Adaptive Modulation und Codierung für breitbandige drahtlose ATM-basierte Punkt-zu-Mehrpunkt Zugangsnetze

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- **Drahtlose PMP Zugangsnetze**
- **Funkkanal**
  (Link Budget, Mehrwegeausbreitung)
- **Adaptive Modulation & Codierung**
  (Zellulare Gleichkanal-Interferenz, Paket-basierte Übertragung)
- **Statistischer Multiplexgewinn → Systemdesign**

The Digital Point-to-Multipoint System

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ETSI BRAN HiperAccess Main Features

General

- interoperable standard
- address residential and business markets
- support of various services and applications, provide managed QoS
- PMP technology, cellular/sectorized coverage
- TDMA as multiple access scheme
- harmonization with IEEE 802.16

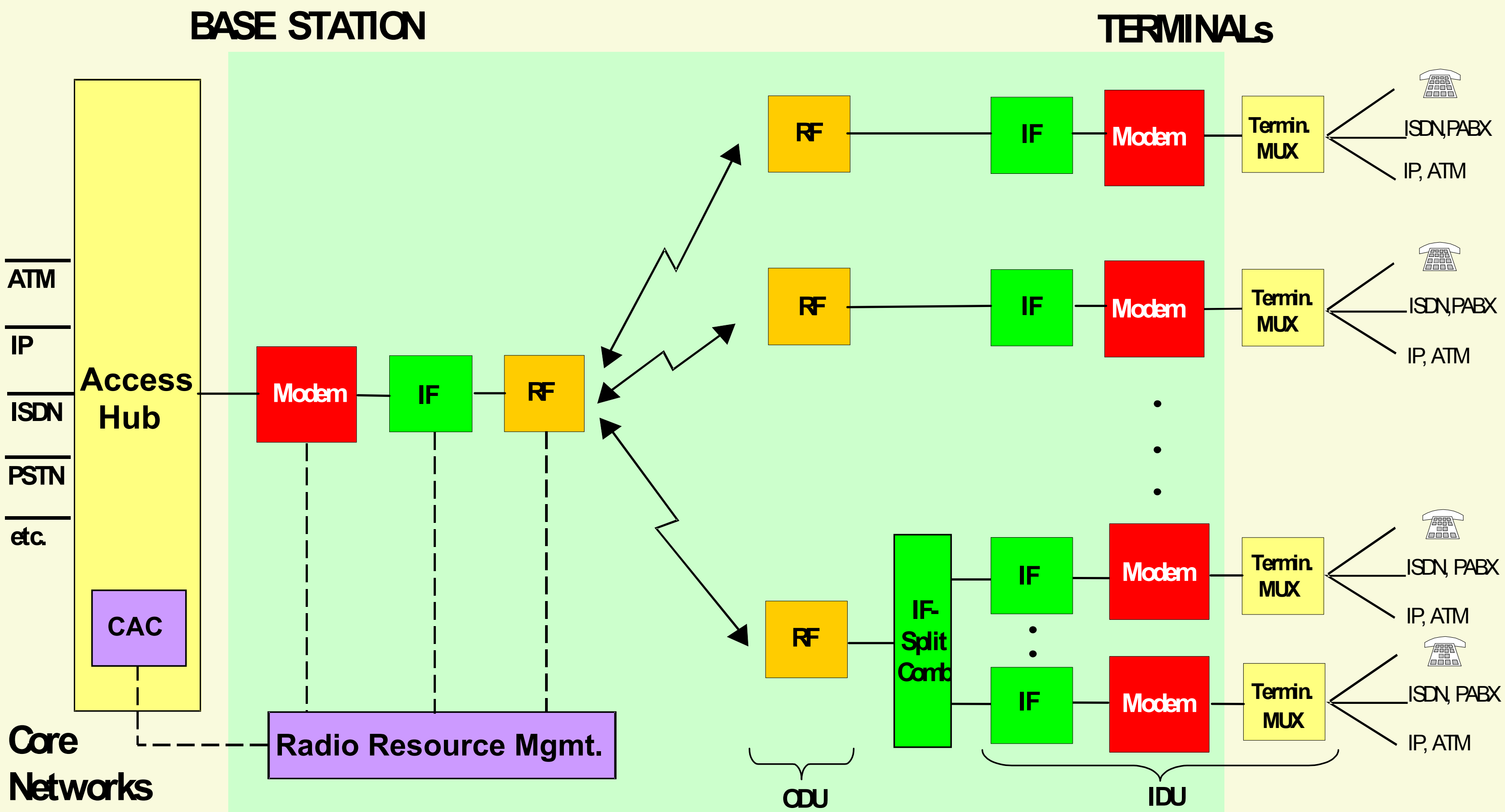
PHY layer

- operate in different frequency bands, e.g. (below 11), 26, 32, 42 GHz
- channelization mainly 28 MHz, duplexing FDD, H-FDD, TDD
- range 2...5 km
- data rates up to 25 Mbit/s per terminal
- concatenated coding (RS + CC)
- adaptive modulation: 4QAM to 64QAM
- adaptive antennas in base station for uplink as on option (tbd)

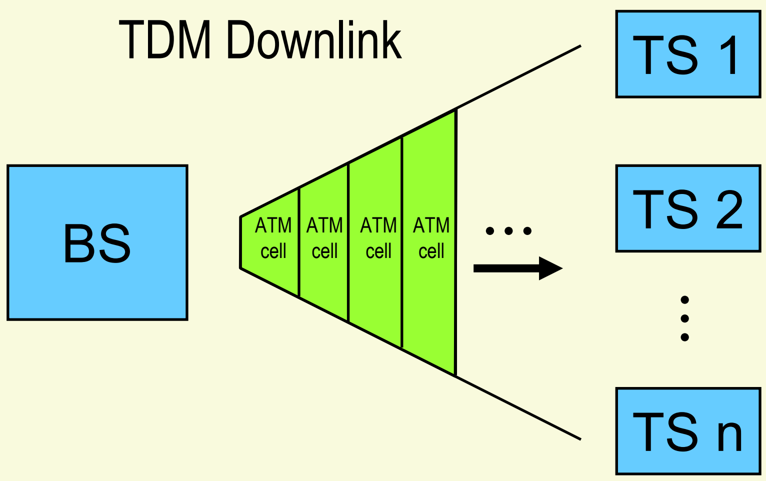
DLC layer

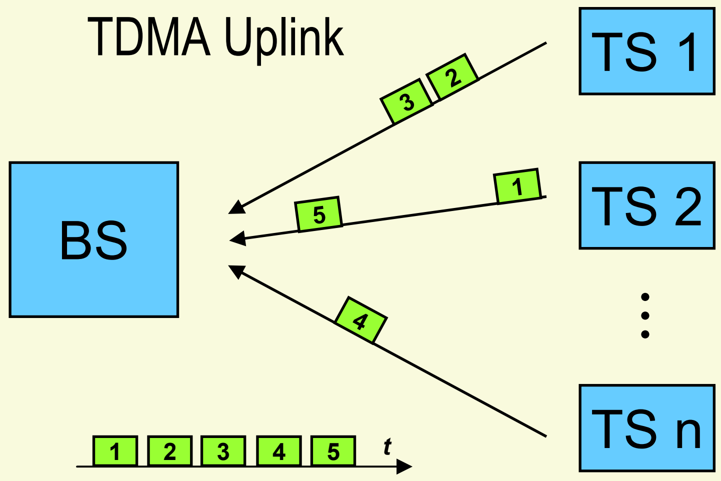
- fixed frame duration (1 ms), fixed PDU size (48 Bytes + ovh)
- variable burst duration

Point-to-Multipoint (PMP) Architecture



Overview of Downlink (DL) & Uplink (UL)





Link budget & rain fading & multipath propagation
- DL and UL identical (if small duplex frequency, no antenna beamforming at BS)

Co-channel interference
- DL: time-invariant, from other BS, allows for adaptive operation
- UL: slot-by-slot time-variant, from other TS

Transmit power
- DL: constant for all TS
- UL: individual per TS and per rain fading to achieve constant received power density

Bandwidth
- could be smaller for UL than for DL (asymmetry at 42 GHz)
- in line for UL: save TX power, use robust QPSK only, less capacity required (SOHO, residential)

Comparison of Multiple Access Schemes

Criterium	FDMA	TDMA	async.CDMA	sync.CDMA	OFDMA
Suitable for burst data, variable bit rate, high stat. multiplex gain	burst data not possible, variable bit rate delayed	packet and slots could be associated	most suitable for voice applications or CBR services		
High data rates			requires broad bands		
Low data rates	sync difficult		best performance, but graceful degradation undesired		requires many subcarriers
Symbol delay	frame relevant				frame relevant
Flexible bandwidth per sector	use part of channel				use only some subcarriers
Spectrum efficiency			inefficient, even for reuse 1		
Reference system gain, frequency reuse			system must be designed for full data rates: no Rx sensitivity benefit		backoff
Robustness to channel impairments (ISI), but not a major problem due to LOS	depends on subcarrier size	more sensitive			
Robustness to interference			reuse 1 possible		
Terminal transmit power required		high, even for low data rates			
Implementation			backoff, UL power control synchronization		orthog. loss, high backoff
Maturity					acad. research

Legend:

excellent	fair	poor

➔ TDMA is the best compromise (BRAN)

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Characteristics of Main Frequency Ranges

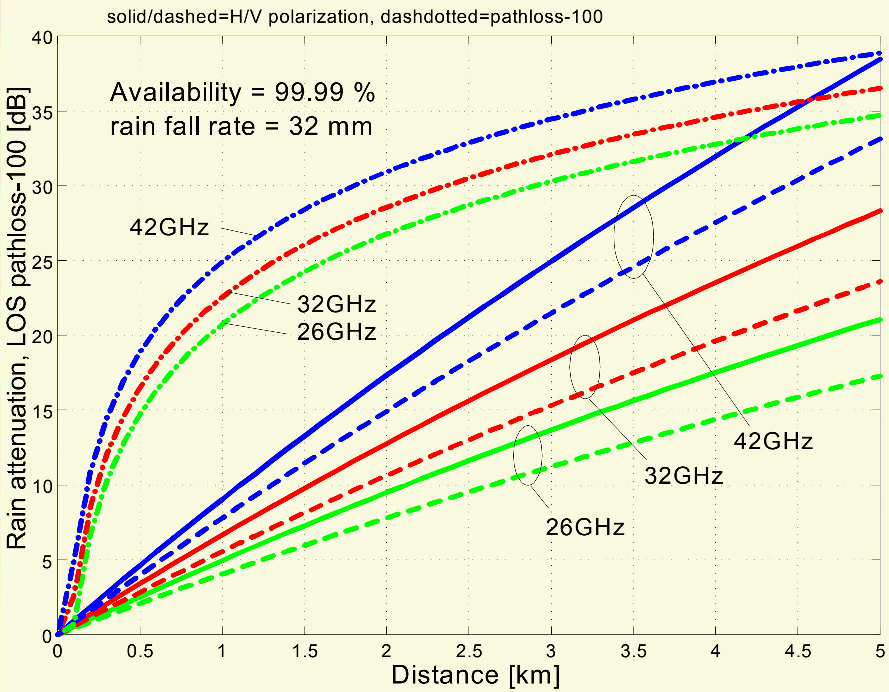
Criterion	low frequencies (e.g. 3.5 GHz)	high frequencies (e.g. 26, 32, 42 GHz)
Spectrum availability	already occupied	about 2 GHz will be available
Radio channel characteristics • ISI • rain fading	 ISI possible no rain fading	 ISI usually small severe rain fading (depending on distance and availability)
Cell radius	large (e.g. 10...15 km)	small (e.g. 2...3 km)
Costs of feeder network	low (adapt to user density)	high
Costs of customer premises equipment (CPE)	low	high (frequency generation, power amplifier)

Calculation of Required Transmit Power

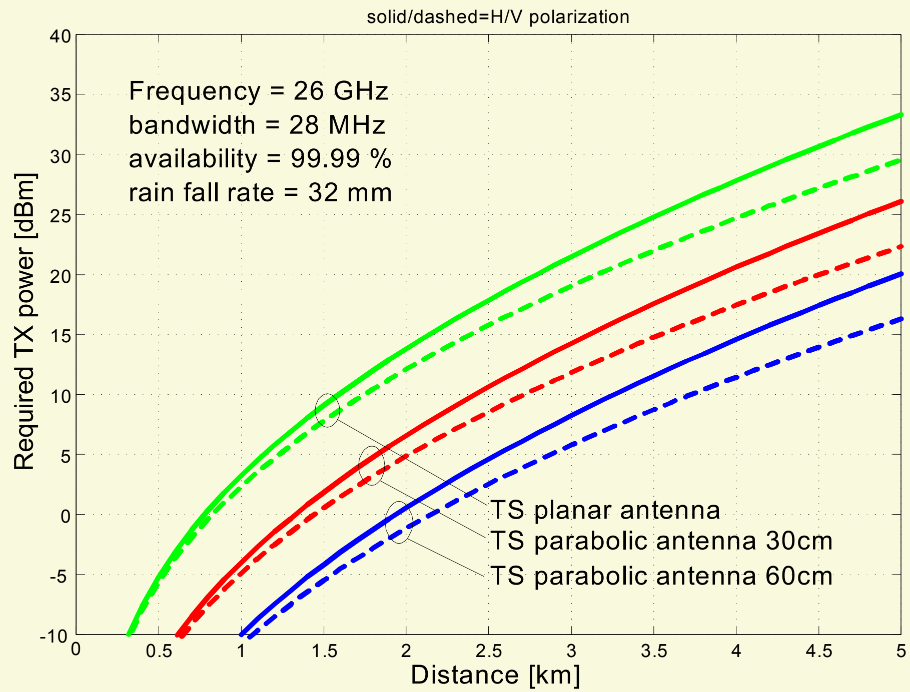
$$P_{TX} = a_{pathloss} + P_{noise} - G_{TX\_antenna} - G_{RX\_antenna} + a_{rain} + offset + \frac{C}{N+I}$$

- $a_{pathloss} = 10 \cdot \log_{10}\left(\frac{4\pi f_c}{c} \cdot d\right)^2$ **[dB] = line-of-sight path loss,**
  f_c **= carrier frequency,** c **= velocity of light,** d **= distance.**
- a_{rain} **= rain fading (depending on availability, rain zone, frequency)**
- $P_{noise} = F \cdot N_{thermal} = F \cdot KT \cdot B$ **= noise power at receiver input,**
  F **= receiver noise figure,** K **= Boltzman constant,**
  T **= temperature,** B **= bandwidth.**
- ***C/(N+I)* depending on modulation and coding and required BER**
- ***G* = antenna gains. Typical values @ 26 GHz (+4 dBi @ 42 GHz):**
  G_{BS} **= 17 dBi (8 sectors)**
  G_{TS} **= 28 dBi (planar), 35...41 dBi (30...60 cm parabolic)**

Rain Fading and Link Budget



Rain fading @ availability = 99.99%
and free-space pathloss
(depending on frequency range)



Required transmit power @ 26GHz
(depending on terminal antenna)

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Influences on the Link Budget

- Bandwidth
- Frequency range
- Distance
- Coding and Modulation
- Rain zone
- Availability (99.9 ... 99.999%)
  - wrt. rain (rain intensity & user traffic may vary with time of day)
  - wrt. C/I (for uplink)
  - at the cell border or averaged over the sector
- Sectorization
- Terminal antenna gain (limited by minimum safety distance)
- PA linearity requirements (depending on modulation)
- Implementation losses (tight tolerance schemes for less power requirements or vice versa?)

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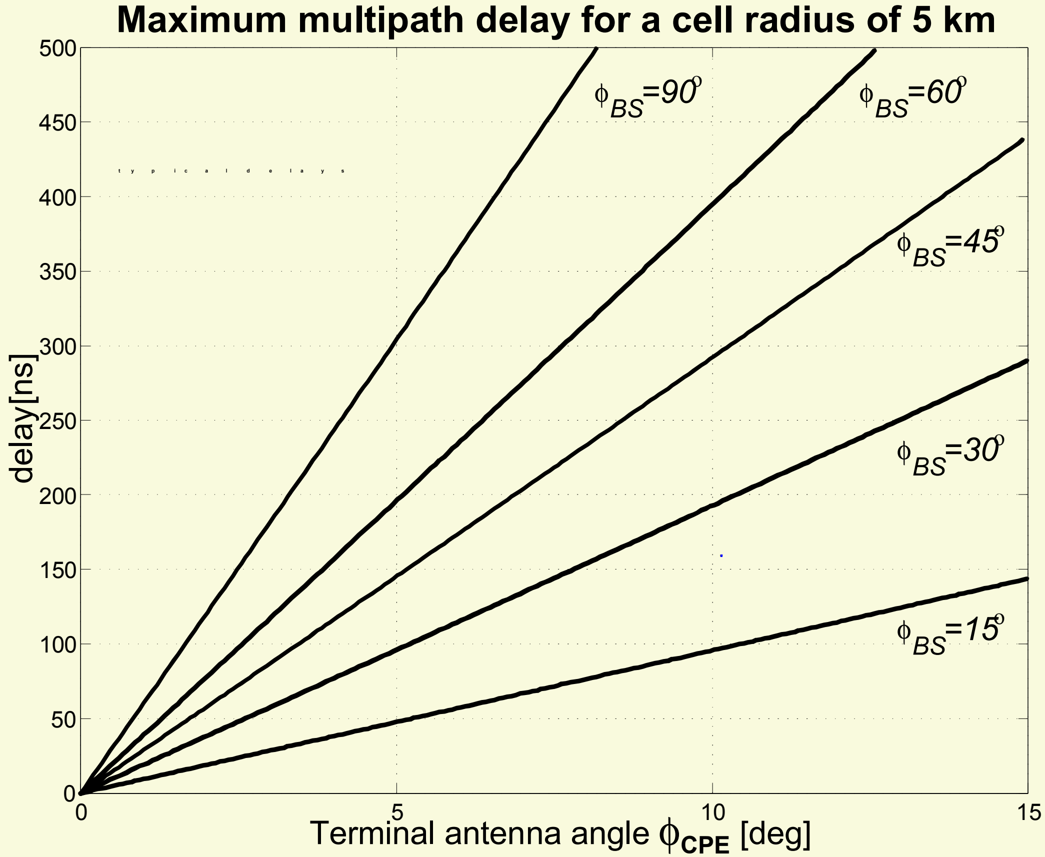
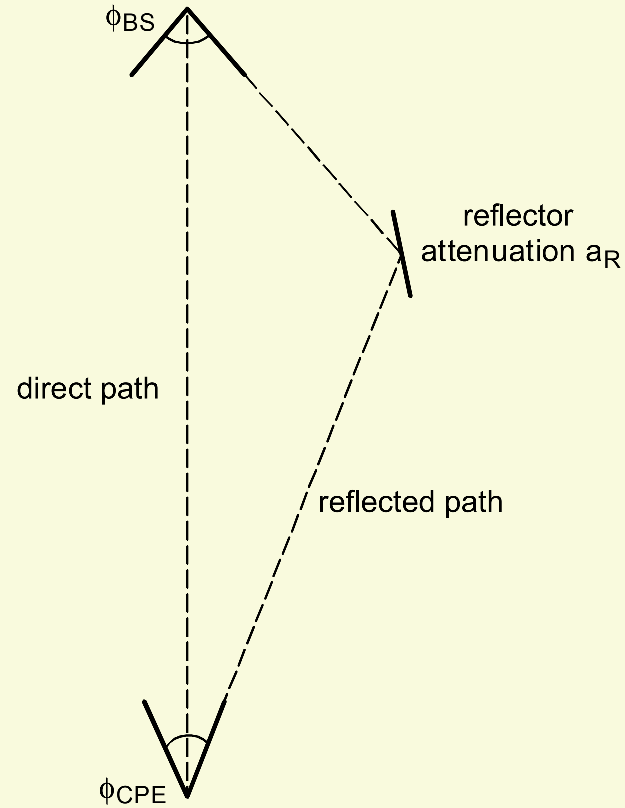
Max. Delay of Multipath Radio Propagation





	Typical delays	Reflector attenuation a_R
High frequencies (2.5km)	40 ns	high (very short wavelength)
Low frequencies (10km, NLOS)	500 ns	low
Multidwelling IF cable	100 ns	very high
SAW IF filter	500 ns	very high

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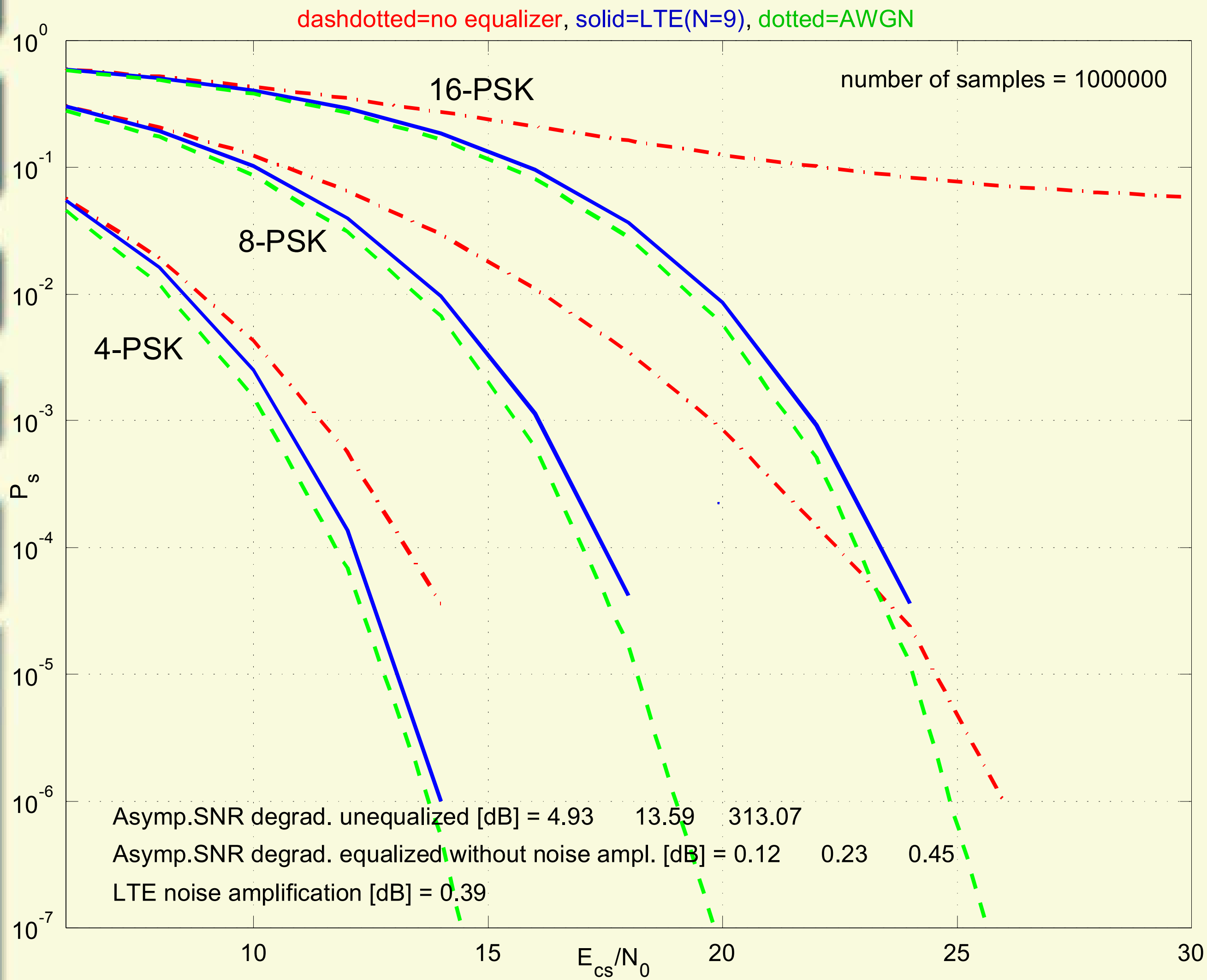
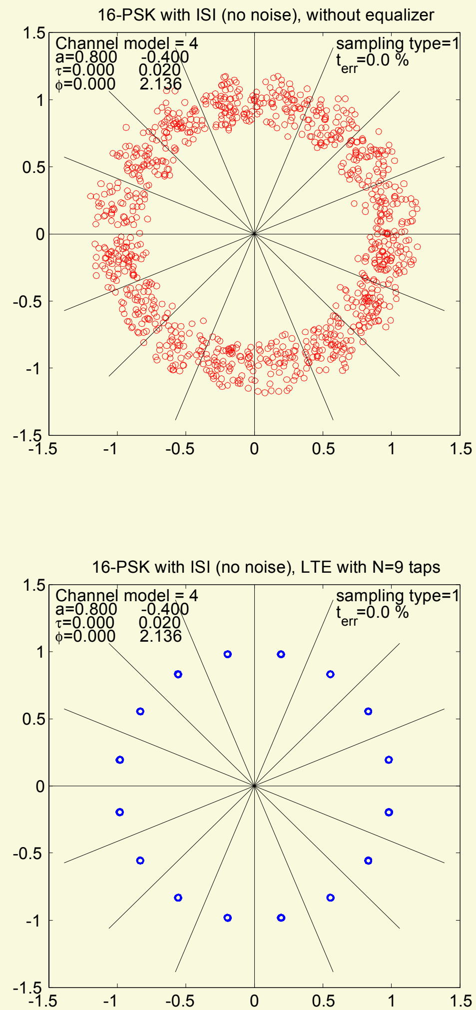
Performance of Linear Transversal Equalizer

(Assumptions: 9 taps, BRAN HA channel 2bis)



Symbol error rate over E_{cs}/N_0



16-PSK plots (no noise)

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Adaptive Modulation & Coding - Basics

Application

- Adaptation in downlink according to distance, rain fading (C/N) and interference (C/I)
- No adaptation in uplink (lower data rates, more sensitive to interferences, fast C/I-changes)
- 4QAM. . .64QAM; convol. and trellis coded modulation, RS codes

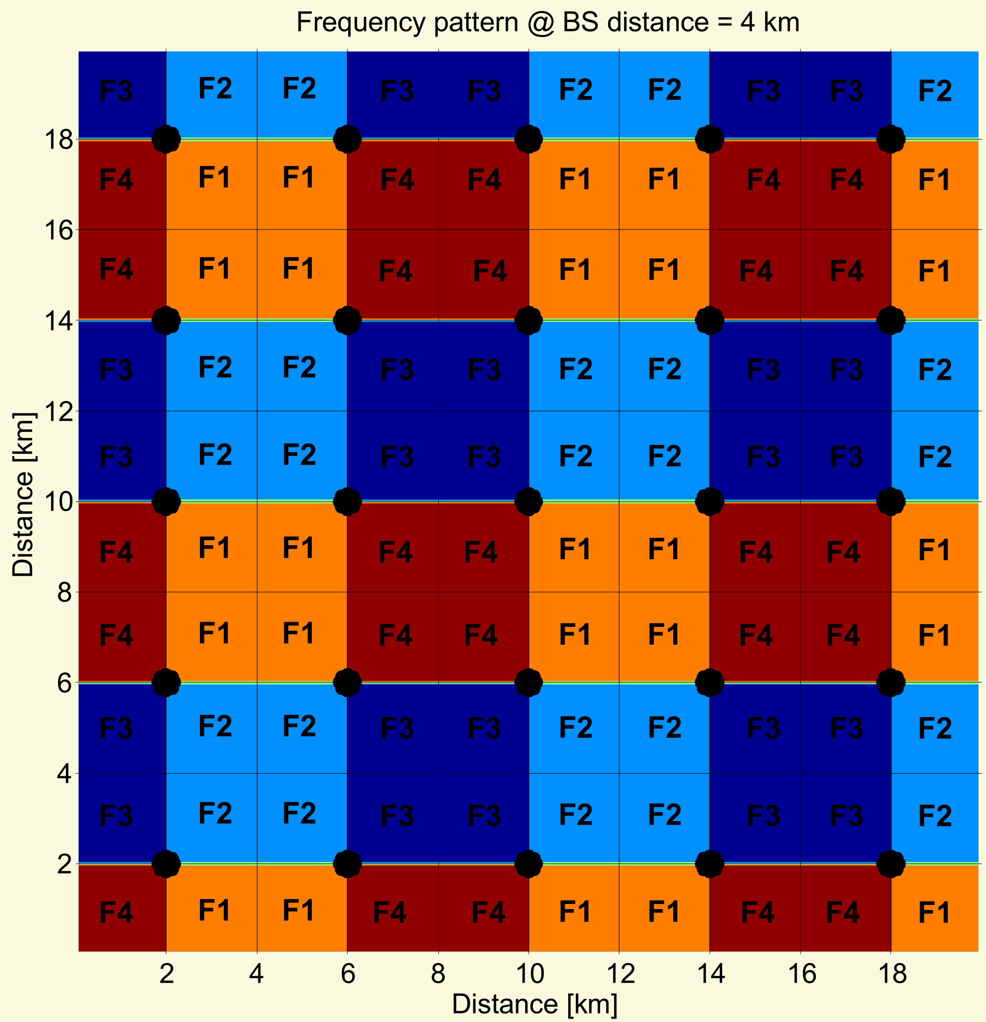
Adaptive modulation requires burst-mode

(e.g. one slot containes one ATM cell)

- TDMA/TDMA instead of TDM/TDMA
- Limited performance of coding (no interleaving, short block codes)
- Each slot requires extra overhead for synchronization

➔ Compare adaptive modulation under real system conditions with best fixed modulation!

Frequency Plan for a Rectangular Constellation (25 cells, 100 sectors, Re-use Factor = 4)



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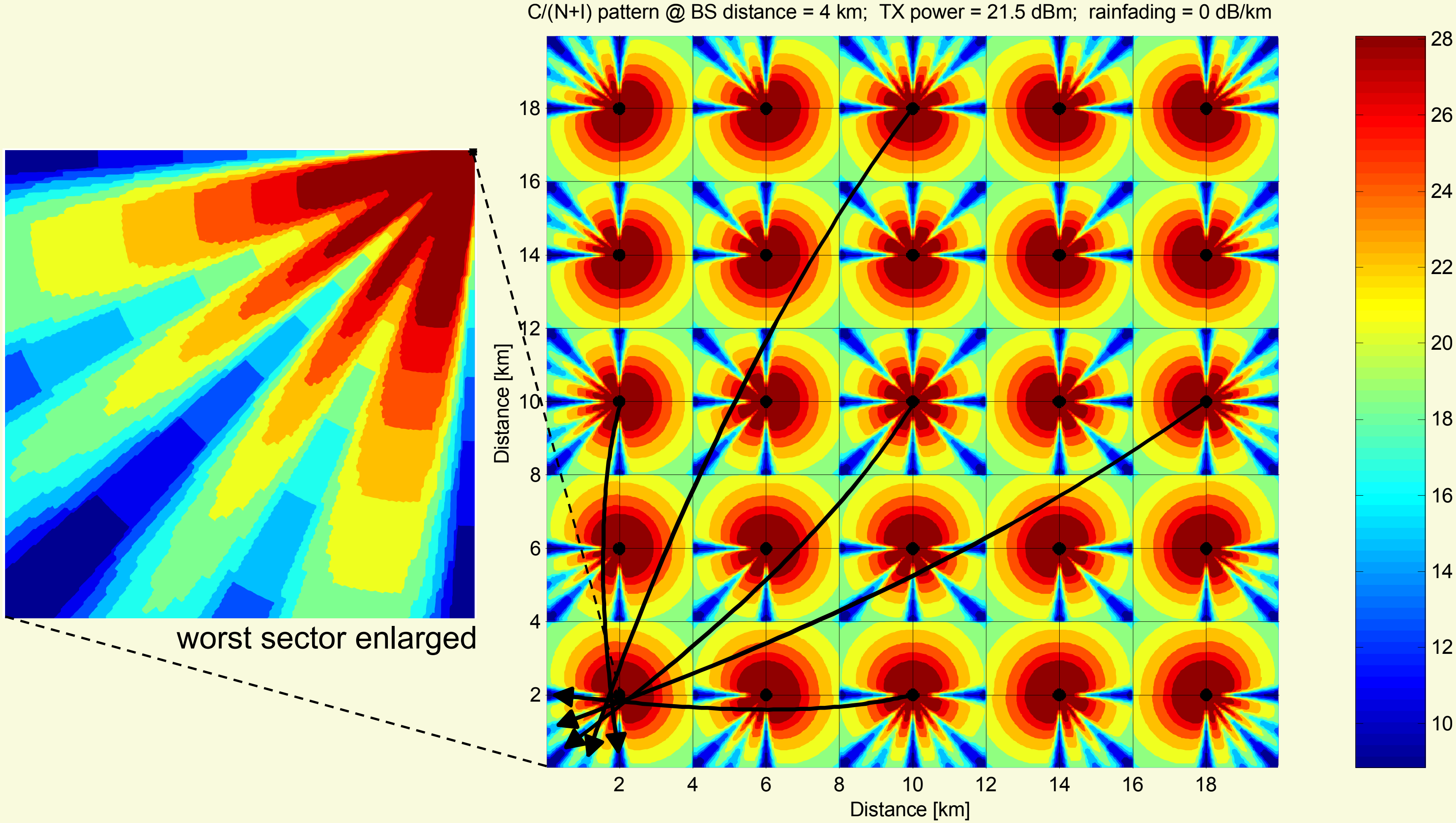
C/(N+I) Distribution in a 5x5 Rectangular Constellation (Re-use Factor = 4)



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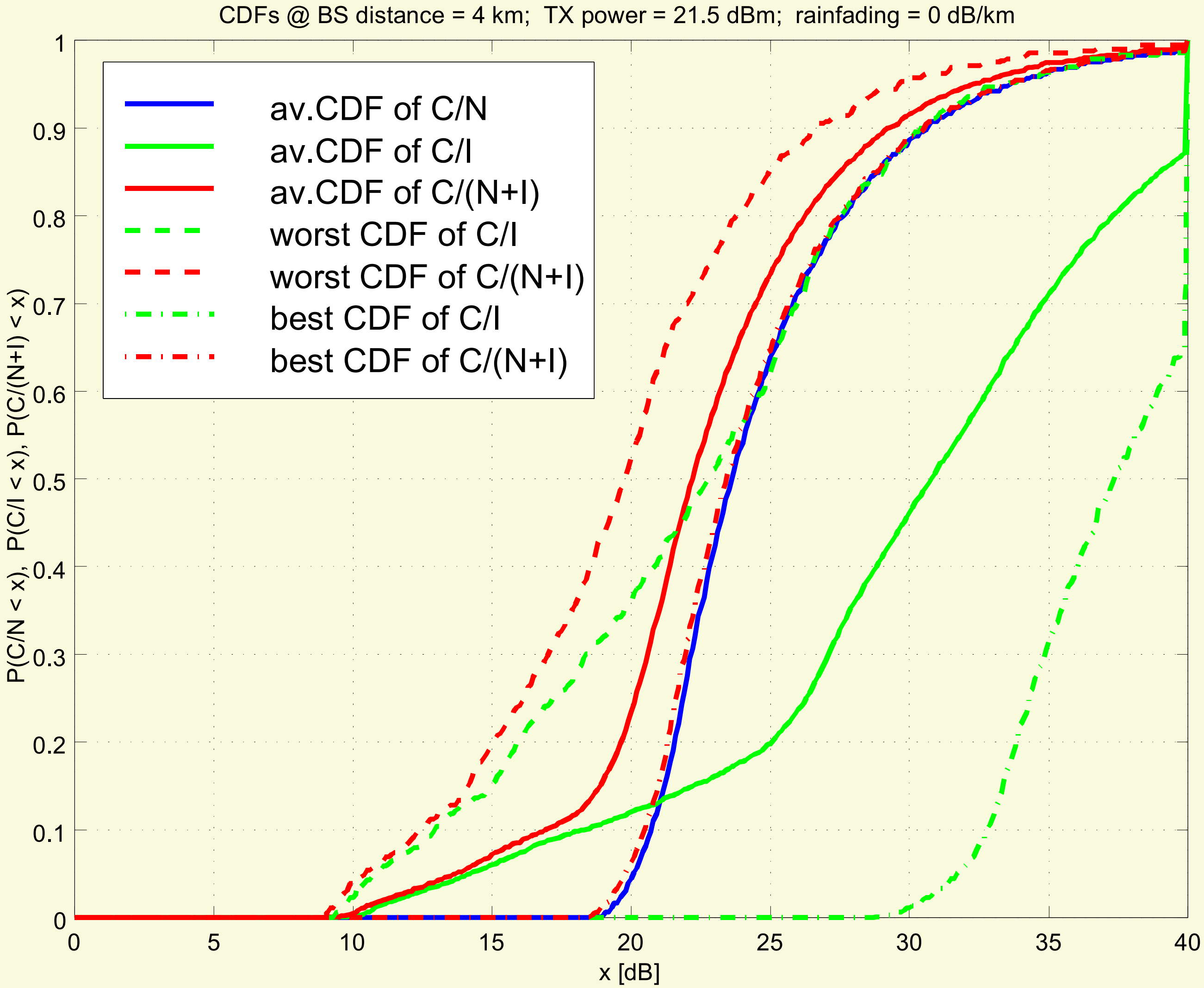
Cumulative Distribution Functions for Rectangular 5x5 Constell. (Re-use=4)



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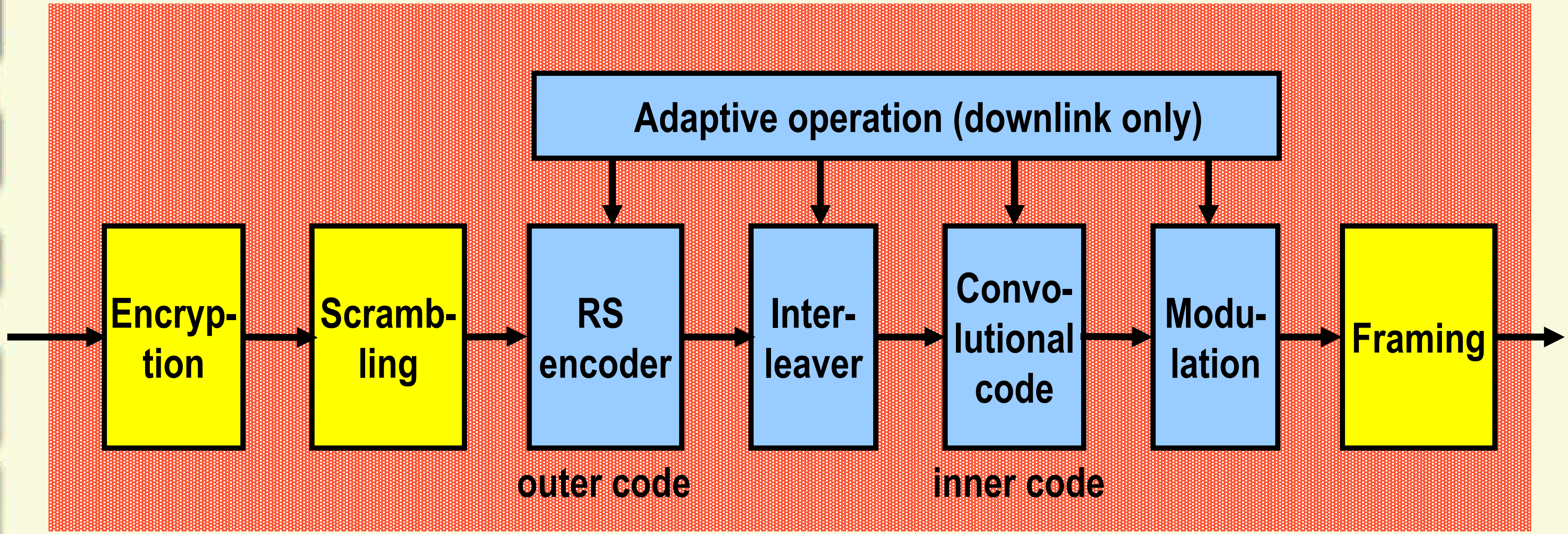
Digital Modem with Concatenated Coding



Downlink:	2...4 ATM cells	RS(228,212) t=8	2...4 blocks	rate 1/2...3/4	QPSK... 64QAM
Uplink:	n/a	RS(69,53) t=8	n/a	R=1/2	QPSK

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Adaptive Modulation & Coding - Candidates

Modulation and inner coding	Outer coding			
	long RS(228,212) interleaving		short RS(69,53) no interleaving	
	C/(N+I) [dB]	Spec.Eff. [bit/symb]	C/(N+I) [dB]	Spec.Eff. [bit/symb]
QPSK, R=1/2	3.2	0.93	4.5	0.73
QPSK, R=2/3	4.8	1.24	6.1	0.95
QPSK, R=3/4	6.0	1.39	7.3	1.06
8PSK TCM	8.5	1.86	9.8	1.37
16PSK TCM	14.5	2.79	16.2	1.96
16QAM TCM	12.0	2.79	13.7	1.96
64QAM TCM	19.3	4.65	21.5	2.98

Note: C/(N+I) refers to BER=10^{-11}
spectral efficiency for short RS includes 32 symbol sync. word

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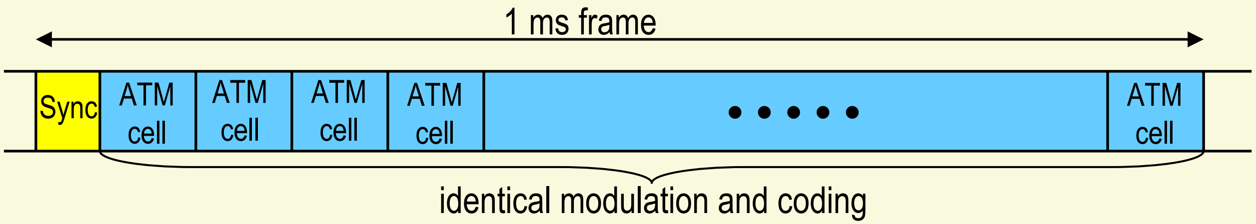
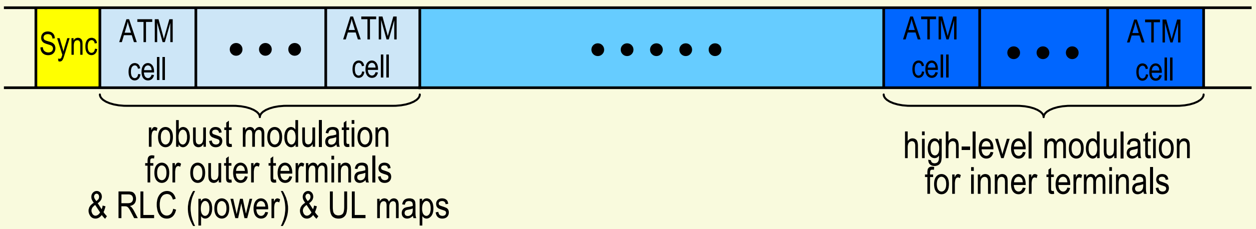
Framing Strategies for DLC Layer

Configurable modulation (downlink TDM)



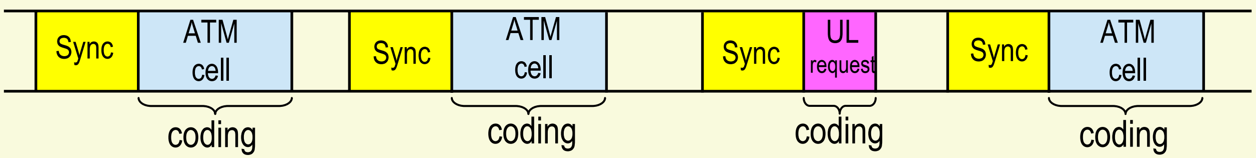
- identical modulation & coding for frame
- long RS code & interleaving over several cells within frame
- worst link determines sector

Adaptation of terminal groups (downlink TDM)



- identical modulation & coding for group
- long RS code & interleaving over several cells within group

Adaptation slot-by-slot (downlink TDMA, uplink TDMA with robust modulation)



- individual modulation & coding for each cell
- short RS code for one cell, no interleaving

Remarks: 1 ms frame contains about 30 ... 250 ATM cells (depending on modulation and overhead)
„ATM cell“ also includes RLC and MAC packets

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Spectral Efficiency with Adaptive Modulation (Re-use Factor = 4)

	Strategy				
	configurable modulation long RS code interleaving	adaptation terminal groups long RS code interleaving		adaptation slot-by-slot short RS code no interleaving	
	QPSK3/4 8PSK 16PSK	QPSK3/4 8PSK 16PSK	QPSK3/4 16QAM 64QAM	QPSK1/2 8PSK 16PSK	QPSK1/2 16QAM 64QAM
	Spectral efficiency in bit/symbol				
Clear sky • worst sector • best sector • average sector	 1.86 2.79 2.01	 2.41 2.65 2.57	 2.86 3.56 3.27	 1.73 1.96 1.89	 1.86 2.28 2.12
Rain condition • worst=best sector	 1.39	 2.25	 2.68	 1.62	 1.72

Assumptions: no terminals below BS beam, no LOS obstructions

Alternatives: more modulation levels, more RS flexibility (n,t), iterative decoding, Turbo codes

Remarks on Spectral Efficiency Results

- The average spectral efficiency for configurable modulation is disappointing for constellations of 5x5 or larger due to many sectors with small critical areas, but better for smaller constellations.

- 64QAM is never applicable for configurable modulation,
  ➔ QPSK-8PSK-16PSK is better than QPSK-16QAM-64QAM.

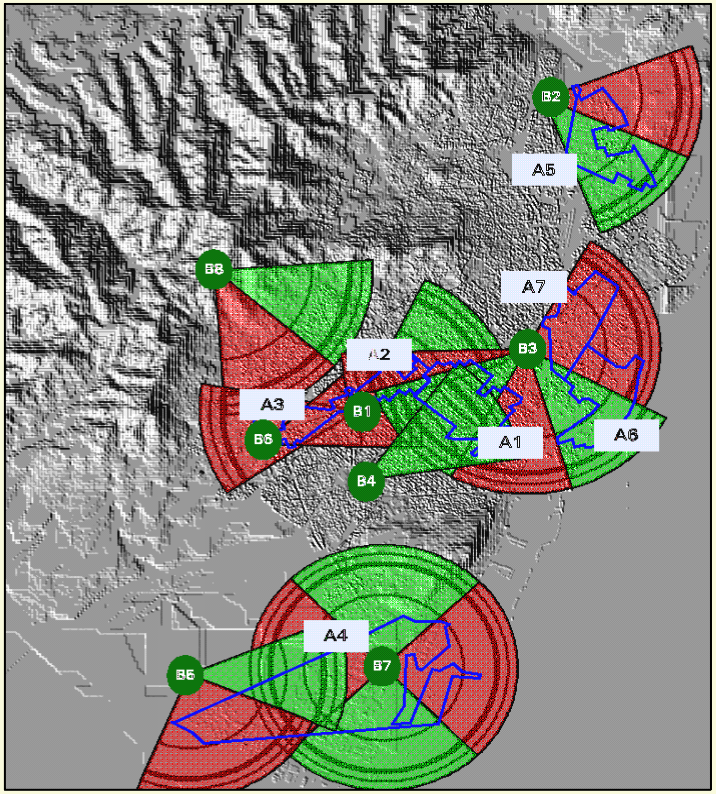
- Adaptation of terminal groups requires some extra overhead (e.g. padding of groups, shifting of terminals to more robust groups).

- All results for worst/best sectors apply also for larger constellations.

- All results depend on many parameters:
  - link budget (P_{TX}, distance, rain fading, rain zone, frequency range, bandwidth, sectorization, availability, antenna gain)
  - frequency re-use factor, constellation size
  - cellular coverage, e.g. overlapping required for better coverage but reduces C/(N+I), particularly irregular constellations in practice
  - only C/N but not C/I depends on P_{TX} (for clear sky)

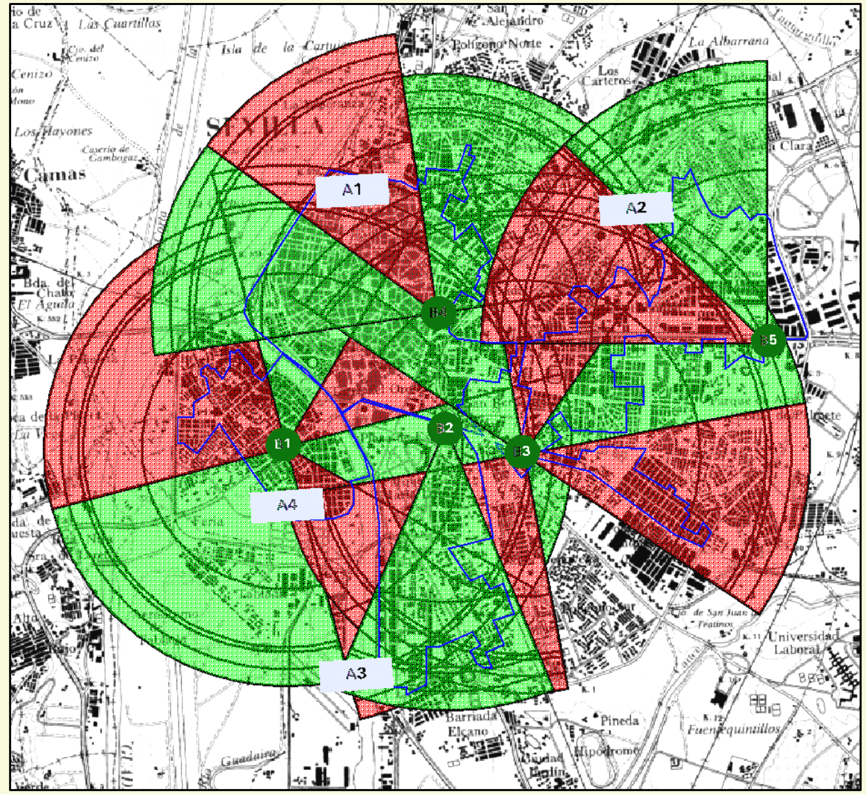
Coverage and Overlapping Sectors

Partly Overlapping Sectors



- Decoupling by polarisation
- LOS < 50 - 70 %
- Reuse 100 %

Fully Overlapping Sectors



- Decoupling by polarisation & frequency
- LOS nearly 100 %
- Reuse nearly 100 %

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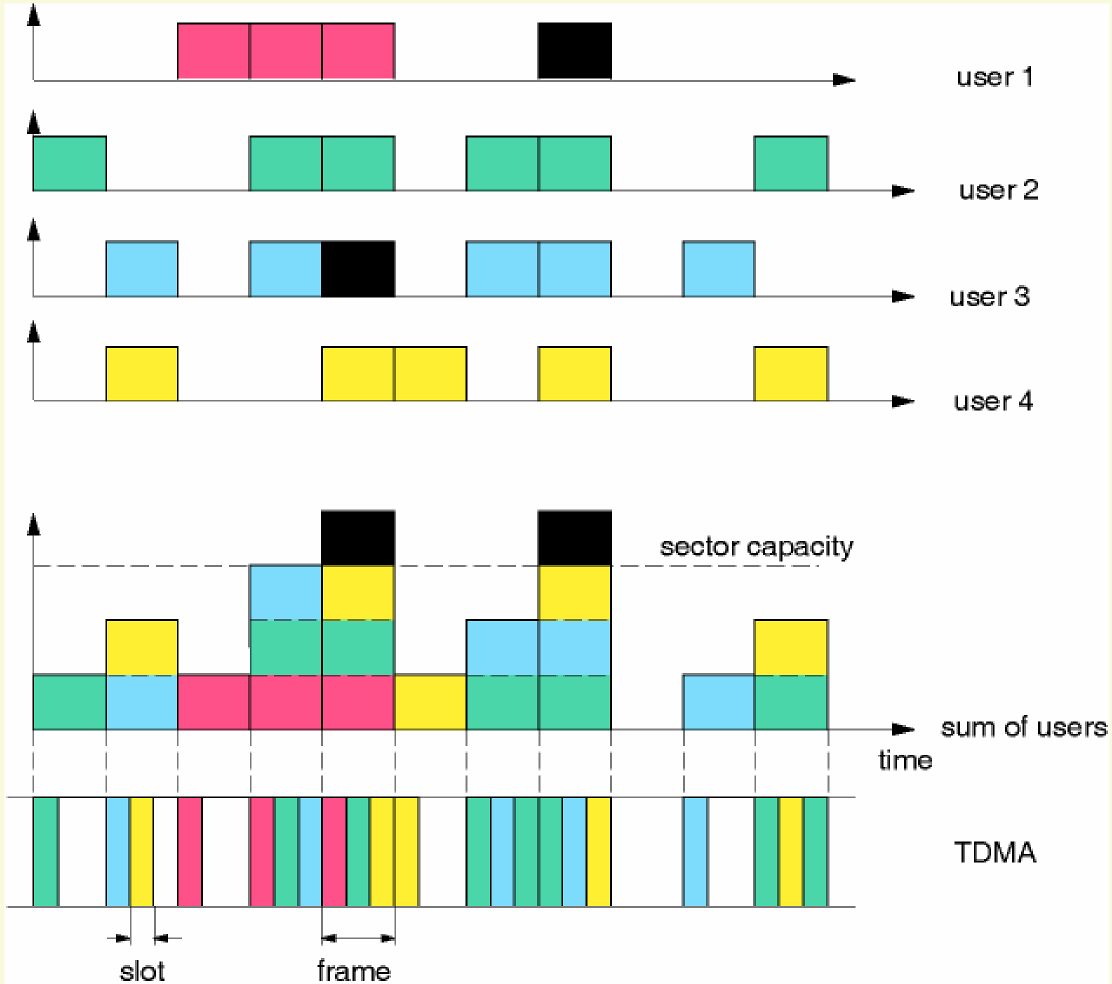
A Simple Traffic Model for Statistical Multiplex Gain Analysis



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Statistical Multiplex Gain - Fundamentals

A PMP system performs as a virtual multiplexer.

Let r_s = total sector rate, r_p = peak data rate per user, r_a = average data rate per user, $b = r_p / r_a$ = burstiness of the data source,

N_{eff} = # users with static collision free multiplex
N_{eff} = # user with statistical multiplex

The statistical multiplex gain ***G***

$$G = \frac{N_{eff}}{N_{cf}} = \frac{\text{max \#users with statistical multiplex}}{\text{max \#users with static collision} - \text{free multiplex}}$$

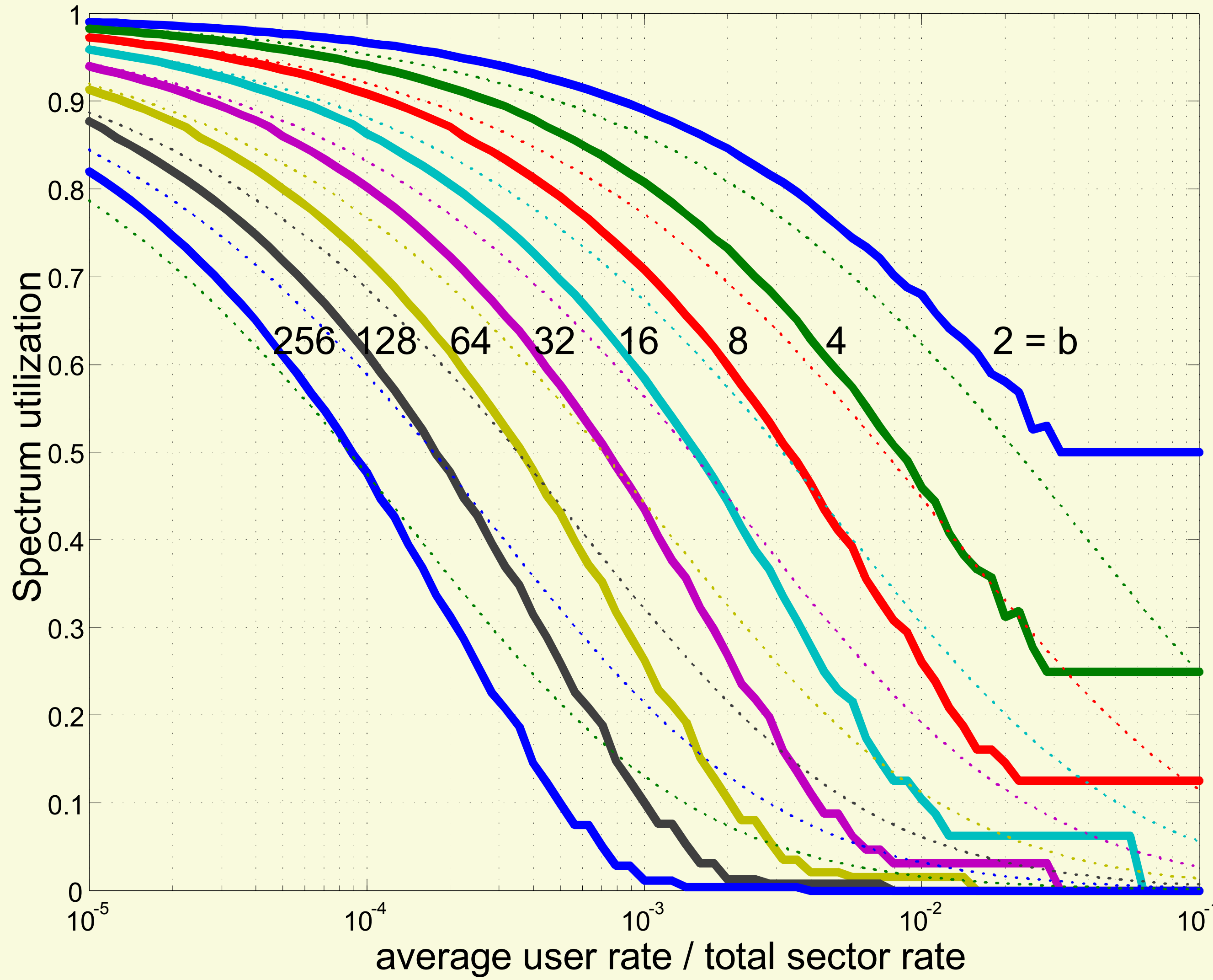
$$= \frac{N_{eff} \cdot r_p}{r_s} = \frac{\text{required total sector rate with static collision} - \text{free multiplex}}{\text{required total sector rate with statistical multiplex}}$$

and the spectral utilization ***U = G/b*** refer to the cell loss rate (CLR)

$$CLR = \frac{\text{average number of lost cells}}{\text{average total number of cells to be transmitted}}$$

$$= 1 - \frac{1}{r_a / r_s \cdot N_{eff}} \cdot \sum_{k<N_{cf}} (k - N_{cf}) \cdot \binom{N_{eff}}{k} \cdot p^k (1-p)^{N_{eff}-k}.$$

Spectrum Utilization (CLR=10^{-6})



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Conclusion on Reasonable Bandwidth

- **High multiplex gain or high spectrum utilization requires a high number of users, i.e. a high bandwidth per sector and large sectors in order to achieve high user densities per sector. However, both large bandwidth as well as wide range imply an increase of the required transmit power in case of pure TDMA.**

- **The difference between poor and excellent spectrum utilization is approximately a factor of 10 to 100, depending on the burstiness and the CLR. Hence a doubling of the bandwidth per carrier has a certain but not overwhelming effect.**

➔ **A bandwidth of 28 MHz per TDM/TDMA carrier is a "reasonable" compromise.**

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Summary

The design of a

- spectral-efficient
- flexible (wrt. to services and deployment)
- cost-efficient

wireless broadband PMP access network is a very complex optimization problem, both for PHY and DLC layer.

Key challenges for R&D include

- digital modem technology,
- multiple access schemes (PHY layer),
- medium access control (DLC layer),
- microwave and antenna technology,
- cell and frequency planning.