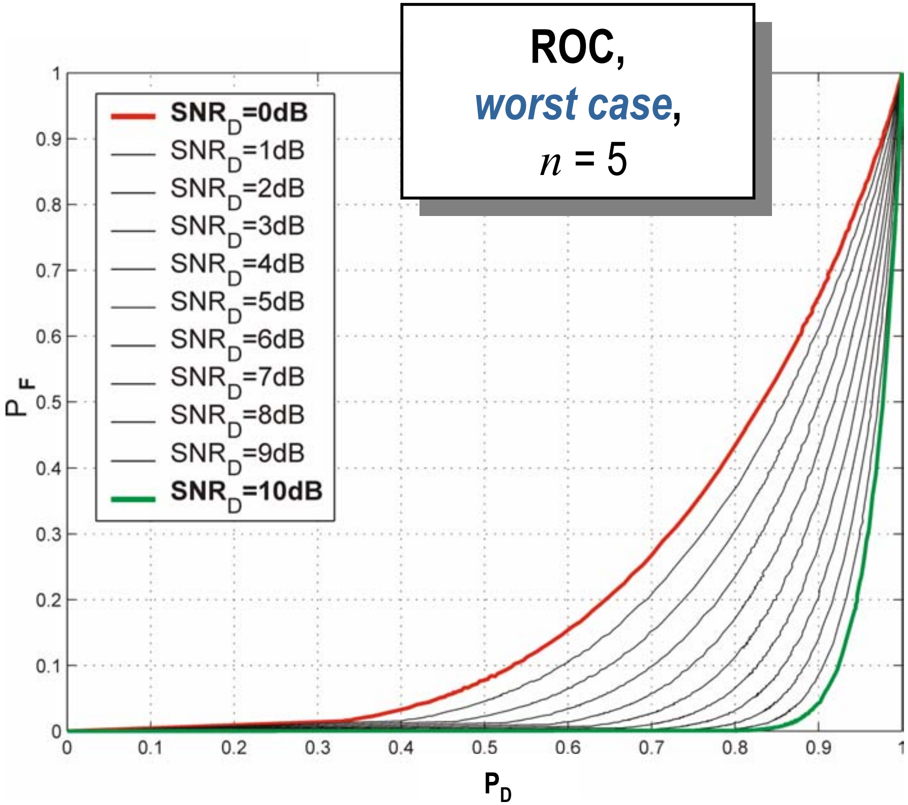
ΔP [dB]	ΔSNR [dB]	SNR_D [dB]
6	1	0.2
6	2	3.7
6	3	6.0
6	4	7.8
6	5	9.3
10	1	4.2
10	2	7.7
10	3	10.0
10	4	11.8
10	5	13.3

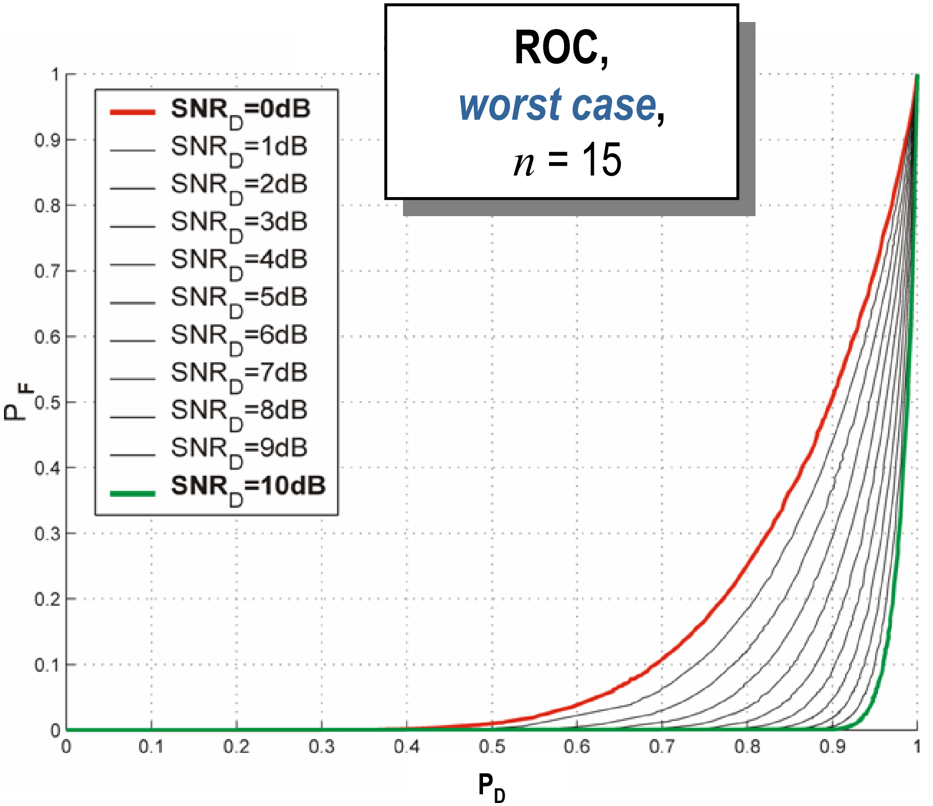
Higher SNR_D ➡ lower P_F ➡ enhanced efficiency

high ΔP is advantageous for detection

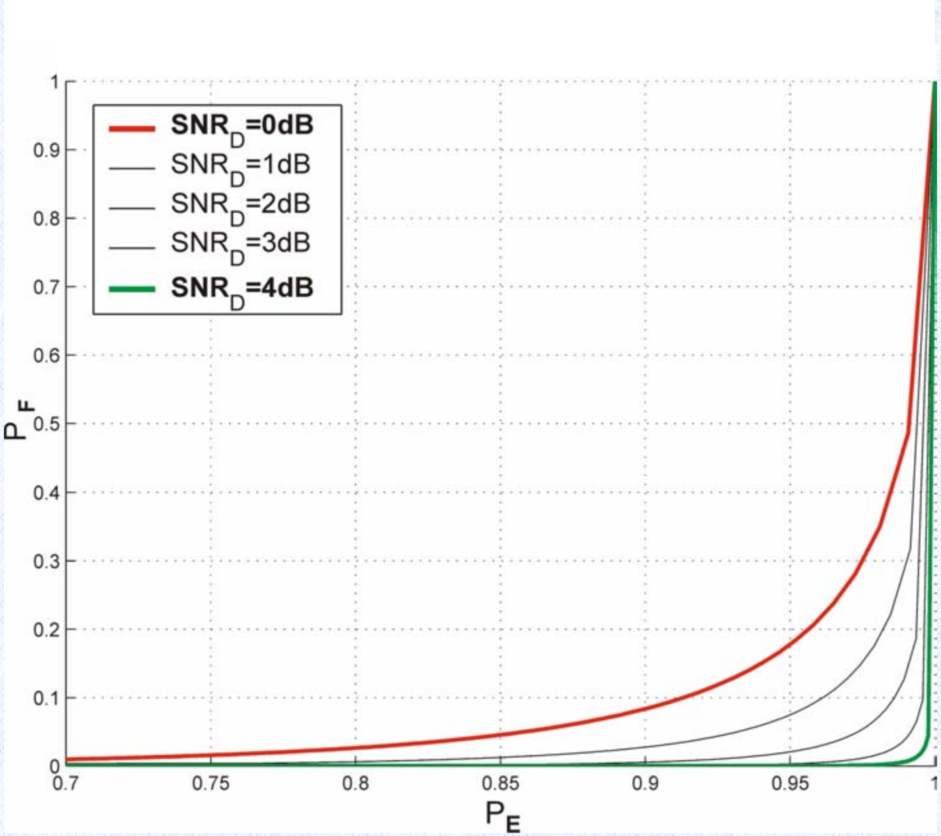
- Simulation results: *worst case* consideration

  ↪ maximal mismatched estimator





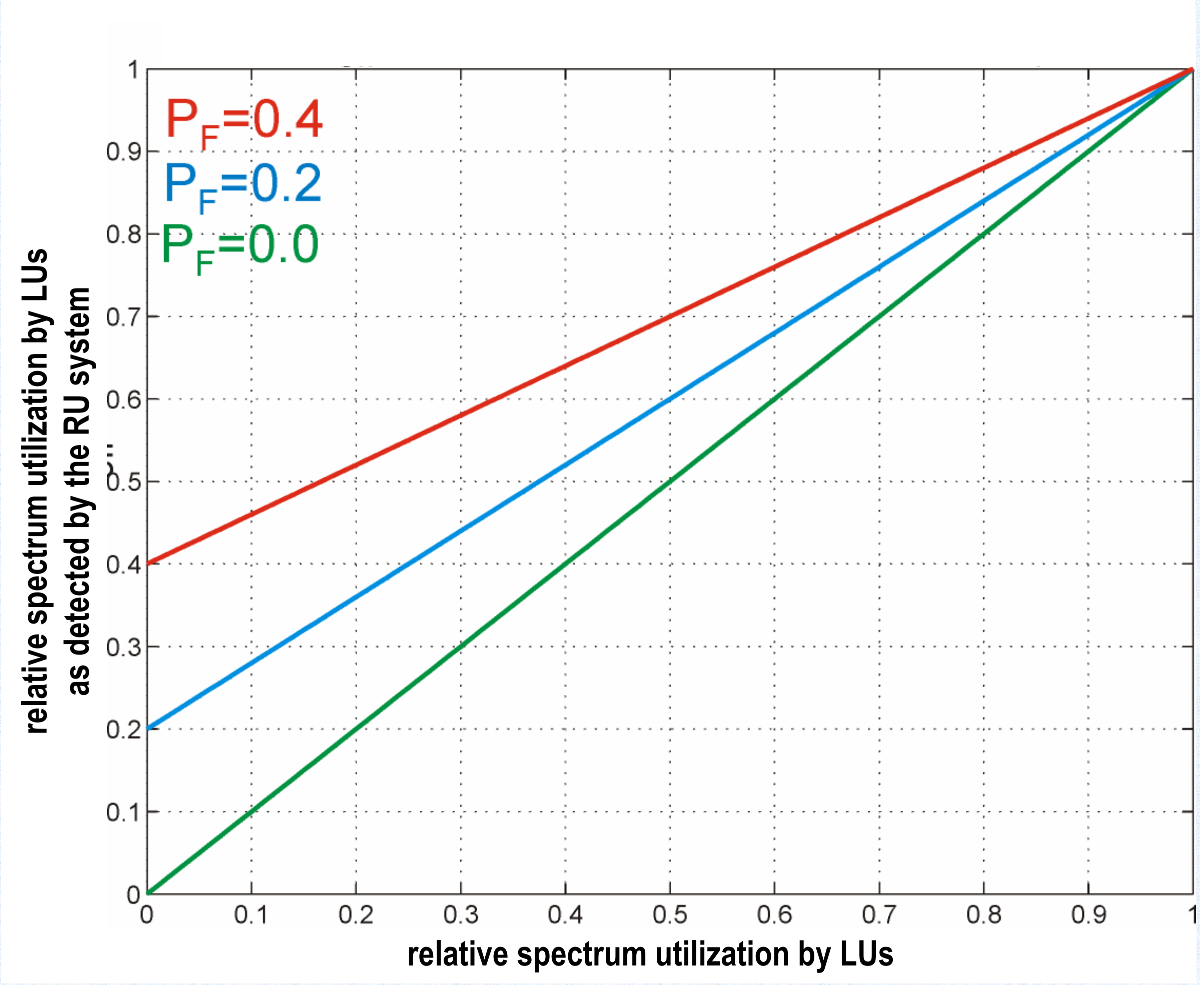
- ***best case* consideration:** Uncorrelated spectrum values



ROC,
***best case*,**
n = 15

Reality is somewhere between *best* und *worst case*
→ Choose n for the *worst case* !?

- **Impact of the false alarm probability P_F on the RU system efficiency**



Given detection probability : $P_D = 0{,}999$

Problems:

multipaths *(fading)*

too high false alarm probability P_F

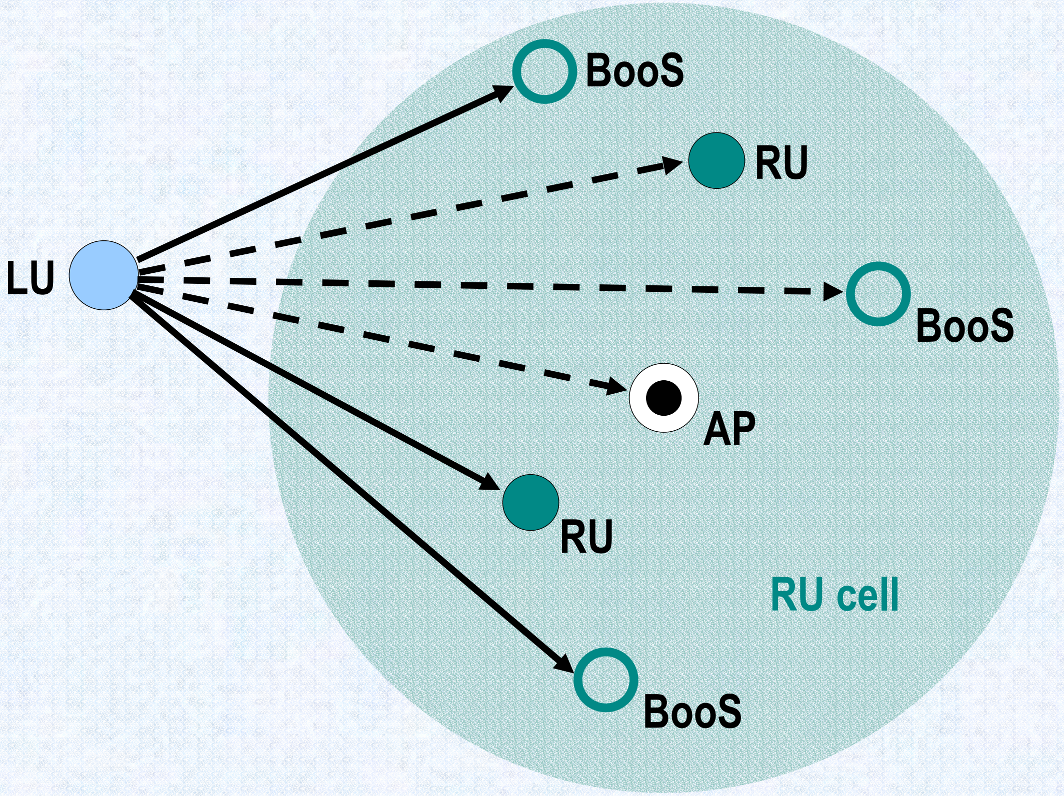
P_D cannot be realized with only one measurement station!

Solution:

distributed detection *(diversity)*

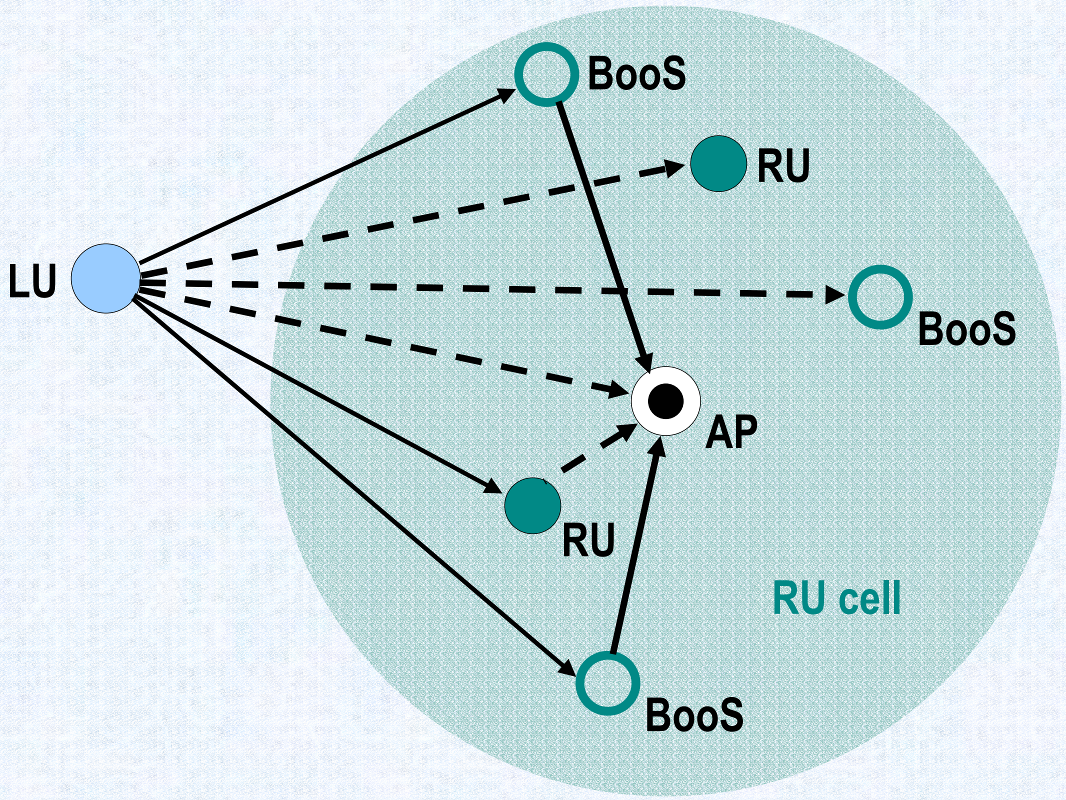
all *mobile terminals* and three additional *Boosting Stations* take measurements jointly

P_D becomes realizable for moderate P_F !



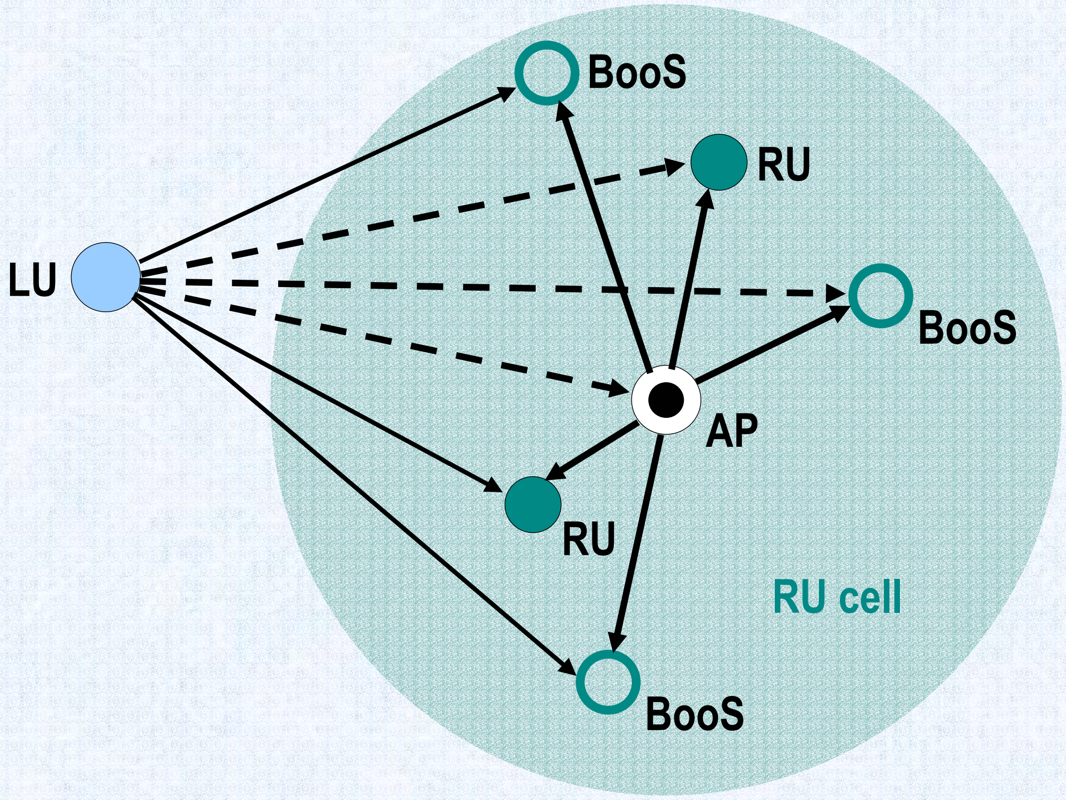
AP	***A**ccess **P**oint*
BooS	***Boo**sting **S**tation*
LU	***L**icensed **U**ser*
RU	***R**ental **U**ser*

- RUs + BooSs → (AP): *Boosting protocol*



AP computes the elementwise „or“ of all OVs

- **AP → RUs + BooSs:** ***Robust time-frequency broadcast***



AP	***A**ccess **P**oint*
BooS	***Boo**sting **S**tation*
LU	***L**icensed **U**ser*
RU	***R**ental **U**ser*

What is the gain of divided detection ?	
diversity	➔ no fading
P_D for a specific RU may be reduced	➔ P_F decreases

The individual detection results are statistically independent.
If the receiving condition at the (m) measuring stations (RUs and BooSs) are similar, we get :

$$P_F^Z(m) \approx 1-(1-P_F)^m$$
$$P_E^Z(m) \approx 1-(1-P_E)^m$$

$$P_F^Z(m) = 1 - \left(1 - P_F\left(1 - \sqrt[m]{(1-P_E^Z)}\right)\right)^m$$

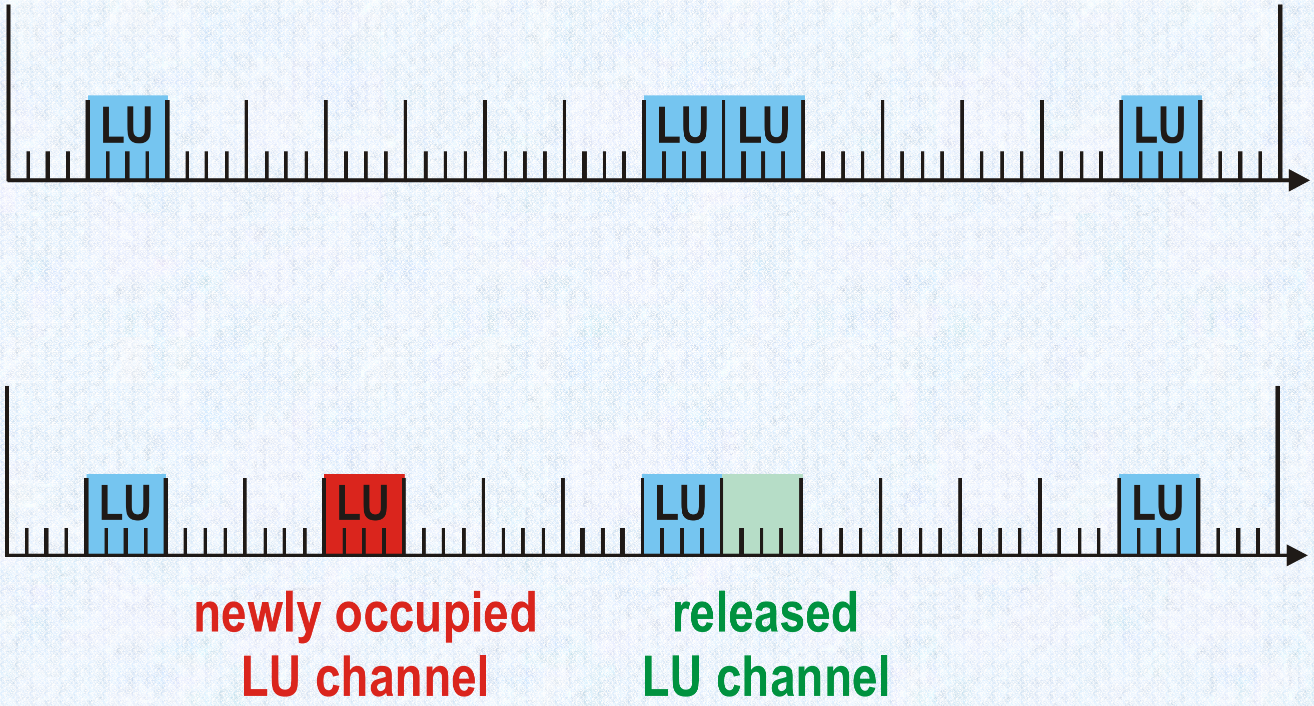
m	P_D	P_F	$P^Z{}_F$
1	0.999	0.982	0.982
2	0.968	0.662	0.886
3	0.900	0.294	0.648
4	0.822	0.100	0.344
10	0.499	0.001	0.010
20	0.292	≈ 0	≈ 0

- Signaling RUs + BooSs → AP ?

- Boosting Protocol

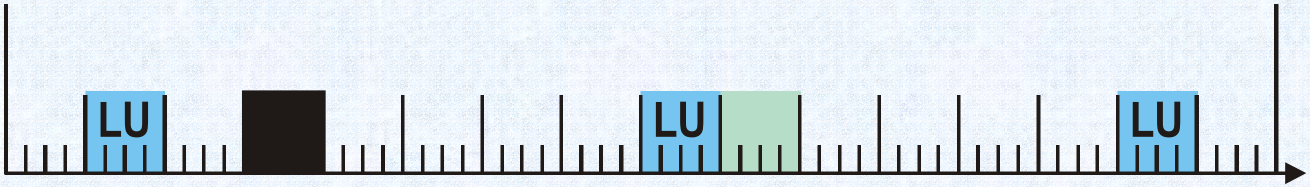
Presently valid OV:

New constellation (after the detection phase) :



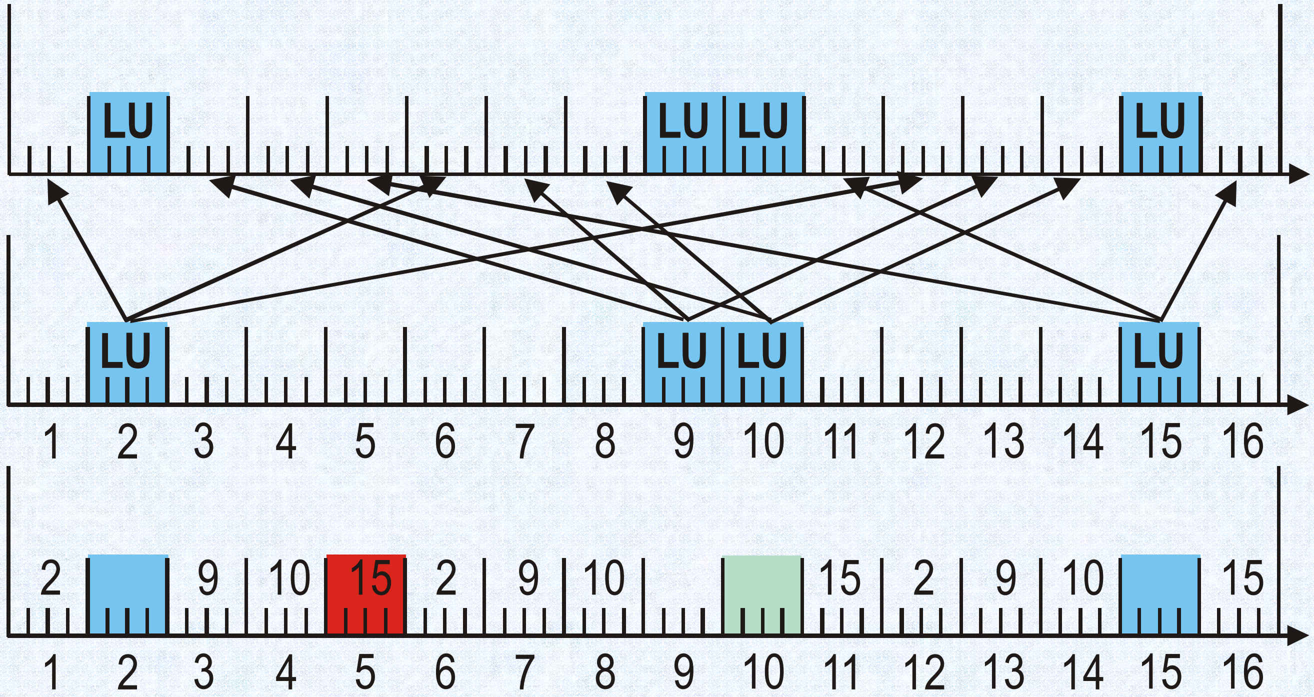
oosting Protocol (2)

Signaling of *newly occupied* channels

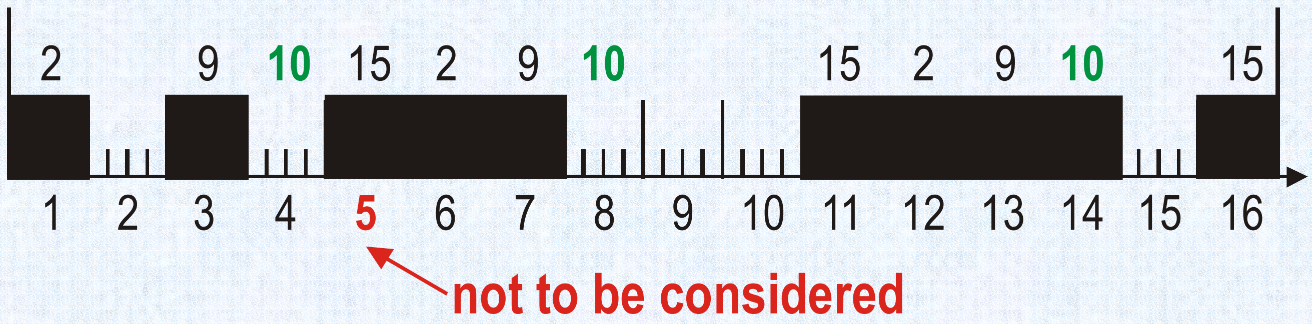


Boosting

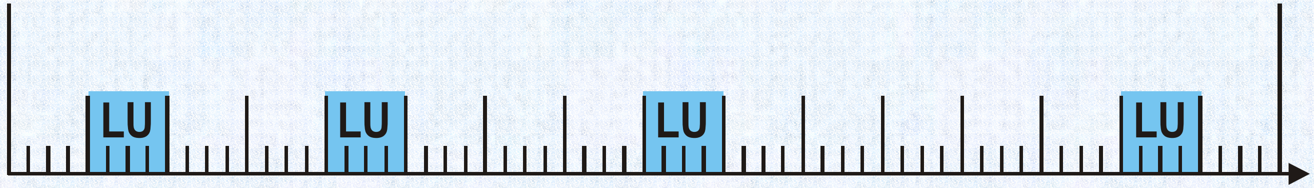
Mapping phase



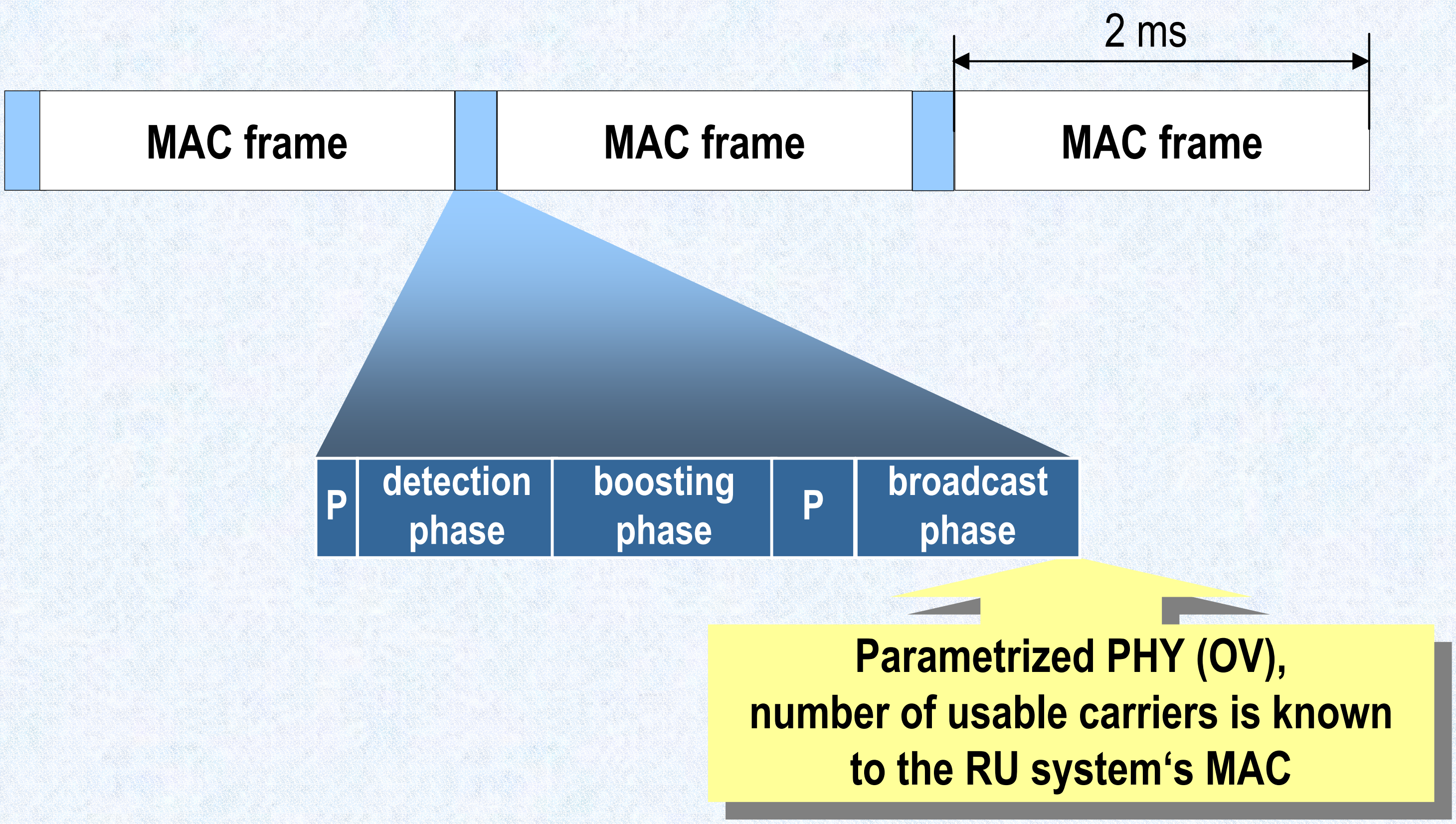
Signaling of further occupied LU channels



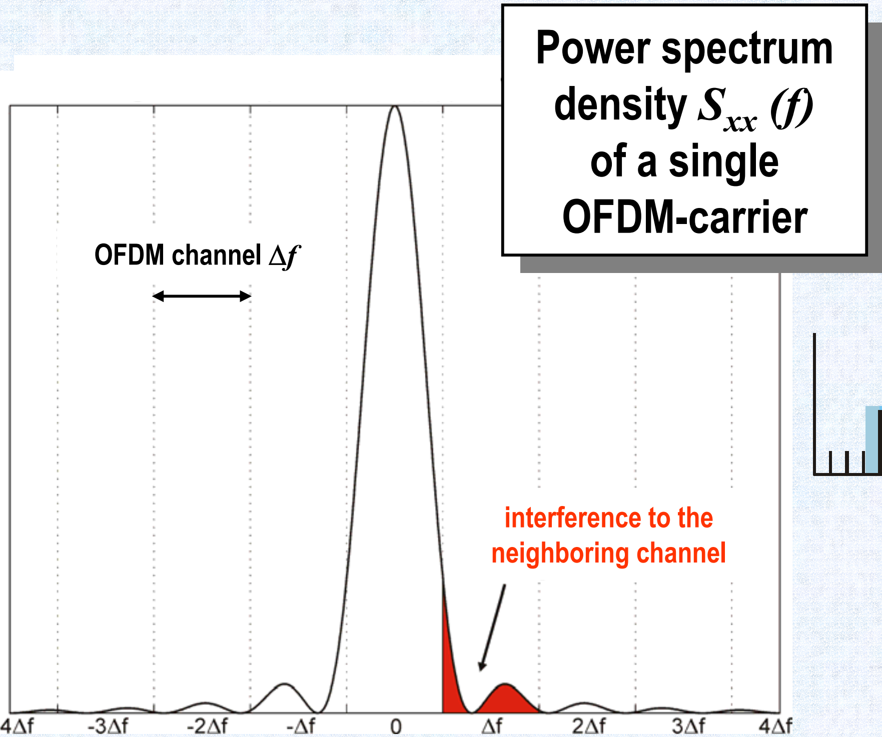
New OV (to be signalized by the AP)

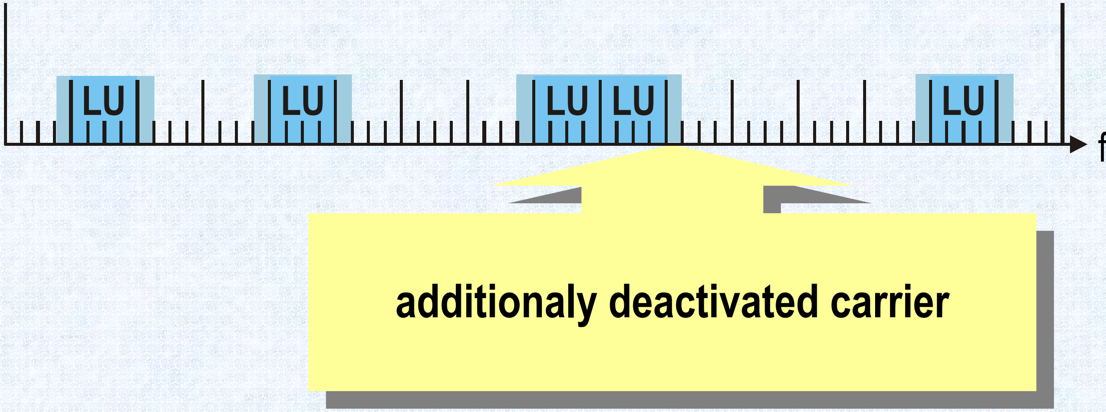


- **Divided detection combined with a boosting protocol and robust Occupancy Vector signaling solves the LU detection problem and leads to a common base of the Physical Layer (PHY).**



- The RUs system‘s efficiency is mainly determined by the interference reducing measures!





ext Steps

- Integration of the results into our OMNeT++ software demonstrator.

- Simulation with respect to all effects and with realistic channel models

  → Tuning of the free parameters

- Adaptive modulation for optimal use of disturbed channels (FFT leakage)

- MAC layer: Investigation of scheduling algorithms particulary resistent against bandwidth variations

- Mobile Radio Communications
- SDR Signal Processing
- Mobile Communication Channels
- Parameter Controlled SDR
- Heading for End-to End reconfigurability
- **Modular SDR**

verview

- Introduction to Modular Software Defined Radio (Mod-SDR)
- Mathematical Modeling of the SDR Design Problem
- Results of a Scheduling Approach
- Enhanced Modeling of Boundary Conditions
- Recent Results of a Partitioning Approach
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troduction to Modular SDR

- Original Software Radio (SR) concept, long-term perspective
- Software Defined Radio (SDR) means:

1. ADCs and DACs as close as possible to the antenna
2. DSP in software, but only as far as flexibility is desirable

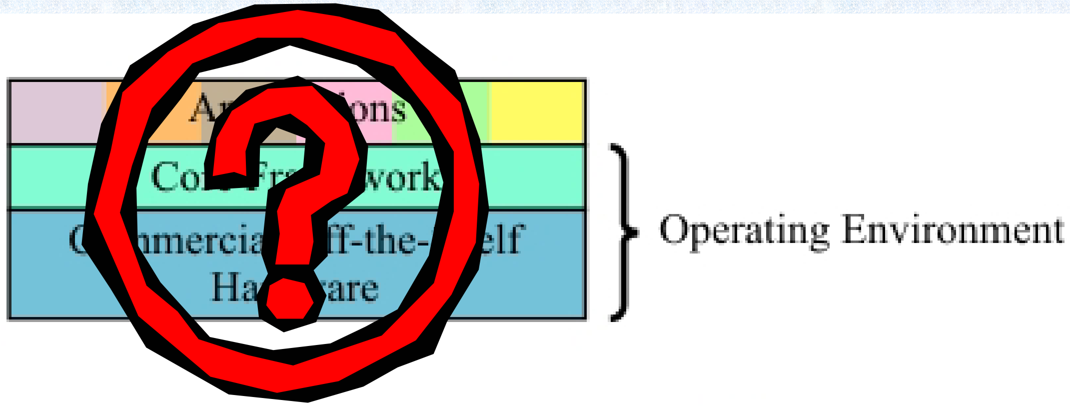
- Technically feasible, commercially attractive („flexibility sells“, time-to-market)
- SDR research, focus on one particular aspect of the signal processing chain
- Baseband processing is centered around *algorithms*

Design guidelines for *modular systems* are in demand

odularity in SDR Systems

- **By definition, "software" in a Software Defined Radio is modular**

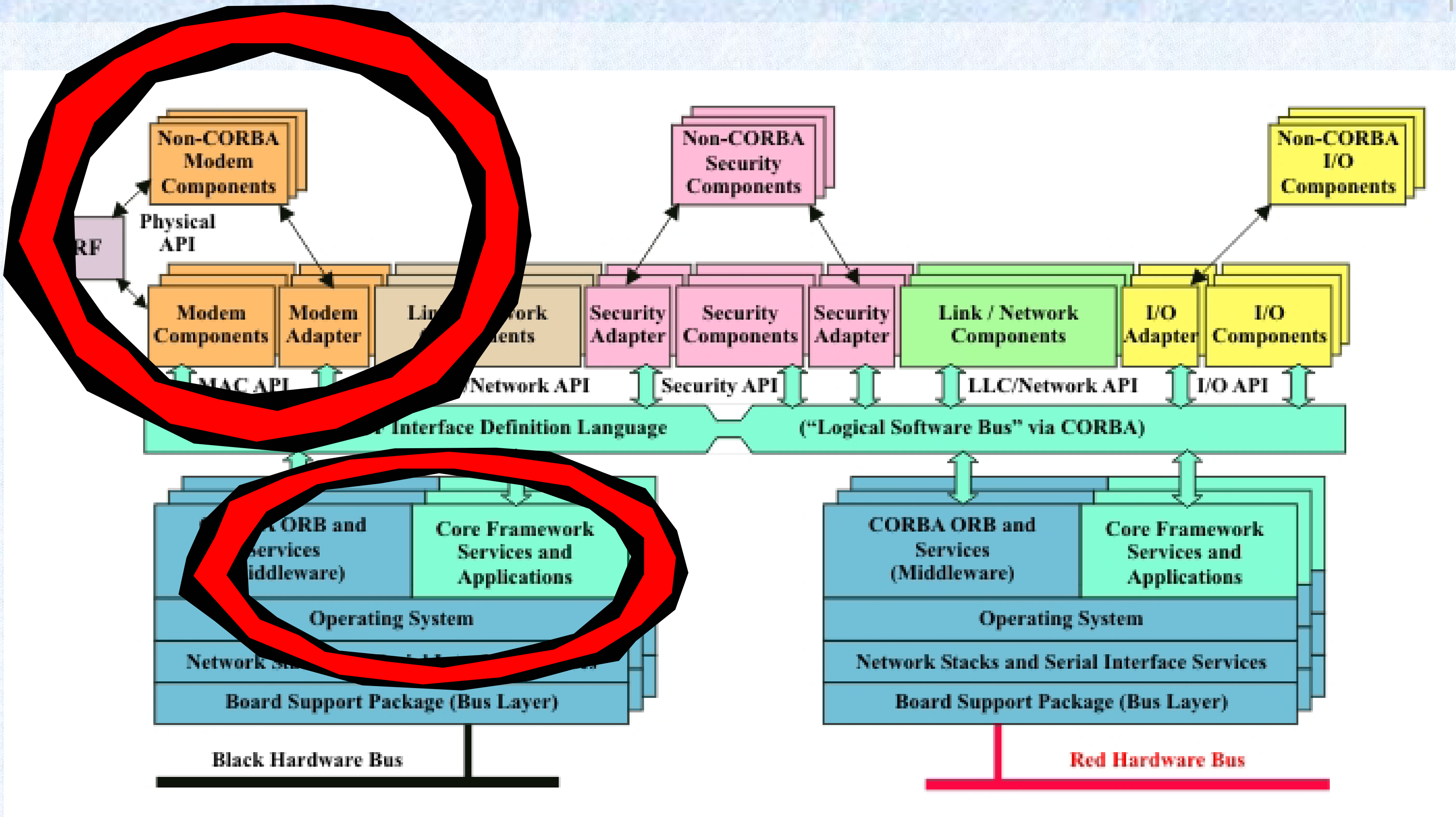
CA Software Structure



- RF Frontend
- Modem Applications
- Network / Link Applications (Black)
- Security Applications
- Side Network / Link Applications (Red)
- Host Applications
- Core Framework (CF) Elements
- COTS Hardware Components

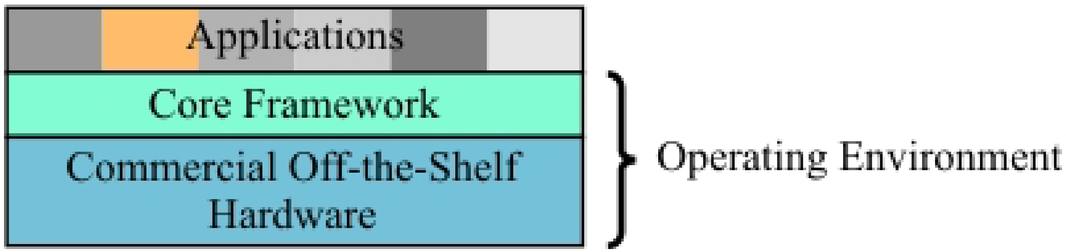
Source: SCA Specification V2.2, JTRS Program Office, http://jtrs.army.mil

CA Software Structure (Zoom)



Source: SCA Specification V2.2, JTRS Program Office, http://jtrs.army.mil

CA Software Structure



- RF Frontend
- **PHY Layer / Digital Baseband**
- Network / Link Applications (Black)
- Security Applications
- Side Network / Link Applications (Red)
- Host Applications
- **Partitioning and Scheduling**
- **DSP, FPGA, ASSP, bus, mem**

Source: SCA Specification V2.2, JTRS Program Office, http://jtrs.army.mil

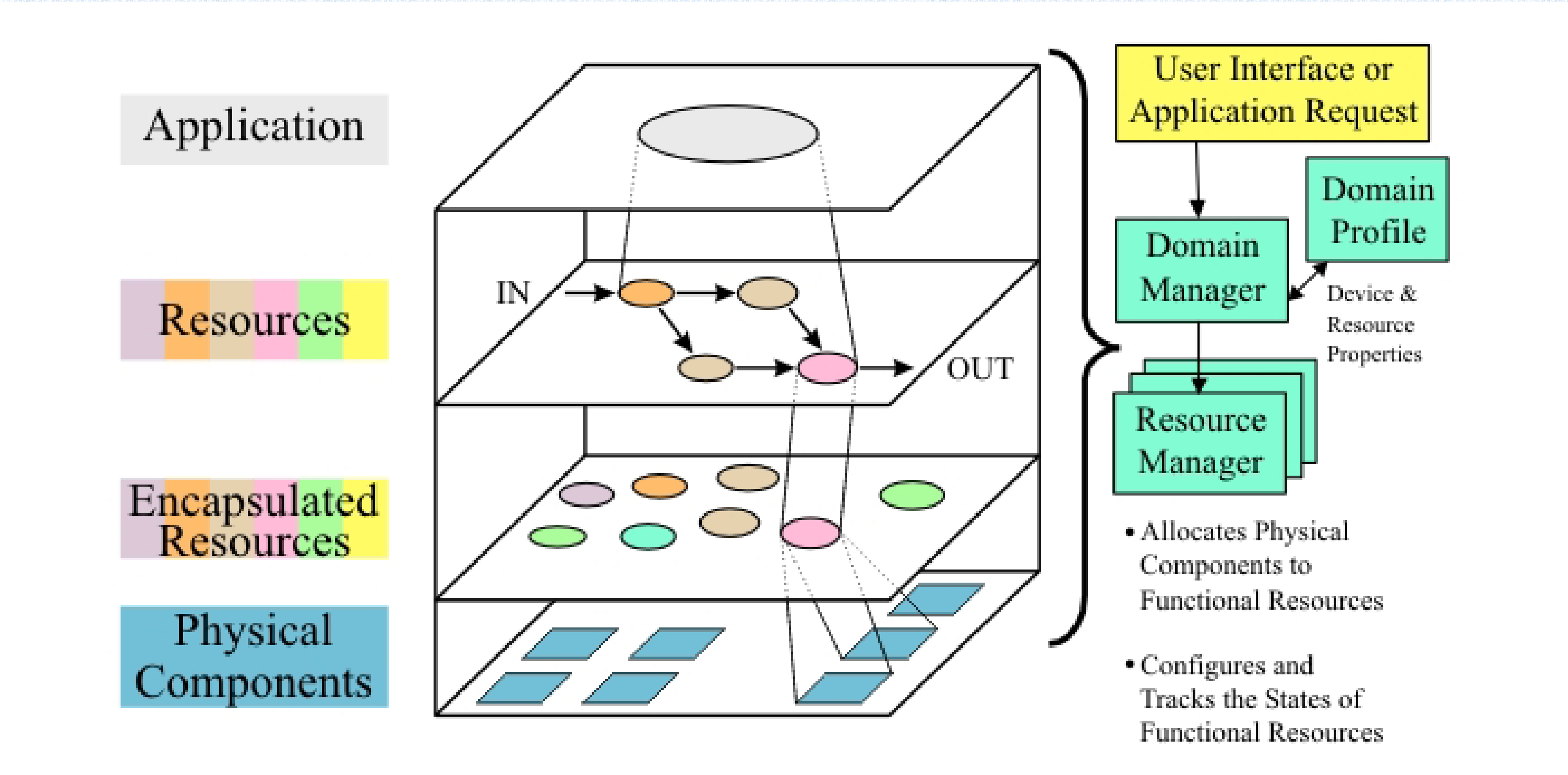
odularity in SDR Systems

INT

- By definition, "software" in a Software Defined Radio is modular

1. Software defined PHY = Communication functions, modules
2. Resource allocation = Partitioning and scheduling

- Communication functions are embedded in logical structures



Source: SDRF Forum, Architecture and Elements of SDR Systems as Related to Standards Technical Report, version 2.1d, Nov 1999

odularity in SDR Systems

- By definition, “software“ in a Software Defined Radio is modular

1. Software defined PHY = Communication functions, modules
2. Resource allocation = Partitioning and scheduling

- Communication functions are embedded in logical structures

Data flow, precedence constraints → Directed Graph

- Physical resources are administered by a non-preemptive RTOS

- Software is executed using some hardware, physical structures

SDR hardware = Multi-processor signal processing system

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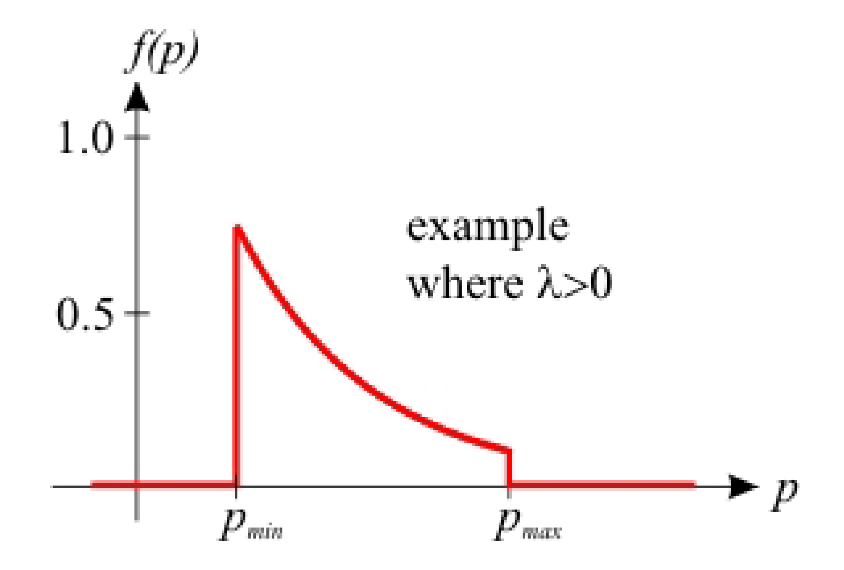
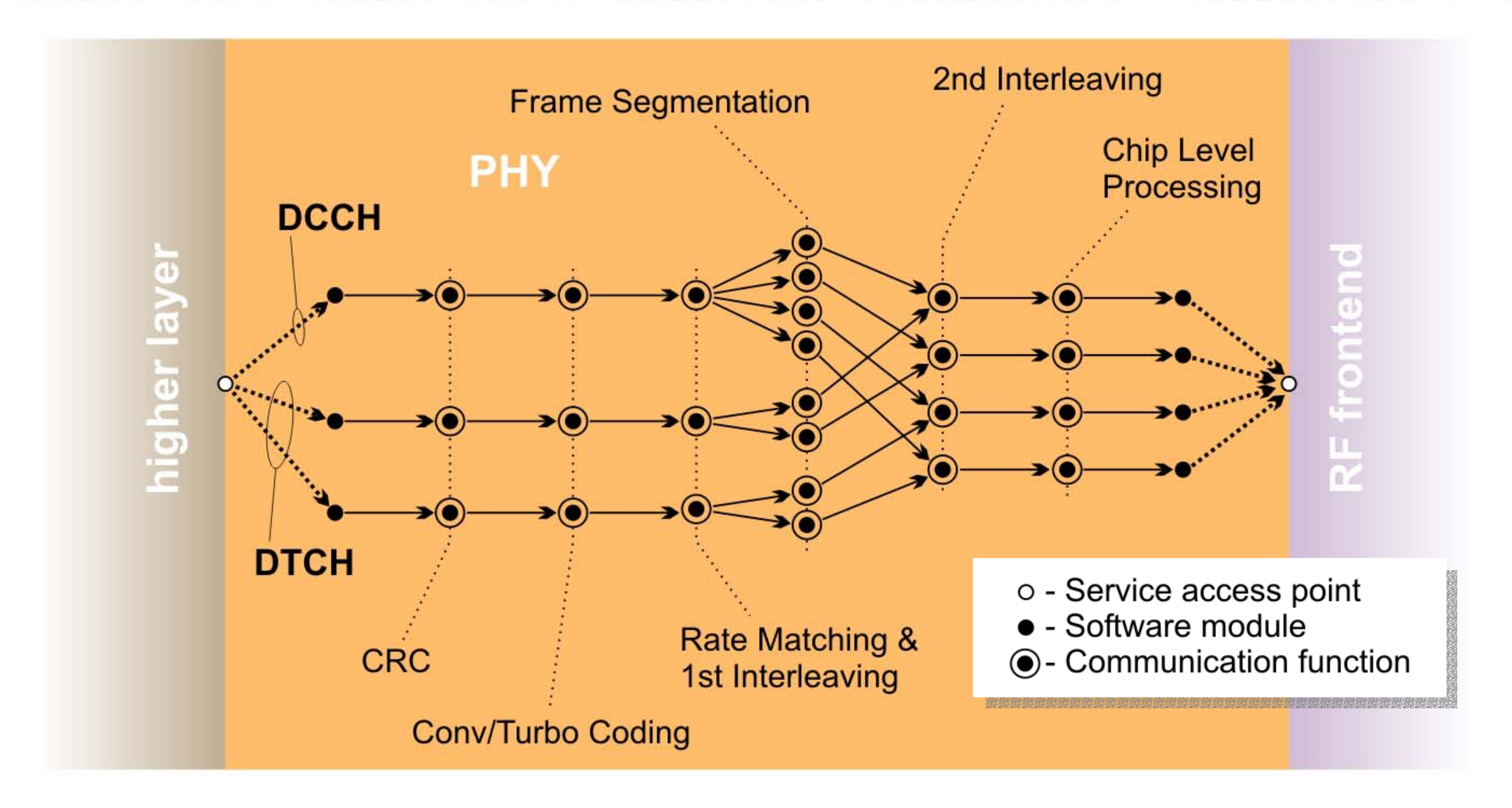
- **Runtime is the main behavioral attribute of modules. Central argument:**

The variety of processing runtimes is so vast that we can merely describe runtime by providing a pdf.



- **Quality measure: speedup, independent of concrete real-time requirements**



UTRA FDD 64kbps UL, transmitter, ETSI TS 125 101, version 5.5.0 (2002-12), pp.51-52

teger Linear Programming (ILP)

INT

- General method for discrete-time resource-constrained allocation problems
- System of equations and inequalities, formally known in CS and OR
- Advantage: Reduction to an ILP formulation makes SDR design accessible to optimal mathematical solution methods.
- Disadvantages: NP hard, optimum solution may need exponential time, branch-and-bound methods

  Good time resolution results in a large system of equations
- Way out: different methods to quickly find a solution, even if sub-optimal

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u Level Scheduling

- Optimum allocation algorithm for unit-runtime scheduling problems
- Works as well with real-valued processing runtimes, Hu Level node attribute

Effective relative spread in processing runtimes of modules has a major influence on the speedup spread, not the pdf shape

- Advantage: **Simple and fast scheduling on L identical processors**
- Disadvantage: **Drops important boundary conditions such as limited memory and speed of inter-processor communications**

- Way out: methods accounting for inter-processor communications

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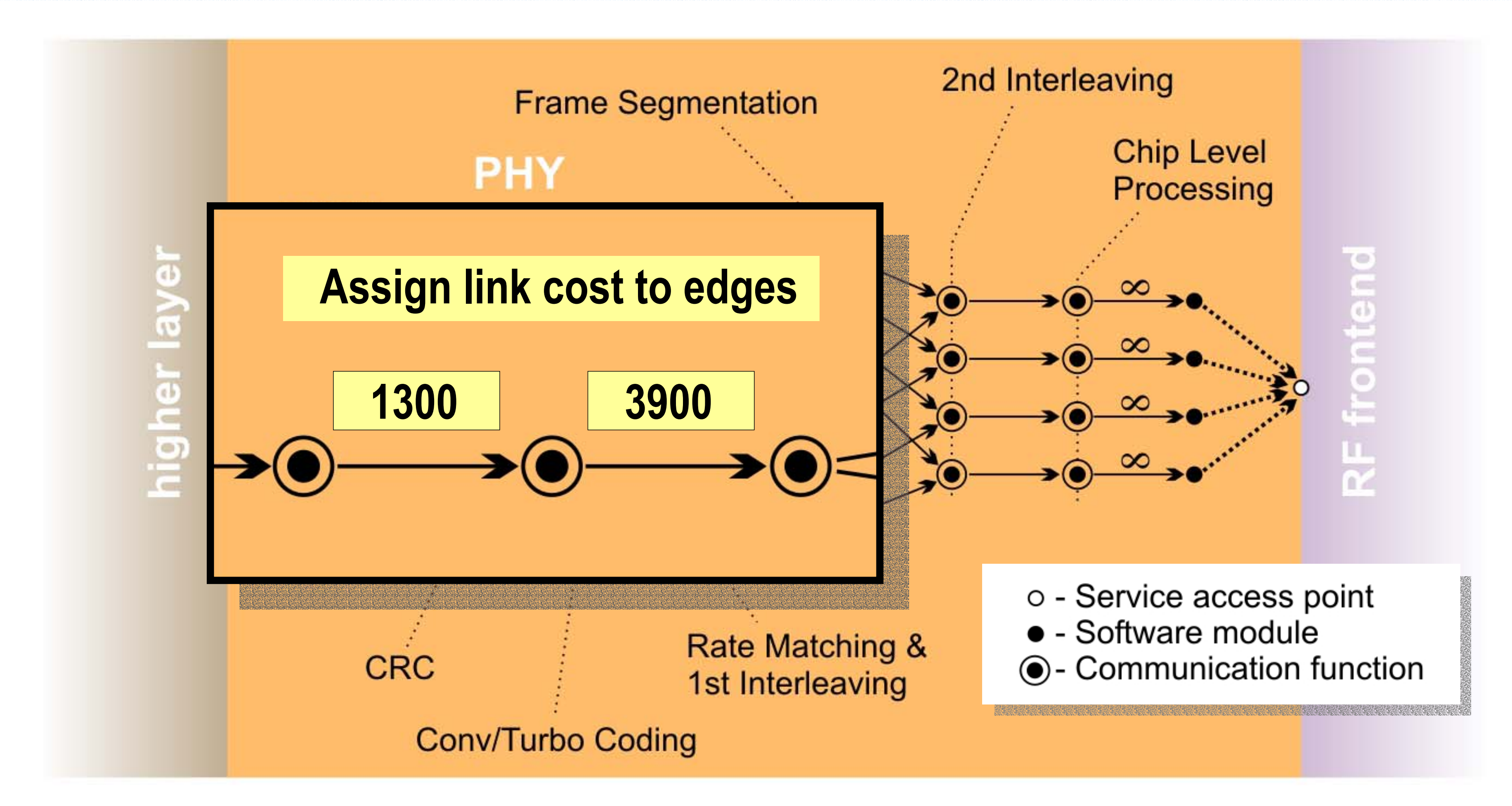
near Resource-Runtime Model

- Intermediate data flow is uniquely determined by a transmission mode
- Nevertheless, in an SDR environment, the multitude of encountered processing runtimes persists

$$p_m = \alpha \cdot c \cdot r_m$$

- Module m has processing runtime p_m and output data memory demand r_m
- α is a processor-dependent specific runtime, absorbed in speedup
- c is unitless and random. Its spread determines how closely realizations follow the strictly linear resource-runtime relation



UTRA FDD 64kbps UL, transmitter, ETSI TS 125 101, version 5.5.0 (2002-12), pp.51-52

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ernighan/Lin Partitioning

- Originally developed to distribute electonic components among PCBs
- Minimize inter-board connections while keeping component count balanced

Adaptated to Mod-SDR, it minimizes inter-processor communications while keeping processor workload balanced (set exchange, local)

- Advantages:
  - Accounts for inter-processor communications
  - Produces dense schedules / high speedup
- Disadvantages:
  - Assumes full mesh topology / suffers from single bus
  - Requires pipelined processing / incurs significant delay
- Way out: methods avoiding local search at first, study pipelining

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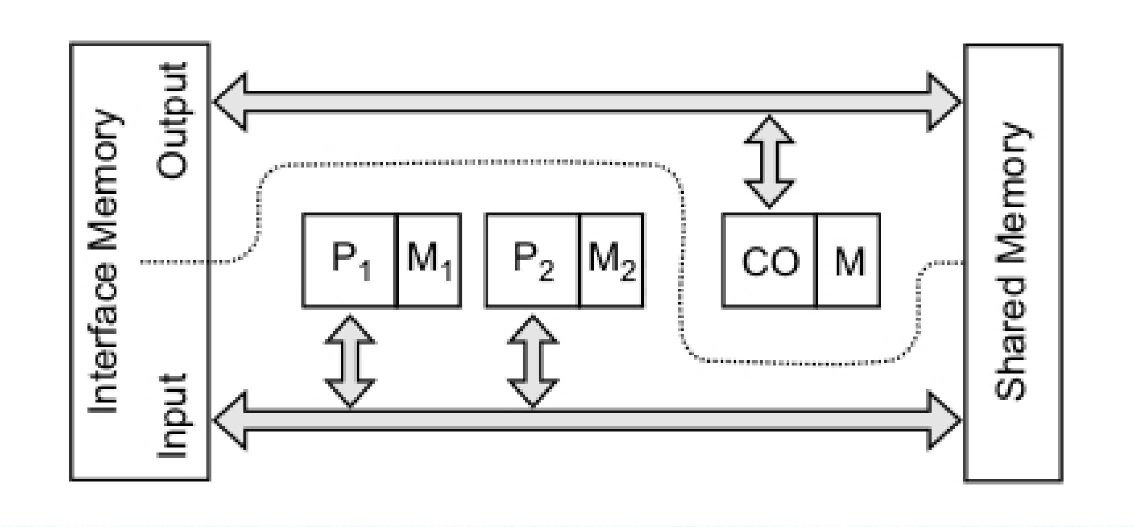
ubsystem Pipelining

- **Application-specific co-processor in cooperation with two identical DSPs**



Shadow memory should be provided at the inter-layer interfaces

Dividing the PHY layer into two separate pipelined subsystems is efficient with respect to dynamic power dissipation

- **Advantage:** **Eventually, less hardware design effort**

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urrent Activities and Future Issues

- **Spectral Partitioning for circuit-switched and packet-switched services**
- **Algorithms for QoS support in Mod-SDR, transmission mode search**
- **Extension of recently studied methods to L identical processors**
- **Generalization of Mod-SDR design guidelines to heterogeneous systems**
- **Incorporation of Mod-SDR guidelines into Real-Time CORBA and products**

Questions $\rightarrow$ Answers

[1] Arnd-Ragnar Rhiemeier, Friedrich Jondral
Mathematical Modeling of the SDR Design Problem
IEICE Transactions on Communications, vol. E86-B, no. 12, December 2003
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[2] Arnd-Ragnar Rhiemeier, Friedrich Jondral
Software Partitioning and Hardware Architecture for Modular SDR Systems
Proceedings of the SDR'03
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[3] Arnd-Ragnar Rhiemeier, Friedrich Jondral
A Software Partitioning Algorithm for Modular Software Defined Radio
Proceedings of the WPMC'03
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[4] Arnd-Ragnar Rhiemeier, Friedrich Jondral
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Proceedings of the DSPeR'03, CD-ROM, contact http://www.DSPeC.org
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[5] Arnd-Ragnar Rhiemeier, Friedrich Jondral
Enhanced Resource Utilization in Software Defined Radio Terminals
Proceedings of the IWK2003, CD-ROM, ISSN 1619-4098
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Hiroshi Harada, Ramjee Prasad: *Simulation and Software Radio for Mobile Communications*. Boston (MA), London (UK) 2002: Artech House

cknowledgement

Since 1996 the work on Software Defined Radio at the Institut für Nachrichten-echnik has been supported by

- Dipl.-Ing. Fatih Capar
- Dr.-Ing. Ralf Machauer (now Robert Bosch GmbH, Stuttgart)
- Ihan Martoyo, M.Sc.
- Dipl.-Ing. Piotr Rykaczewski
- Dr.-Ing. Henrik Schober
- Dr.-Ing. Gunther Sessler
- Dipl.-Ing. Timo Weiss
- Dr.-Ing. Gunnar Wetzker (now Philips, Eindhoven)
- Dr.-Ing. Anne Wiesler (now Fraunhofer Gesellschaft, München)

... and by numerous graduate students of Electrical Engineering and Information Technology at the Universität Karlsruhe

Submit a paper to and visit the

3rd Karlsruhe Workshop on Software Radios

Karlsruhe (Germany), March 17/18, 2004

Further Information:

http://www.int.uni-karlsruhe.de