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Chapter 8.3
3rd Generation Mobile Networks - UMTS

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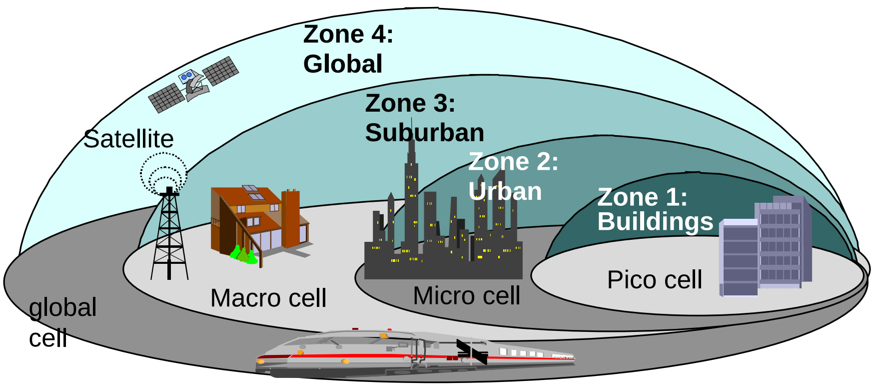
Chapter 8 Mobile Communications Networks

Targets and Main Structure

Targets:

- Mobile communication with higher data rates and new services
- Integration of voice and data traffic
- Service provisioning „*anyone, anywhere, and anytime*"
- Concept of the „*mobile office*"



2Gs: Satellite networks

Public mobile and fixed networks

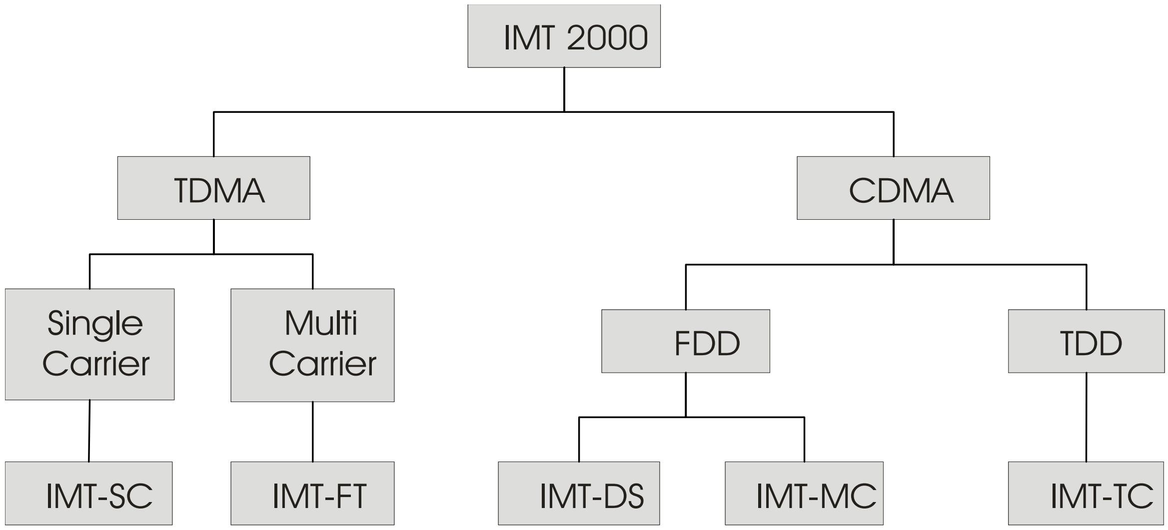
Private fixed networks in housing areas

Mobile Communication Networks of the 3rd Generation

- 3G Networks standardized by the ITU (International Telecommunication Union) as IMT-2000 with several alternatives for the air interface:
  - IMT-DS (Direct Sequence, UTRA FDD)
  - IMT-MC (Multi Carrier, cdma2000)
  - IMT-TC (Time Code, UTRA TDD, TD-SCDMA in china)
  - IMT-SC (Single Carrier, EDGE)
  - IMT-FT (Frequency Time, DECT)
- 3rd Generation Partnership Project (3GPP) works on technical specifications for GSM, i.e. UMTS and EDGE
- 3rd Generation Partnership Project 2 (3GPP2) works on technical specifications for cdmaOne standards, i.e. cdma2000

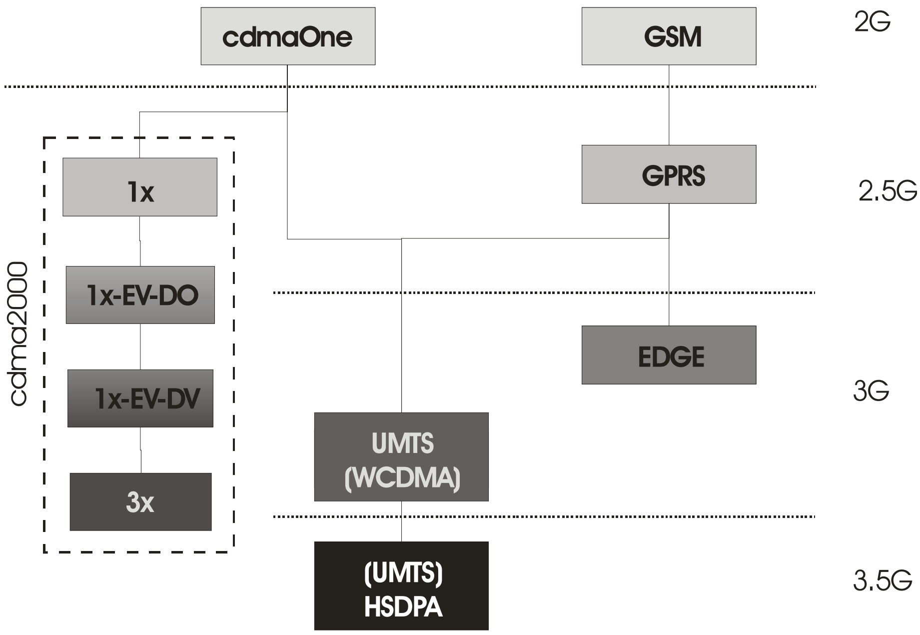
IMT-2000

Standardization of 3rd generation mobile networks:
International Mobile Telecommunications-2000 (IMT-2000)



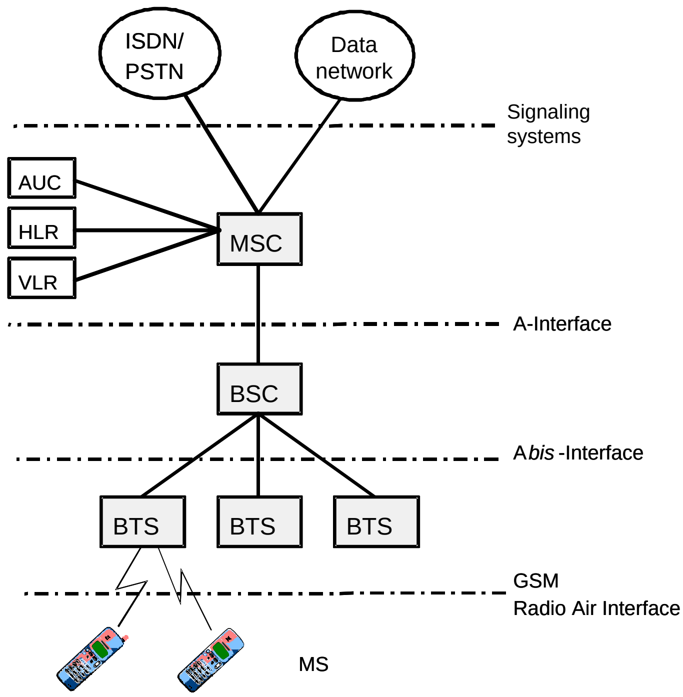
Evolution of Mobile Communication Standards

Overview of the evolution of mobile network standards from 2G to 3.5G



Chapter 8 Mobile Communications Networks

For Comparison: Architecture of the GSM Network



PSTN: Public Switched Telephone Network

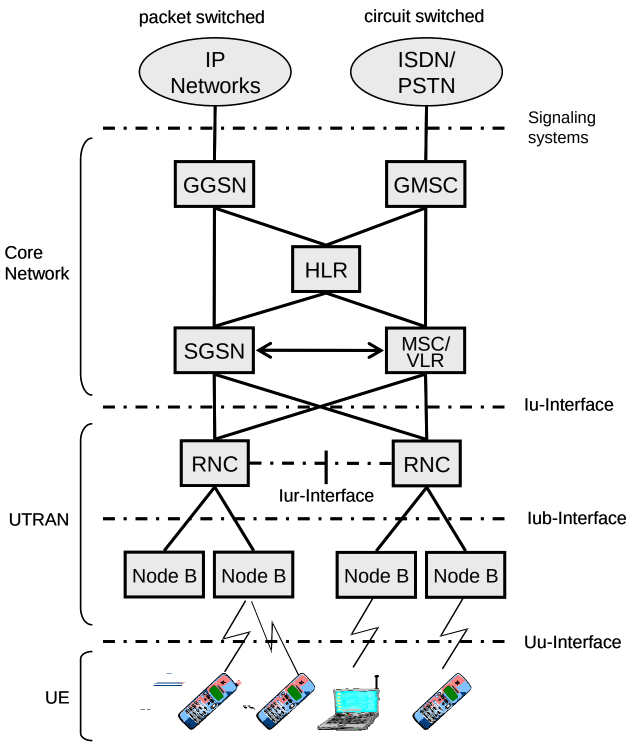
AUC: AuthenticationCenter
HLR: Home Location Register
VLR: Visitor Location Register
MSC: Mobile SwitchingCenter

BSC: Base Station Controller

BTS: Base Transceiver Station

MS : Mobile Station

Architecture of a UMTS Network



GGSN: Gateway GPRS Support Node
GMSC: Gateway MSC

HLR: Home Location Register

SGSN: Serving GPRS Support Node
MSC: Mobile Switching Center
VLR: Visitor Location Register

UTRAN: UMTS Terrestrial Radio Access Network
RNC: Radio Network Controller

Node B: Base Station in UMTS network

UE : User Equipment

UMTS Network Architecture

- The architecture of UMTS comprises
  - **UE** (User Equipment) : Corresponds to a MS (Mobile Station) in GSM
  - **UTRAN** (UMTS Terrestrial Radio Access Network) : Includes all radio relevant functionalities
  - **CN** (Core Network) : Fixed network or transport network, responsible for routing and switching
  - **UMTS-PLMN** (PLMN: Public Land Mobile Network) : Subnet of a network operator or UMTS service provider

UMTS Network Architecture

- **UE (User Equipment)** consists of
  - ME (Mobile Equipment) : Hardware element of the UE
  - USIM (UMTS Subscriber Identity Module) : Smartcard with all relevant user data

- **UTRAN** (**UMTS Terrestrial RAN** – (RAN: Radio Access Network))
  - „NodeB“ : corresponds to a „Base Station“
  - RNC (Radio Network Controller) :
    - Connected to several NodeBs,
    - Manages and controls radio resources of the connected NodeBs

UMTS Network Architecture

CN (Core Network)

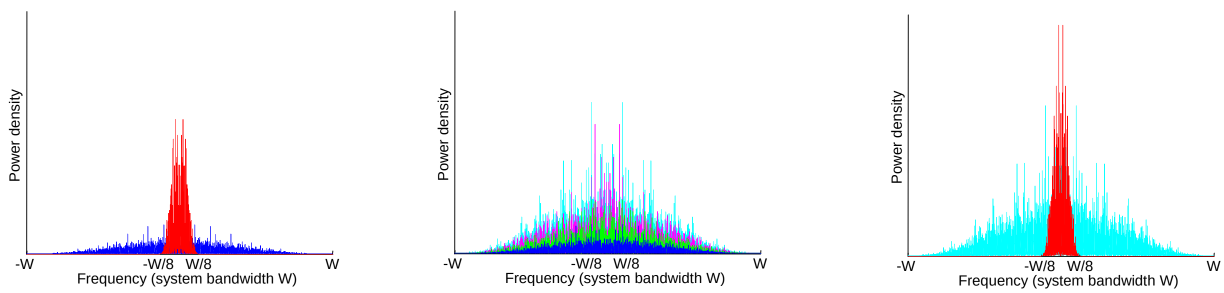
- Circuit switched domain:
  - MSC/VLR (Mobile (Services) Switching Center/Visitor Location Register)
    - MSC: Mobile Switching Center
    - VLR: Data base with information of users which are temporarily in the domain of the MSC
  - GMSC (Gateway MSC): Interface between the service provider’s own network (UMTS-PLMN) and external networks (e.g. telephone networks)
- Packet switched domain:
  - SGSN (Serving GPRS Support Node)
  - GGSN (Gateway GPRS Support Node)
- HLR: Home Location Register, data base with information about users registered in the operator domain; consists of fundamental user data (services, tariff, etc.)

Chapter 8 Mobile Communications Networks

CDMA-Technology

General Aspects:

a) Spreading b) Multiplexing: Interference c) De-spreading



CDMA-Technology: History

- **CDMA :** Code Division Multiple Access
  - **July 1993**: The proposition of QUALCOMM for the air interface of the north American cellular standard is approved (IS-95, CDMAone)
  - **1995**: ANSI J-STD-008 CDMA Standard for PCS (Personal Communications Services).
  - **January 1998:** The ETSI chooses Wideband-CDMA as FDD access technology for the UMTS air interface.
  - **Spring 2004:** Introduction of the first UMTS systems in Germany

CDMA-Technology: Principles of Transmission

- Principles of code multiplex transmission
  - Spreading of the signals with
    - Orthogonal codes (channelization codes) and
    - Pseudo-orthogonal codes (uplink in IS-95)
  - Separation of spread signals originating from spatially distant sources by using pseudo-orthogonal codes (scrambling codes)
  - Recovery of the signal at the receiver by
    - Correlation filtering
    - Other signals with different scrambling codes are seen as random noise

Orthogonal Codes (Channelization Codes)

- Code is a vector $c = c_1, c_2, \ldots, c_n$ with $c_j \in \{+1, -1\}$
- Length n of the codes is called spreading factor
- Two codes c and d are orthogonal if and only if the inner (scalar) product $c \bullet d$ is zero:

$$c \bullet d = \sum_{j=1}^{n} c_j \cdot d_j = 0.$$

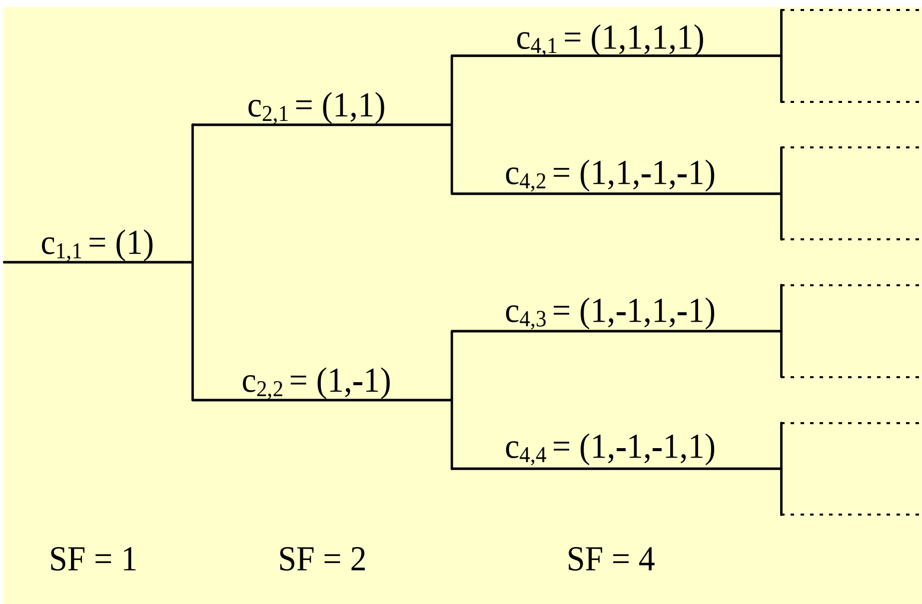
- The scalar product of a code with itself is equal to the spreading factor of the code:

$$c \bullet c = \sum_{j=1}^{n} c_j . c_j = n$$

- In UMTS: maximal spreading factor 512, minimal spreading factor 4

Orthogonal Codes (Channelization Codes)

- The generation of orthogonal codes follows the OVSF-tree (Orthogonal Variable Spreading Factor)



Pseudo-Orthogonal Codes (Scrambling Codes)

- Pseudo-orthogonal codes are uncorrelated pseudo-random +1/-1 -sequences
- Generation of pseudo-orthogonal codes with shift registers
- Scalar product of pseudo-orthogonal codes with size n:

$$E[c \bullet d] = 0 \quad \text{and} \quad VAR[c \bullet d] = n$$

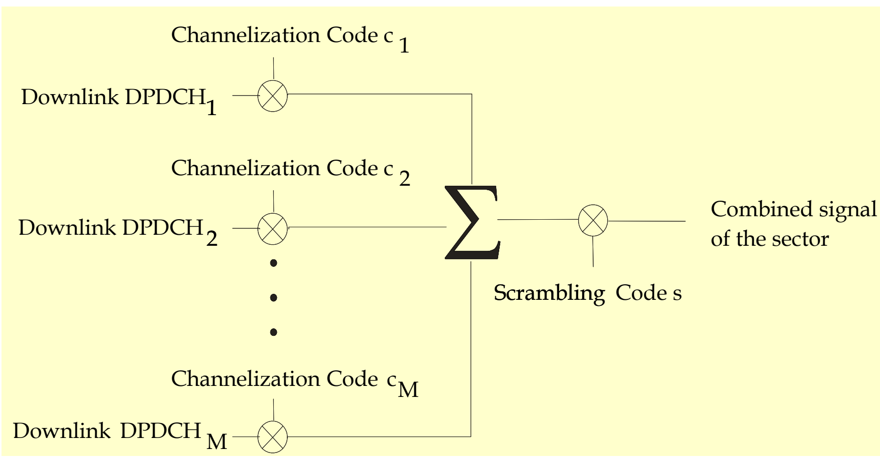
- Small autocorrelation of pseudo-orthogonal codes:

$$\sum_{j=1}^{n} c_j \cdot c_{j+k} \approx 0 \quad \text{for} \quad k = 1,2,\ldots$$

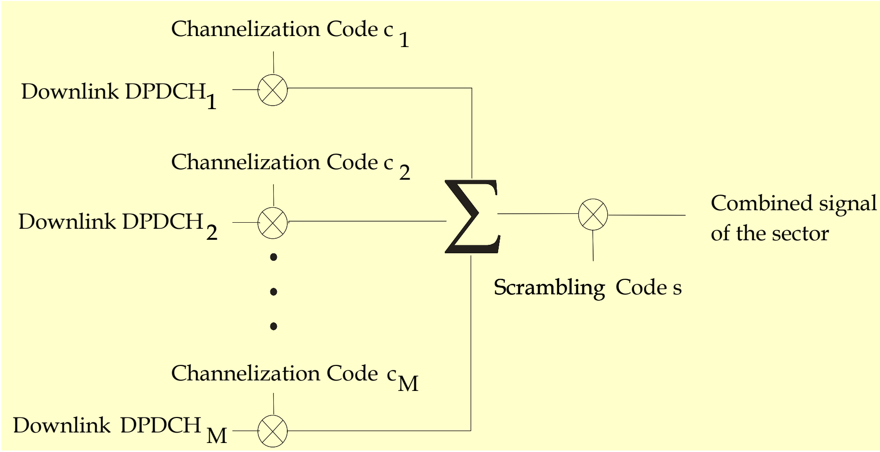
- Multipath propagation can lead to multiple time-shifted receptions of the same signal
- With the small autocorrelation of the scrambling code the signals are almost orthogonal and the interference is still small
- In IS-95, pseudo-orthogonal codes are used for spreading

Scrambling

- In UMTS, a signal is first spread to the system chip rate by using orthogonal codes
- The result is then bit-wise multiplied with a scrambling code of the same chip rate
- Channelization and scrambling of the signals in one sector on the UMTS downlink (DPDCH=Dedicated Physical Data Channel):



Scrambling



- The scrambling does not change the chip rate of the signal
- The signal of a user (corresponding to a downlink DPDCH) is orthogonal to the other signals in the same sector and pseudo-orthogonal to the signals from other sectors and NodeBs

Spreading and De-spreading of a Signal

- Signal of user i consists of one bit $x_i, i = 1,\ldots, M$
- User i uses spreading code $c_i = c_{i,1} \ldots c_{i,n}$
- Signal of user i after spreading $z_i = x_i \cdot c_i = x_i \cdot c_{i,1} \ldots x_i \cdot c_{i,n}$

  i.e. $z_{i,j} = x_i \cdot c_{i,j}$ für $1 \le j \le n$

- Superimposed signal at the receiver (j -th bit):

$$Z_j = \sum_{i=1}^{M} z_{i,j} = \sum_{i=1}^{M} x_i \cdot c_{i,j}$$

- K-th receiver depreads signal (Scalar product $Z \bullet c_k$)

$$y_k = \frac{1}{n}(Y \bullet c_k) = \frac{1}{n} \cdot \left[\sum_{j=1}^{n} \left(\sum_{i=1}^{M} x_i \cdot c_{i,j} \right) \cdot c_{k,j} \right]$$

$$= \frac{1}{n} \cdot \left[\sum_{i=1}^{M} x_i \cdot \left(\sum_{j=1}^{n} c_{i,j} \cdot c_{k,j} \right) \right] = \frac{1}{n} \sum_{i=1}^{M} x_i \cdot (c_i \bullet c_k) = x_k + \frac{1}{n} \sum_{\substack{i=1 \\ i \ne k}}^{M} x_i \cdot (c_i \bullet c_k)$$

Spreading and De-spreading of a Signal

- Recovery of the signal: $x_k^{'} = \mathrm{sign}(y_k)$
- For orthogonal codes holds $y_k = x_k$

$$y_k = x_k + \frac{1}{n} \cdot \sum_{\substack{i=1 \\ i \neq k}}^{M} x_i \cdot \left(\overbrace{\sum_{j=1}^{n} c_{i,j} \cdot c_{k,j}}^{=0} \right) = x_k$$

- For pseudo-orthogonal codes holds

$$y_k = x_k + \frac{1}{n} \cdot \sum_{\substack{i=1 \\ i \neq k}}^{M} x_i \cdot \left(\sum_{j=1}^{n} \overbrace{c_{i,j} \cdot c_{k,j}}^{\substack{\text{random} \\ +1 \text{ or } -1}} \right) = x_k + I_k$$

- If pseudo-orthogonal codes are used the interference due to other signal is called *multiple access interference* (MAI) I_k
- The MAI is the sum of random bits, i.e. the sum of many independent and identically distributed random variables, so following the law of large numbers it is well approximated by a normal distribution

Example of a Transmission with Orthogonal Codes

- Every bit on the input is multiplied with a unique spreading code, what leads to the spreading of the signal in the frequency domain (data rate is increased)

  Code receiver 1: $c_1 = +1, -1, +1, -1$

  Code receiver 2: $c_2 = +1, +1, -1, -1$

- The chosen codes A and B are orthogonal:

$$c_1 \bullet c_2 = (+1 \cdot +1) + (-1 \cdot +1) + (+1 \cdot -1) + (-1 \cdot -1) = 0$$

- Sender 1 transmits data bit $x_1 = +1$
- and sender 2 transmits data bit $x_2 = -1$

Example of a Transmission with Orthogonal Codes

- Both senders spread their data bits with the respective codes:

$$z_1 = x_1 \cdot c_1 = (+1,-1,+1,-1)$$
$$z_2 = x_2 \cdot c_2 = (-1,-1,+1,+1)$$

- The code multiplex signal is the superposition of both spread signals:

$$Z = z_1 + z_2 = (0,-2,+2,0)$$

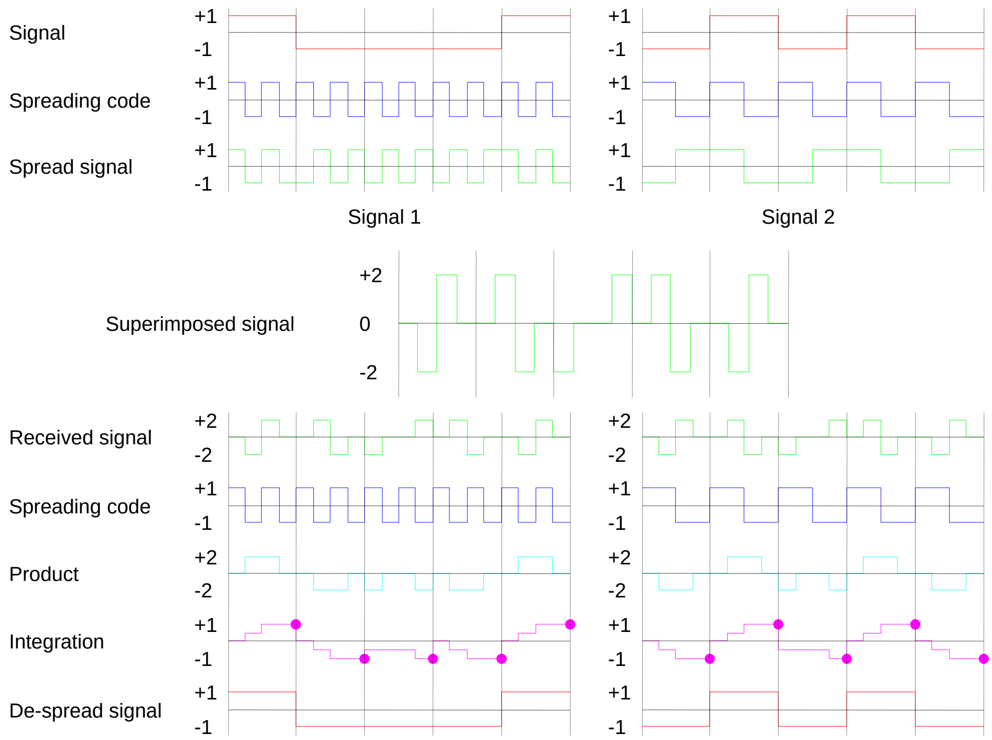
- Recovery of the data bits and decoding by receiver 1, using the same spreading code c_1:

$$y_1 = Z \bullet c_1 = \frac{1}{4}(0,-2,+2,0) \bullet (+1,-1,+1,-1) = \frac{1}{4} \cdot +4 = +1 = x_1$$

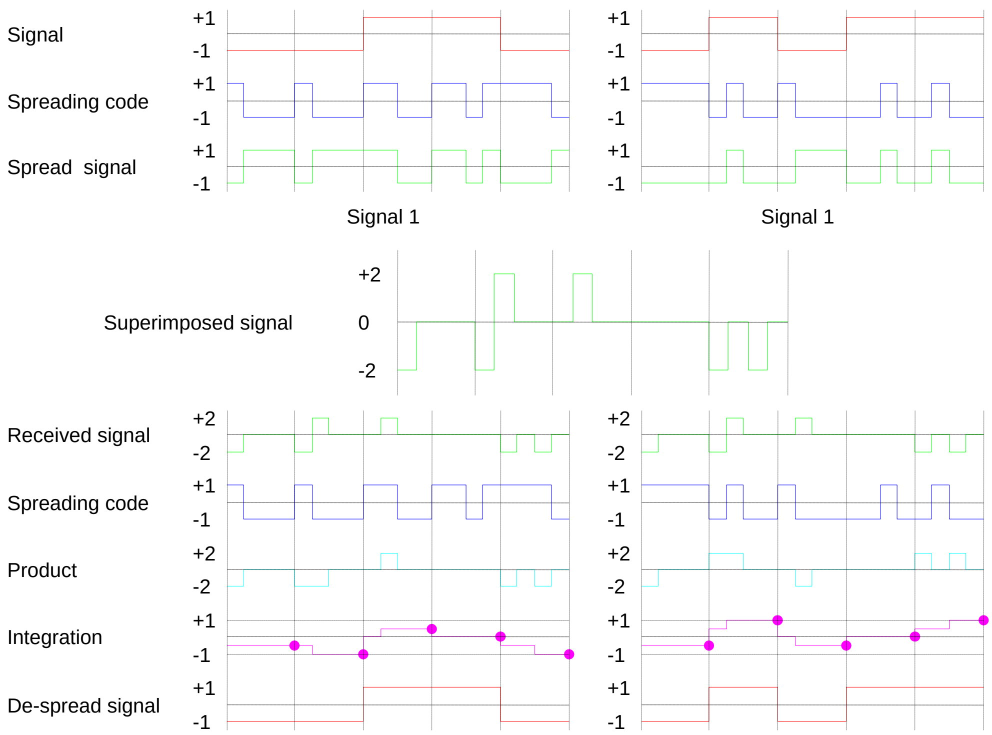
- The decoding by receiver 2 is done analogously:

$$y_2 = Z \bullet c_2 = \frac{1}{4}(0,-2,+2,0) \bullet (+1,+1,-1,-1) = \frac{1}{4} \cdot -4 = -1 = x_2$$

Example of a Transmission with Orthogonal Codes



Example of a Transmission with Pseudo-orthogonal Codes



Interference and Thermal Noise with Pseudo-orthogonal Codes

- Consider the interference of one user

$$I_k = \frac{1}{n} \cdot \sum_{\substack{i=1 \\ i \neq k}}^{M} x_i \cdot (c_i \bullet c_k)$$

- The pseudo-orthogonal codes are uncorrelated, so it holds:

$$E[I_k] = 0$$

$$VAR[I_k] = \frac{1}{n^2}(M-1) \cdot VAR[(c_i \bullet c_k)] = \frac{1}{n^2} \cdot (M-1) \cdot n = \frac{M-1}{n}$$

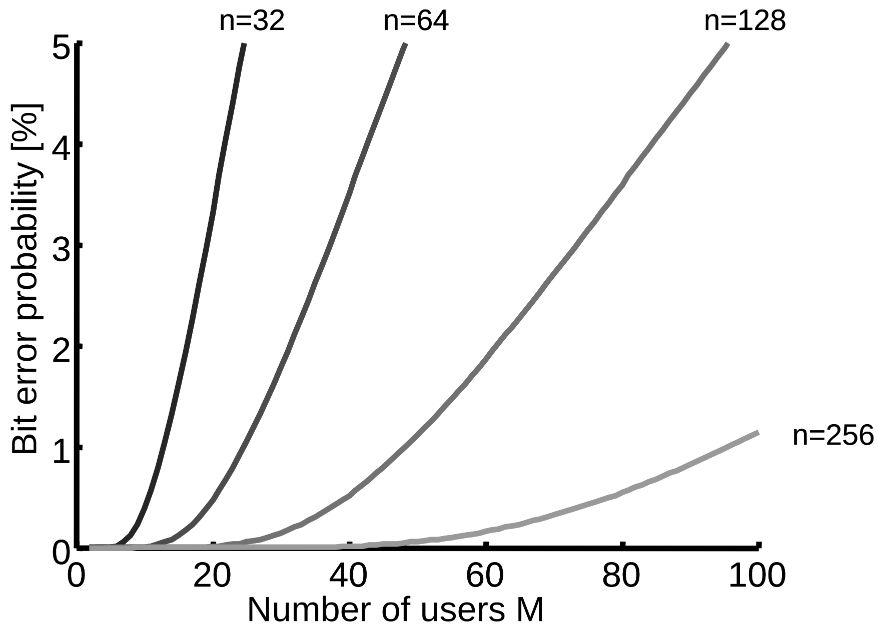
- The interference is approximately Normal distributed with $\mathbf{N}\left(0, \sqrt{\frac{(M-1)}{n}}\right)$

- A bit error occurs if y_k and x_k are differently signed. Consider the case x_k= -1. Then it holds:

$$p_b = P\{I_k > 1\} = P\left\{\mathbf{N}\left(0, \sqrt{\frac{M-1}{n}}\right) > 1\right\} = Q\left(\sqrt{\frac{n}{M-1}}\right)$$

Bit Error Probability

- Bit error probability depending on the number of users M and on the spreading factor n :



Bit Error Probabilities in Real Systems

- Signals are not received with „+1“ or „-1“ but with power S

$$\Rightarrow p_b = Q\left(\sqrt{n\frac{S}{(M-1)S}}\right)$$

- The spreading factor is denoted by W/R (system bandwidth W, signal bit rate R)

$$\Rightarrow p_b = Q\left(\sqrt{\frac{W}{R}\frac{S}{(M-1)S}}\right)$$

- Additionally to the $MAI = (M\text{-}1)S$ from the users in the own cell the thermal noise N_0 and the multiple access interference I_{other} from users in the surrounding cells is received

$$\Rightarrow p_b = Q\left(\sqrt{\frac{W}{R}\frac{S}{N_0+I_{other}+(M-1)S}}\right)$$

- The interfering signals are shifted in phase. This halves the variance of the interference

$$\Rightarrow p_b = Q\left(\sqrt{2\frac{W}{R}\frac{S}{N_0+I_{other}+(M-1)S}}\right) = Q\left(\sqrt{2\frac{E_b}{I_{total}}}\right) = Q\left(\sqrt{2\,.\,Eb/N0}\right)$$

Bit Error Probabilities in Real Systems

- The $Eb/N0$-value of a signal corresponds to the ratio of energy per bit to interference and defines the bit error probability
- In UMTS, instead of the *spreading gain* the *processing gain* is used, where W doesn‘t have to be a multiple of R, since in this case the energy per bit also comprises the effects of the channel coding
- The $Eb/N0$-value corresponds to the ratio of the energy per bit before the channel coding to the interference
- For planning and capacity estimation purposes, for every service a target-$Eb/N0$-value of the corresponding *processing gain* is determined which is required to maintain the target frame error rate of the service

Bit Error Probabilities in Real Systems

- Then, for every user j and for pseudo-orthogonal codes it holds:

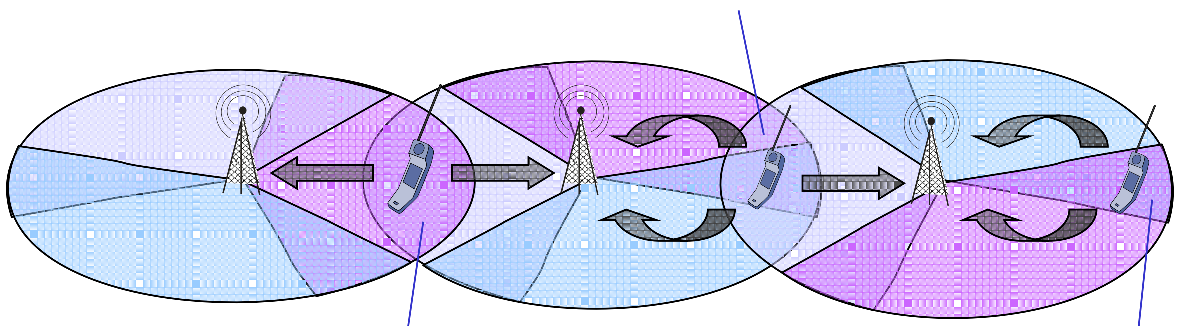
$$Eb/N0 = \frac{W}{R} \cdot \frac{S_j}{N_0 + \sum_{i \neq j} S_i}$$

S_i : Transmit power of user i
N_0 : Background noise or thermal noise
W : Frequency bandwidth or system bandwidth in cps (chips per second)
R : Data rate (bps)

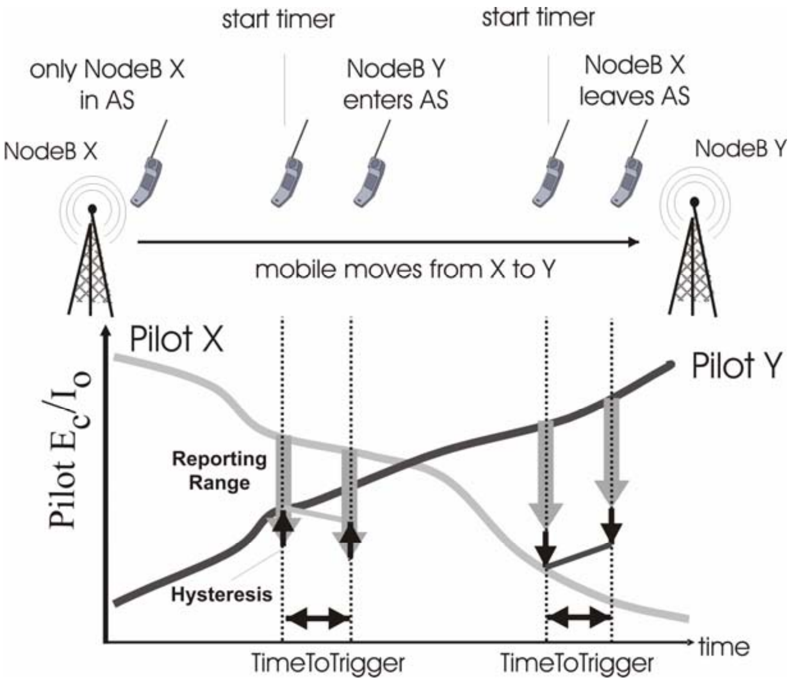
Chapter 8 Mobile Communications Networks

Soft-Handover and Softer-Handover

- **Soft Handover:** a mobile station is connected to several NodeBs
- **Softer Handover:** a mobile station is connected to several sectors of one NodeB

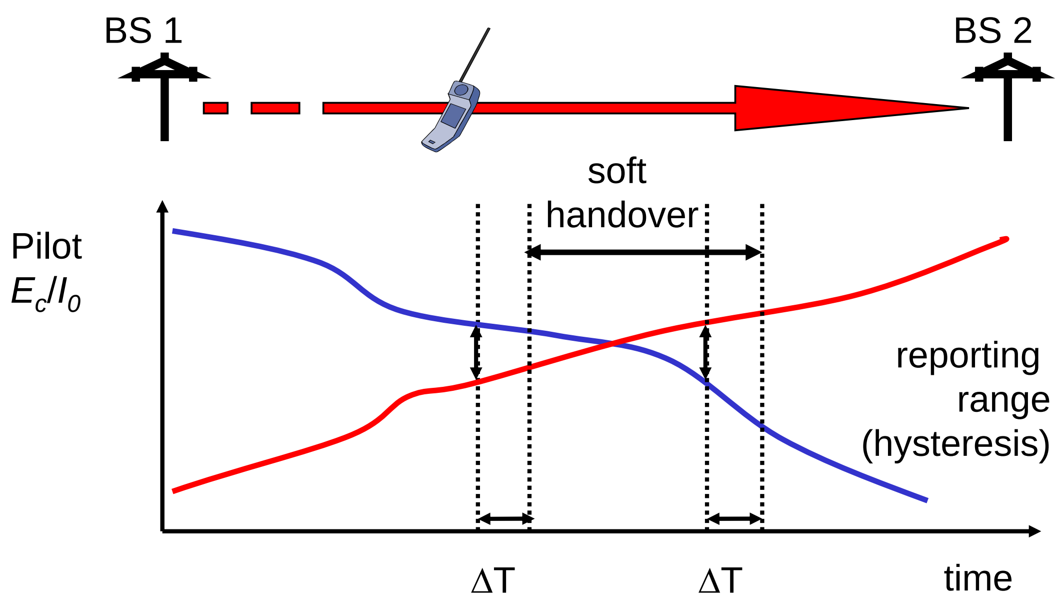


Soft-Handover and Softer-Handover



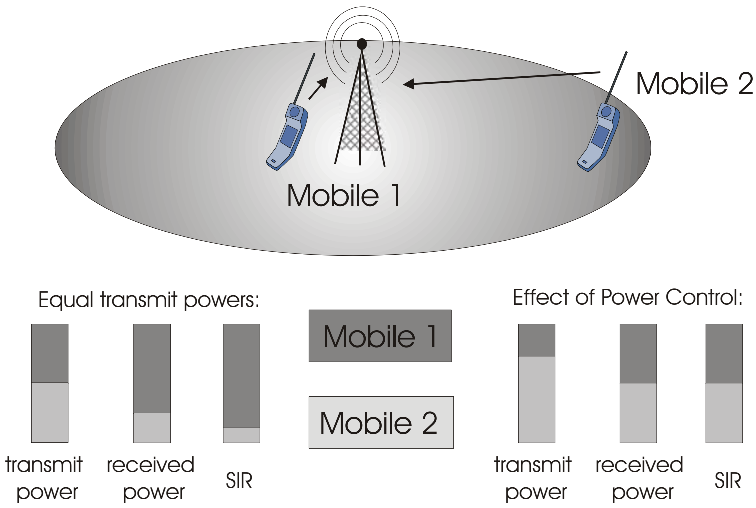
- Example: a mobile station moves from NodeB x to NodeB y.
- **Active Set** of a mobile station: Set of the NodeBs the mobile station is connected to
- Handover control defines the Active Set of a mobile station

Soft Handover (UMTS)



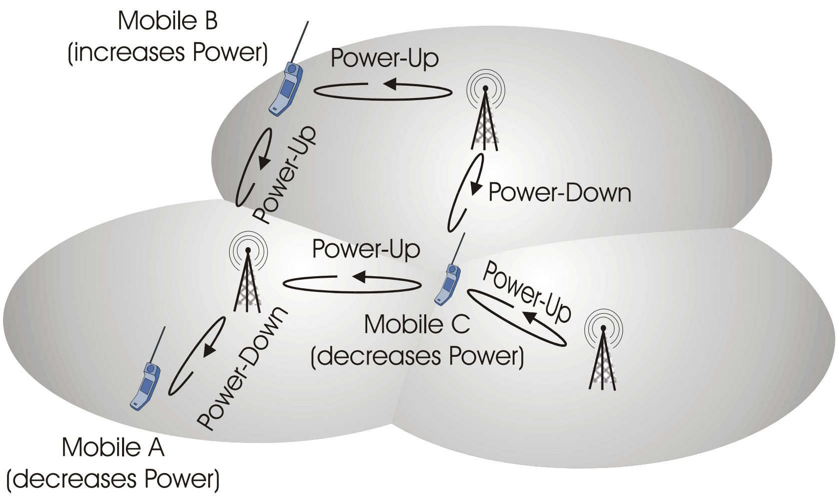
Power Control

- To minimize interference and to maximize capacity, the signals of all mobile stations with equal service should be received with equal strength, if possible. This means $S_i = S_j$ for all i, j
- A fast control loop for the transmit powers of the mobile stations is required to compensate different propagation losses („*near-far-problem*“)

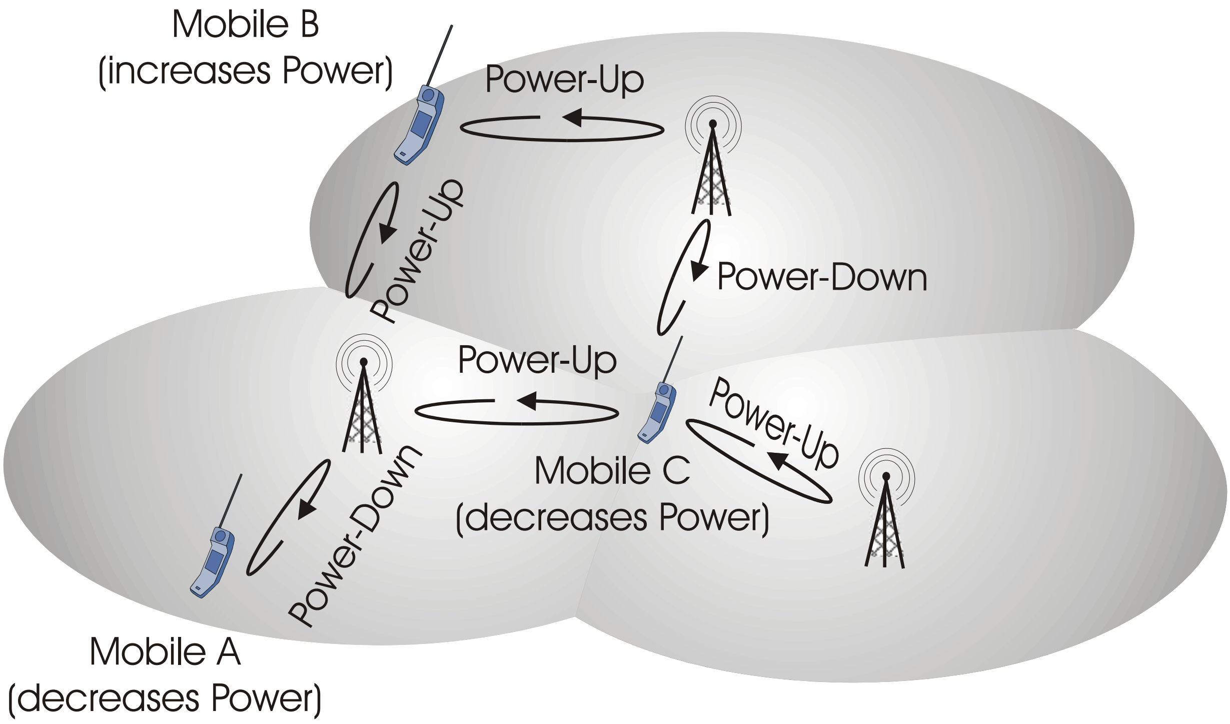


Uplink Inner Loop Power Control

- Every NodeB in the Active Set of a mobile station measures the Eb/N0-value and every 0.667ms reports the corresponding Power-Up or Power-Down command to the NodeB.
- A mobile station receives one or more Power Control commands and
  - reduces the transmit power (by one dB), if it receives at least one Power-Down command
  - increases the transmit power (by one dB), if it receives only Power-Up and no Power-Down command



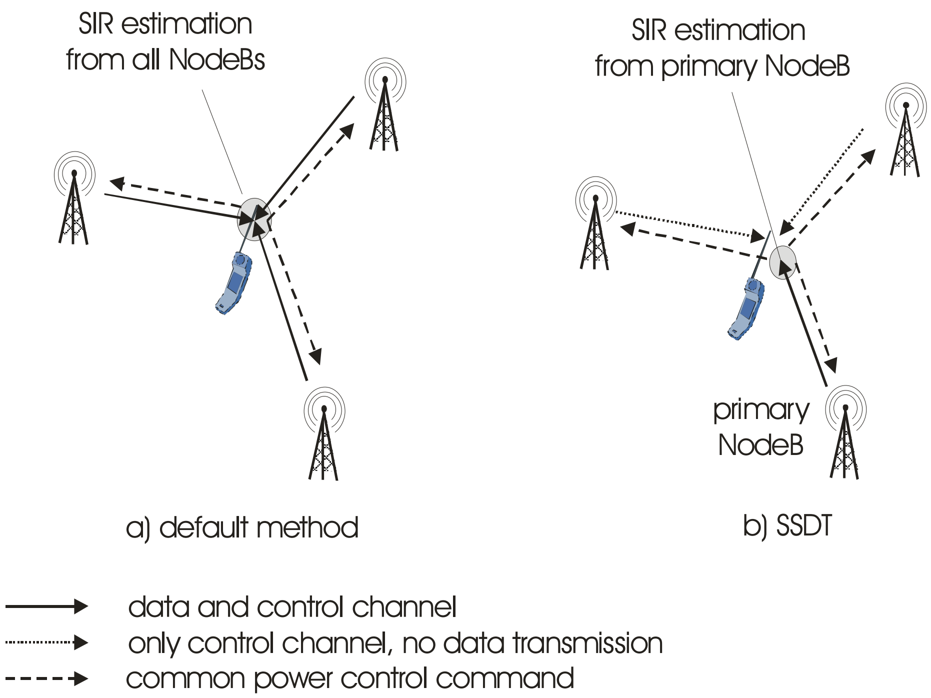
Uplink Inner Loop Power Control



Downlink Inner Loop Power Control

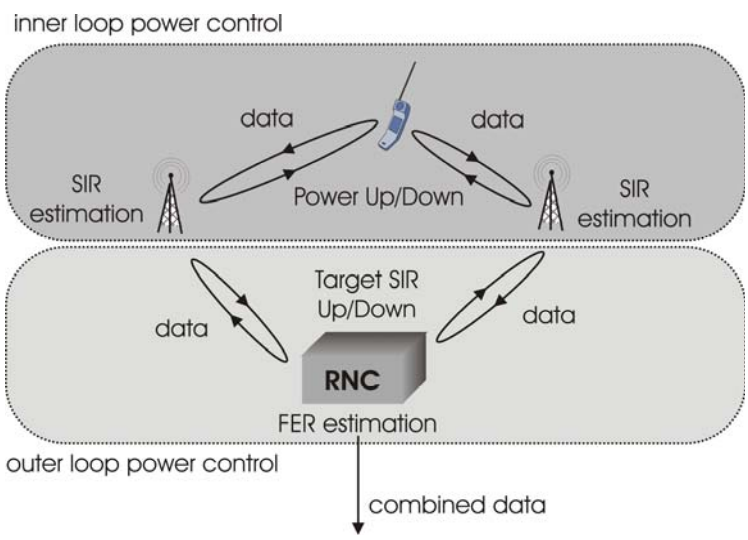
- A mobile station receives signals from all NodeBs in the Active Set and combines them with „Maximal Ratio Combining“.
- This results in a common Eb/N0-value, which corresponds to the sum of the single Eb/N0-values.
- The mobile station sends a single Power-Control command to all NodeBs in the Active Set.
- All NodeBs in the Active Set adjust their transmit powers, such that all NodeBs transmit with equal power.
- Alternative: SSDT (Site Selection Diversity Transmit Power Control)
  - Mobile station selects the best NodeB in the Active Set every 10ms.

Downlink Inner Loop Power Control



Outer Loop Power Control

- Adaptation of the target Eb/N0-value to the target error rate (FER=Frame Error Rate)
- On the uplink between RNC and NodeB, on the downlink within the mobile station
- Exact execution of the Outer Loop Power Control is not specified in the standard



Chapter 8 Mobile Communications Networks

Soft Capacity and Coverage Area

- **„Soft Capacity":**
  - A CDMA cell does not have a fixed capacity, i.e. there is no fixed number of channels as in a FDMA/TDMA system like GSM
  - Instead, the possible number of users in a cell depends on their activity, their position and the interference from other cells
- **„Soft Blocking":**
  - Corresponding to the soft capacity, the admission control is not based on the number of users but on the mean measured interference
  - The interference does not depend directly on the number of users, but also on the user activity and the other-cell interference. Therefore the term "soft blocking" is introduced
- **„Cell Breathing" and coverage area:**
  - The size of a CDMA cell, i.e. the area which is covered by a NodeB, depends on the cell load. If more users are in a cell, the cell shrinks and vice versa.

Pole-Capacity

- **Pole Capacity:** Peak capacity of a CDMA cell given unlimited transmit power
  - For a given bit error probability, it holds that $p_B = \varphi(M) \Rightarrow M = \varphi^{-1}(p_B)$
  - For a given target- E_b / N_0-value ε it holds that $M = \left\lfloor \frac{W}{R \cdot \varepsilon} \right\rfloor + 1$