Lecture 3
Introduction to WCDMA

Outline

- What is spread spectrum.
- Spreading.
- Correlation and RAKE receiver.
- Uplink and Downlink Diversity.
- WCDMA Power control.
  - Closed loop.
  - Open loop.
- WCDMA handovers.
  - Soft handover.
  - Softer handover.

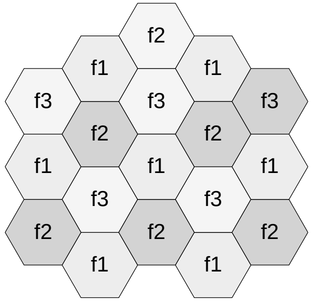
Properties of the Spread Spectrum

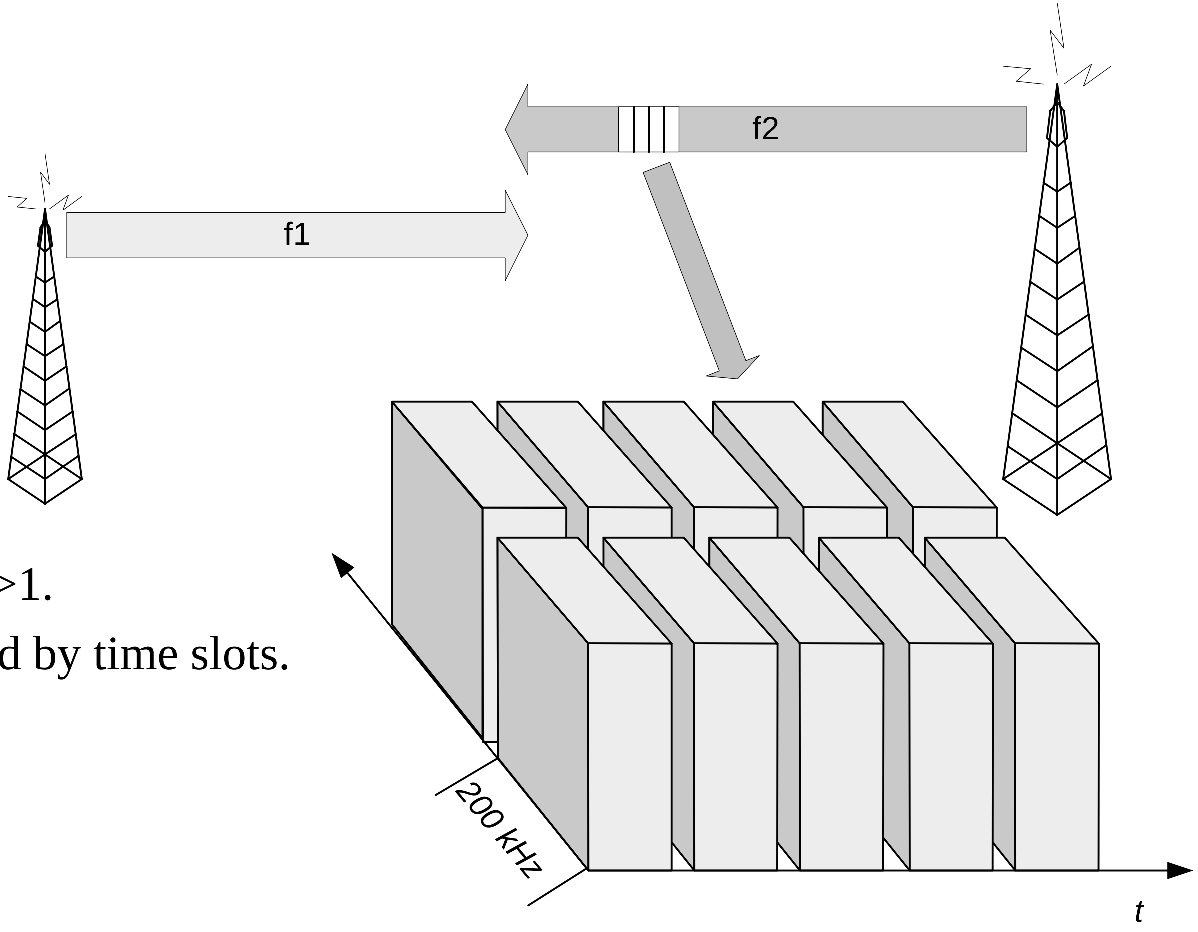
- Transmission bandwidth is much larger than information bandwidth.
- Bandwidth does not depend on the informational signal.
- Processing gain = Transmitted bandwidth/ Information bandwidth.
- Classification:
  - Direct sequence: Data is scrambled by user specific pseudo noise code at the transmitter side.
  - Frequency Hopping: The signal is spread by changing the frequency over the transmitted time of the signal:
    - Fast frequency hopping.
    - Slow frequency hopping.
  - Time Hopping: The data is divided into frames, that itself are divided into time intervals. The data is burst is hopped over the frames by utilising code sequences.

Background of SS

- First publications late 40s.
    - Patent proposal in 1941.
- 1949 C. Shannon and R. Pierce develop basic ideas of CDMA.
- First applications 50s.
    - Military with very low C/I, Anti-jam.
- RAKE receiver patent 1956.
- Cellular applications proposed late 70s.
- Investigations for cellular use 80s.
- IS-95 standard 1993.
    - Commercial introduction in 1995.
- 1997/1998 3G technology choice in ETSI/ARIBA/TTA … .

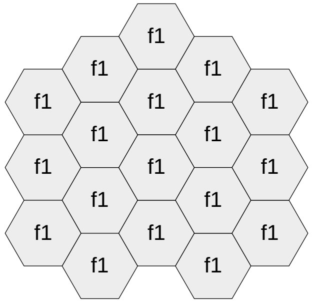
TDMA based system

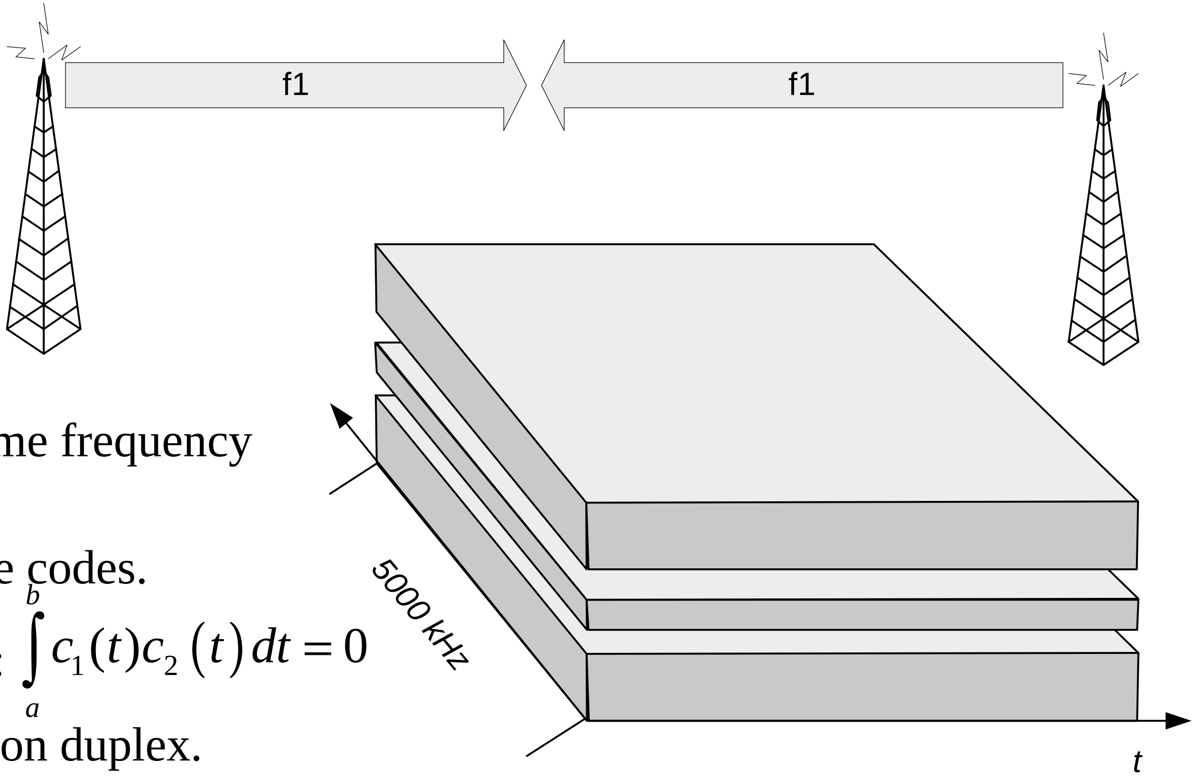




- Frequency reuse >1.
- Frequency divided by time slots.

WCDMA based system

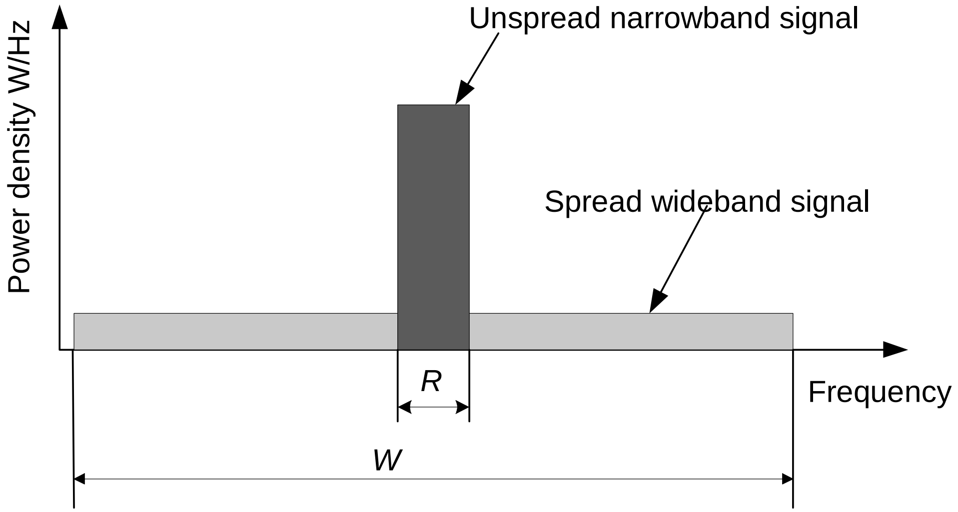


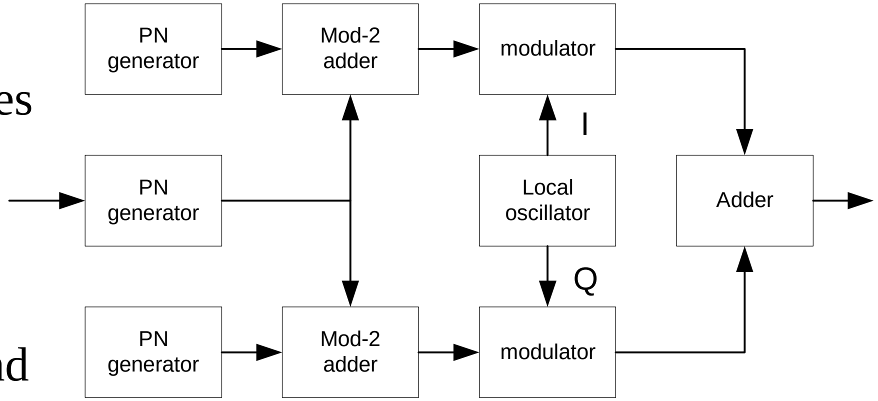


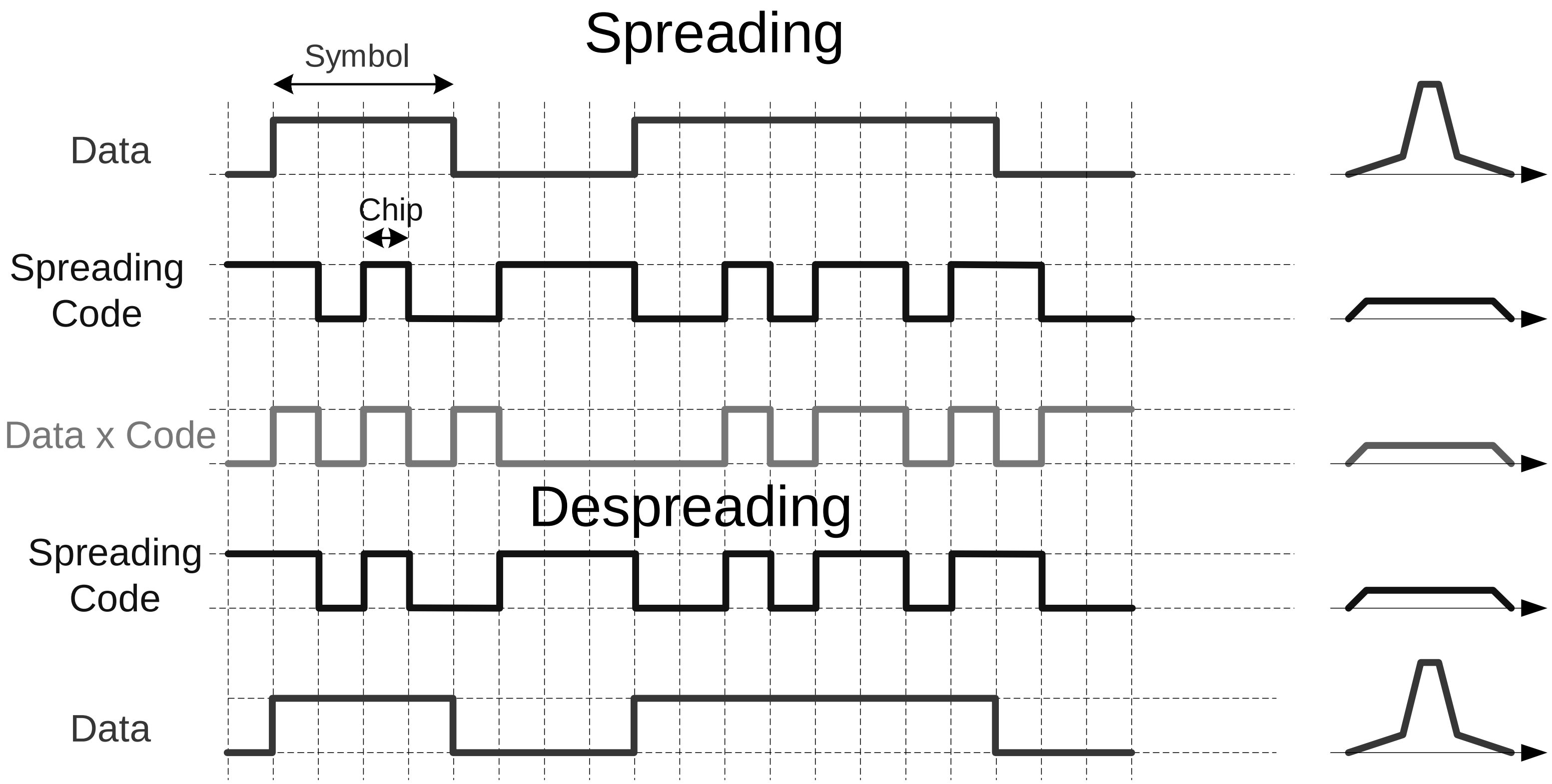
- All users share the same frequency time domain.
- Users separated by the codes.
- Codes are orthogonal: $\int_a^b c_1(t)c_2\left(t\right)dt = 0$
- FDD frequency division duplex.
  - Uplink, downlink in separate frequency bands
- TDD time division duplex.
  - Uplink, downlink in the same frequency band and separated in time.

Processing Gain and Spreading

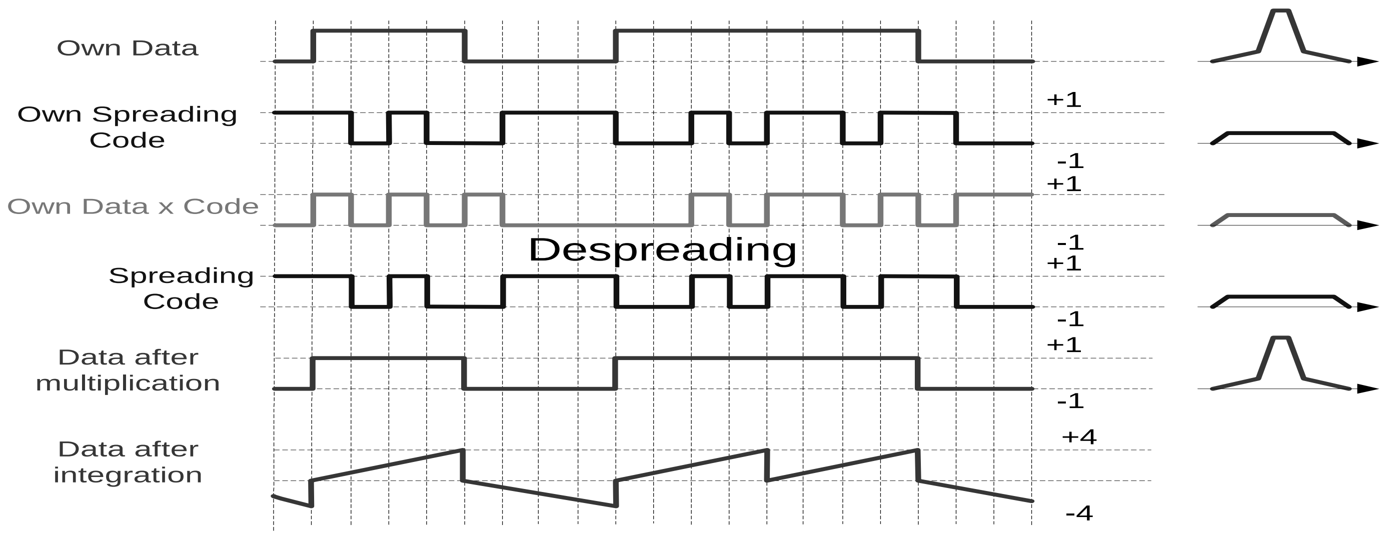
- A narrowband signal is spread to a wideband signal.
- Information rate at the input of the encoder is $R\,\frac{bits}{s}$
- Available bandwidth is $W\ Hz$
- In order to utilize the entire available bandwidth the phase of the modulator is shifted pseudo randomly, according to the pattern from the PN generator at a rate $W\,\frac{times}{s}$
- Chip is the rectangular pulse which occupies the whole bandwidth $\frac{1}{W}=T_c$
- The duration of T_c is called chip interval
- High bit rate means less processing gain and higher transmit power or smaller coverage.



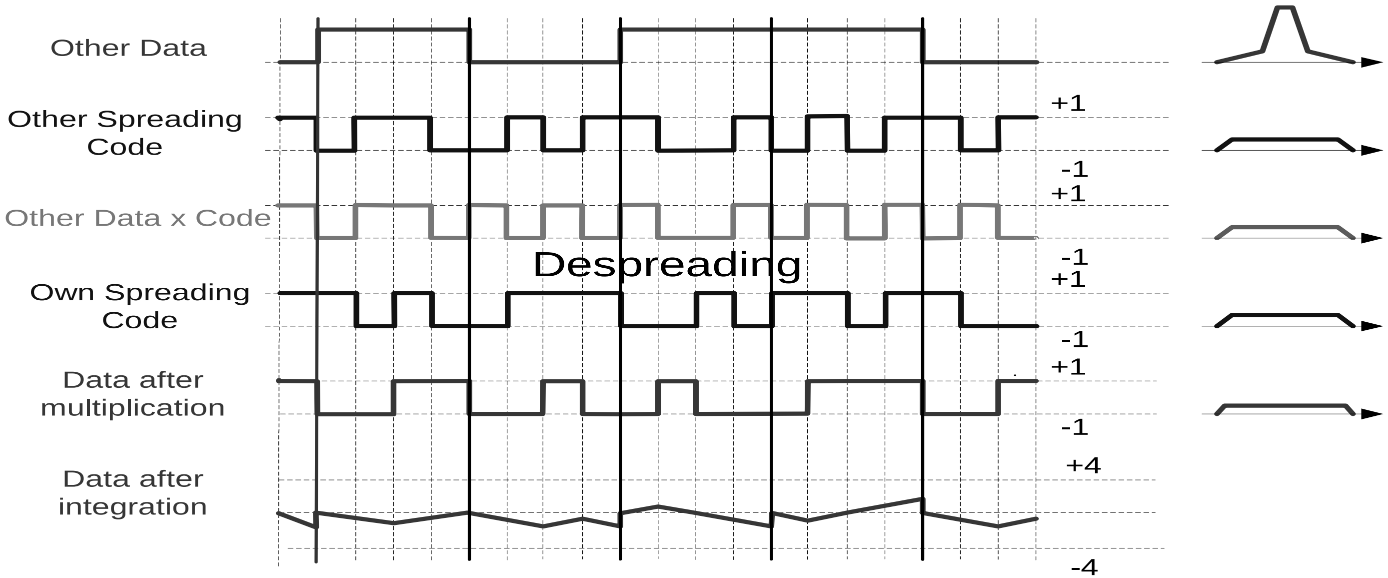



Spreading
Symbol
Data
Chip
Spreading Code
Data x Code
Despreading
Spreading Code
Data

Detection own signal



Detection other signal



Codes (1)

- Requirements for the spreading codes:
  - Good auto-correlation properties. For separating different paths.
  - Good cross-correlation properties. For separating different channels.

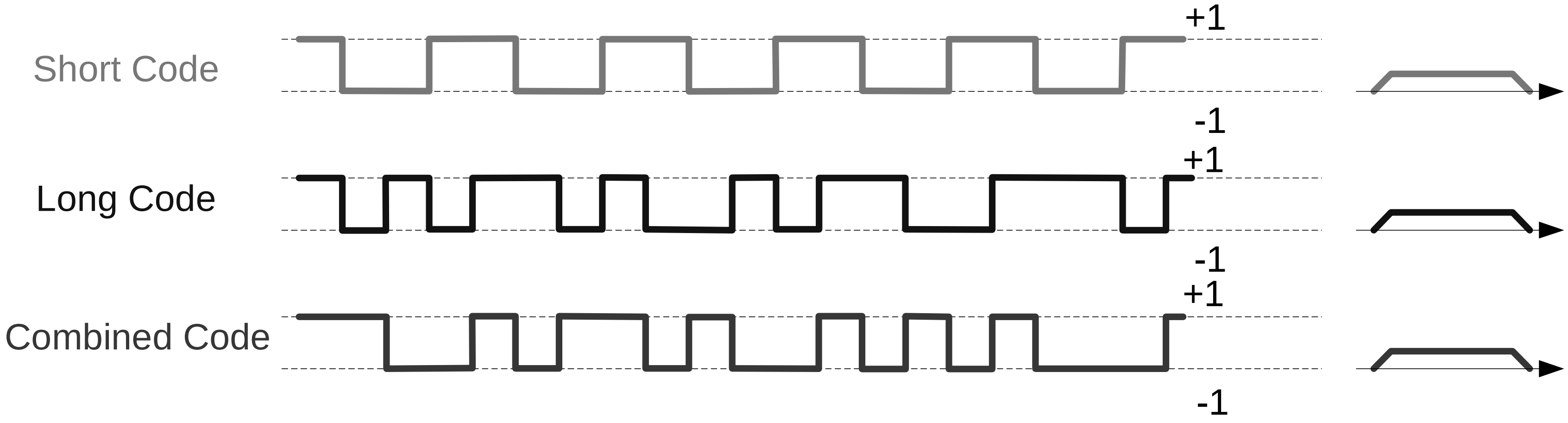
Channelisation codes used for channel separation from the same source.

- Same codes from all the cells.
- Short codes: used for channel separation in Uplink and Downlink.
  - Othogonality property, reduce interference.
  - Different spreading factors, different symbol rates.
  - Limited resource, must be managed.
  - Do not have good correlation properties, need for additional long code.

Scrambling codes.

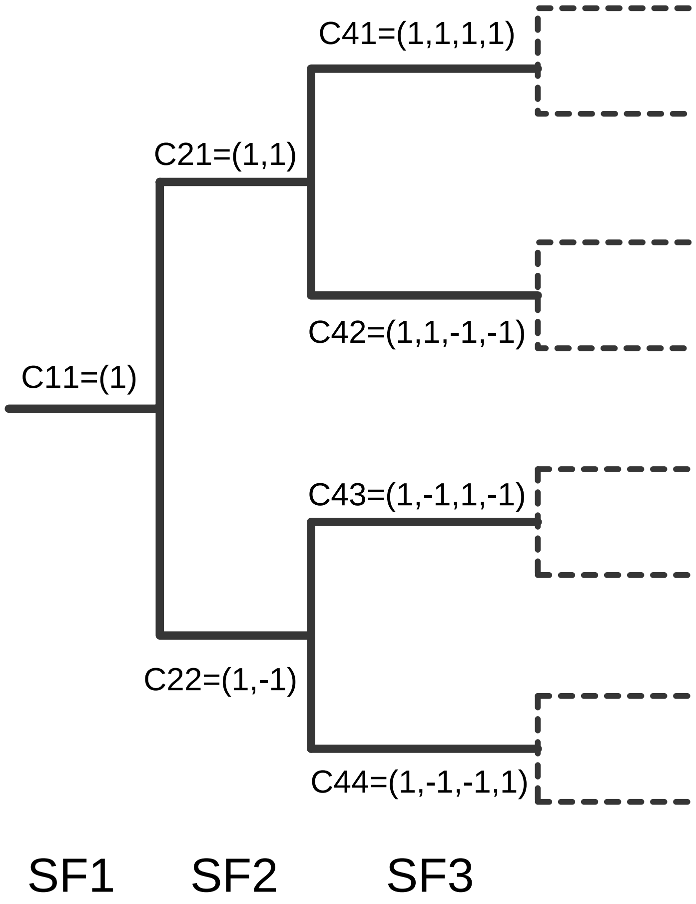
- Long Codes:
  - Good correlation properties.
  - Uplink: different users.
  - Downlink: different BS.

Long and Short Codes



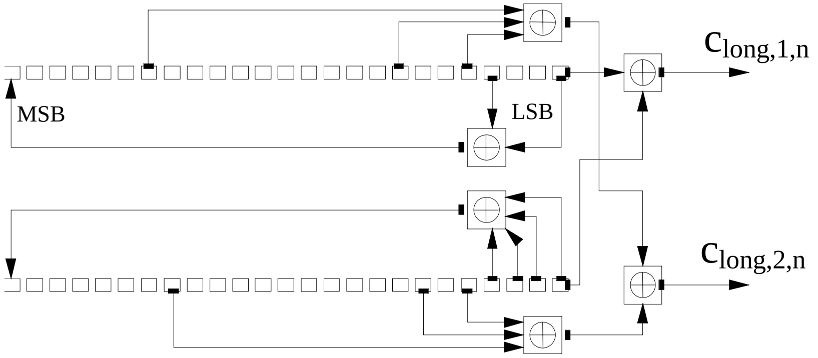
The tree of orthogonal codes

- Orthogonal short codes will only be useful if channel can be synchronised in the symbol level.
  - Mainly used in DL.
- Orthogonal Variable Spreading Factor technique.
- Orthogonality preserved across the different symbol rates.
- Codes must be allocated in RNC.
- Code tree may become fragmented code reshuffling may be needed.
- Provision of multiple code trees within one sector by concatenation with multiple sector specific long codes.



Generation of a scrambling codes

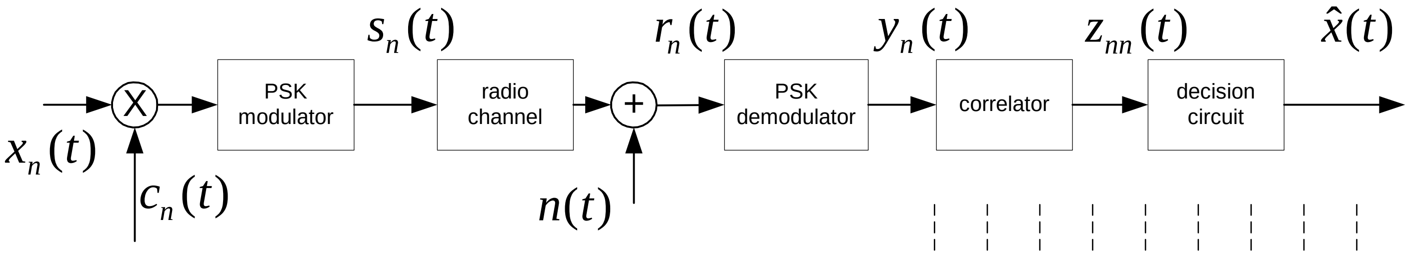
- Spreading code is output of the binary shift register generator.
- Pseudo random codes are used: cyclic.
- Maximal length codes m-sequences: sequences that have maximal possible sequence given the length of the shift registers.
- UL long scrambling code: complex scrambling codes, sum of two m-sequences (Gold sequence) generators:
  - $X^{25}+X^{3}+1.$
  - $X^{25}+X^{3}+X^{2}+X+1.$



Configuration of uplink long scrambling sequence generator

- UL short scrambling codes.
  - Used to supporting Multiuser detection.
  - Sequence length around 255 chip.
- DL scrambling sequences:
  - Constructed by combining two real sequences with generator polynomials:
  - $1+X^{7}+X^{18}$
  - $1+X^{5}+X^{7}+X^{10}+X^{18}$

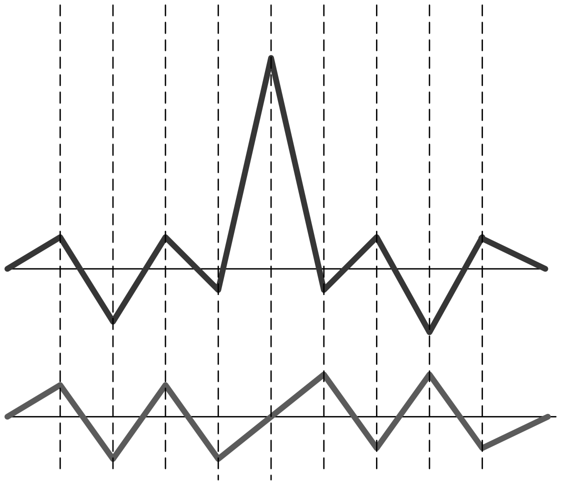
Direct sequence (DS) Spread Spectrum



$x_n(t)$	user *n* information signal.
$c_n(t)$	user *n* spreading code.
$s_n(t)$	user *n* transmit signal.
$n(t)$	noise.
$r_n(t)$	user *n* receive signal.
$z_{nn}(t)$	user *n* correlation signal.
$\hat{x}(t)$	user *n* output information signal.

$$z_{nn}(t)=\int_T y_n(t)c_n(u+t)\,du$$

T symbol duration.



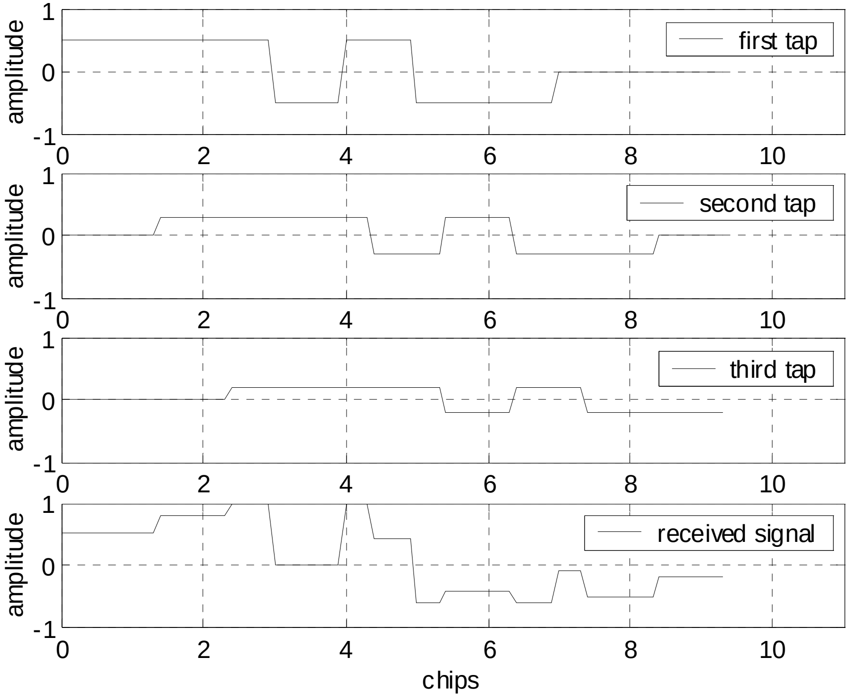
With ideal spreading codes and correct timing the cross correlation between different users is zero

Channel Repeating

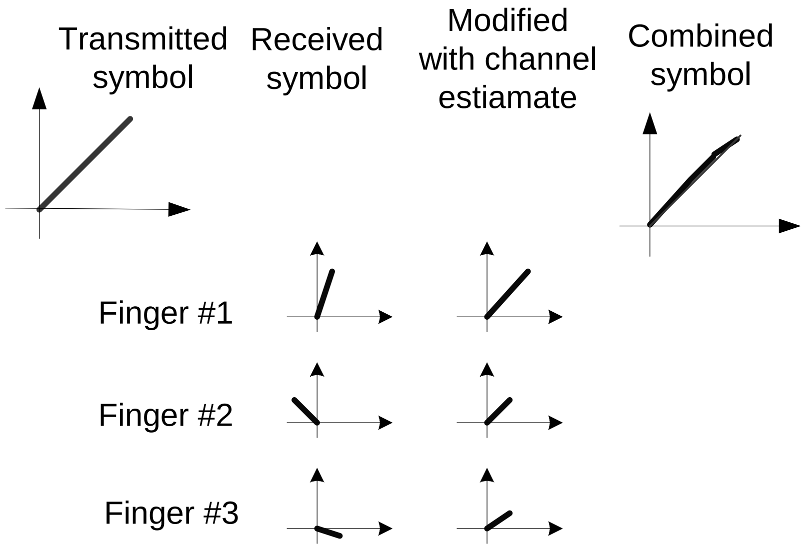
- A multipath channel: $h(\lambda,t)=\sum_{k=0}^{M-1} h_k e^{j2\pi\nu_k t}\delta(\lambda-\tau_k)$
- Received signal is convolution of the received signal and the channel.

$$y_n(t)=\sum_{l=0}^{L-1} h_k e^{j2\pi\nu_k t} s_n(t-\tau_k)$$

- Multipath will destroy the codes orthogonality:
  - The codes are orthogonal if they are synchronised, start at the same moment
  - If the codes are not synchronised the cross correlation is not zero.
  - In multipath channel signal components arrive at different time moments.
  - If the receiver is syncronised to a tap. The integration covers part of the previous symbol and next symbol from an another tap.

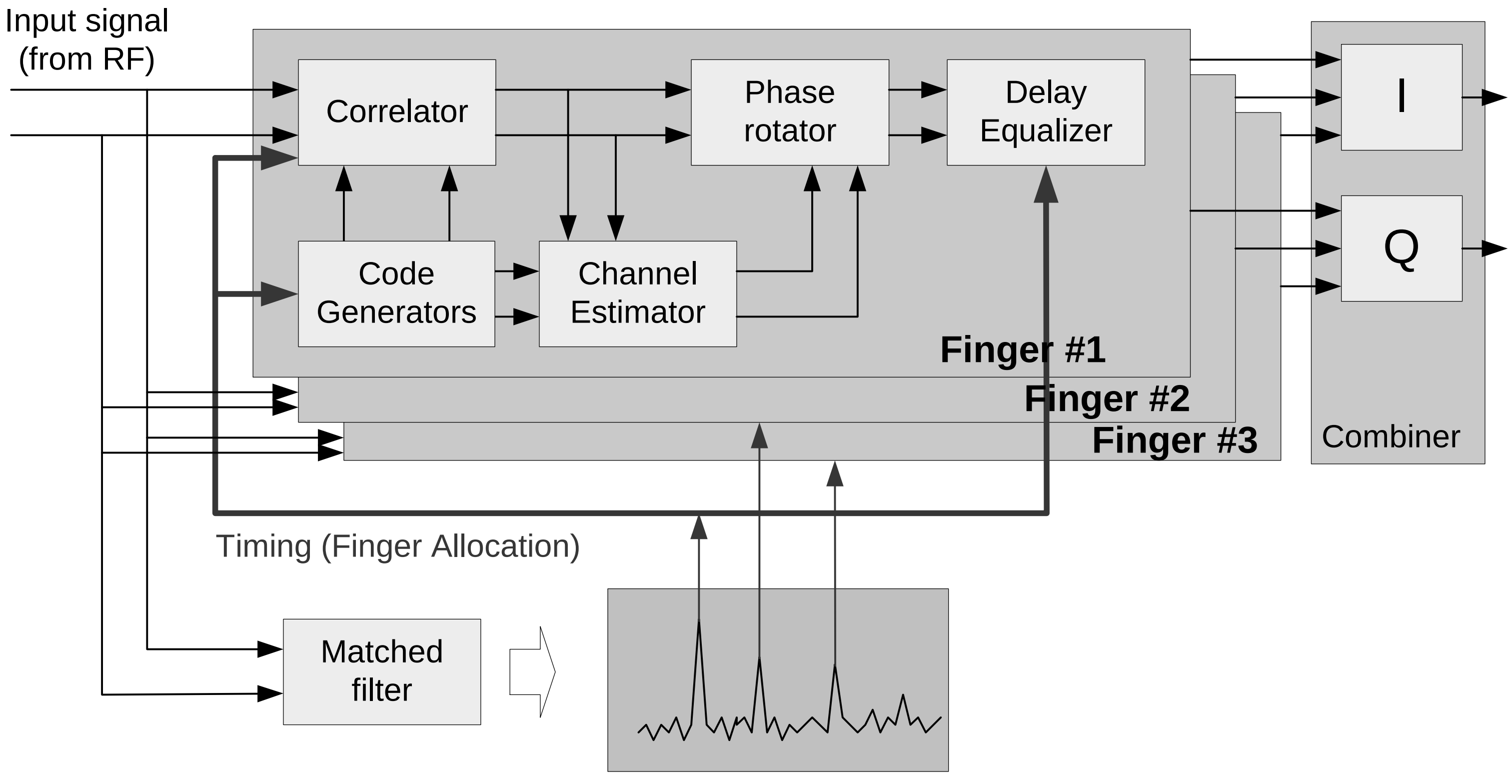


Maximal ratio “RAKE” combining of symbols



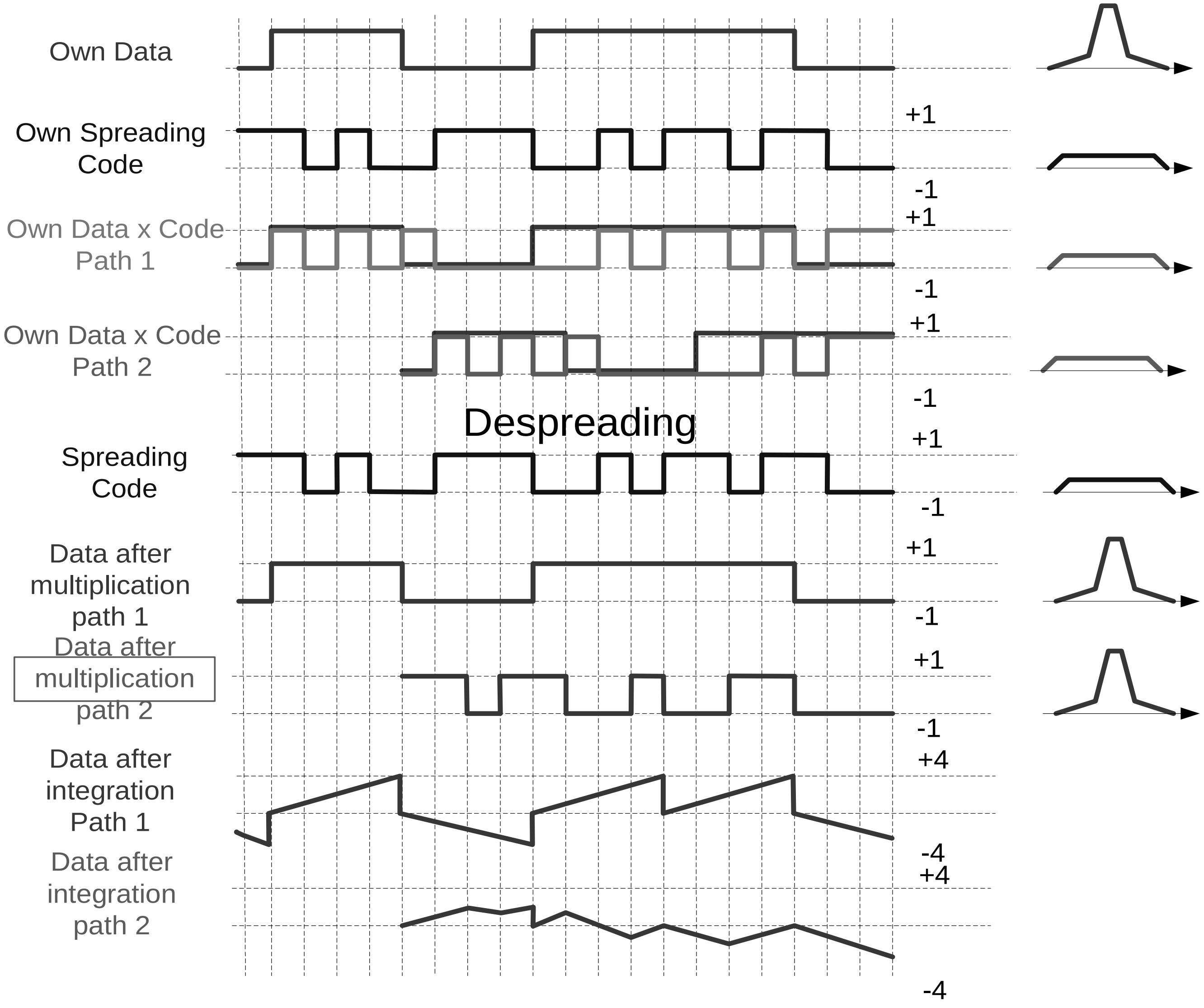
- Channel can rotate the signal to any phase and to any amplitude.
- QPSK symbols carry information in phase.
- Energy splitted to many finger -> combining.
- Maximal ratio combining corrects channel phase rotation and weights components with channel amplitude estimate.
- Same method used also for antennae combining (BTS, MS), and softer handover (BTS), and soft/softer handover (MS)

RAKE diversity receiver

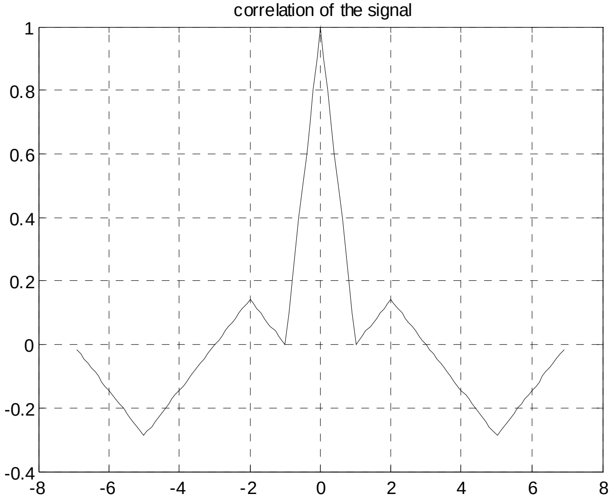


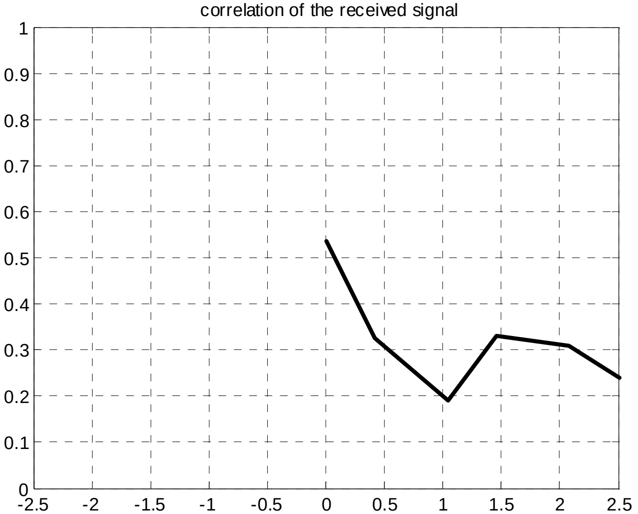
Ortogonality in multipath channel

Detection own signal



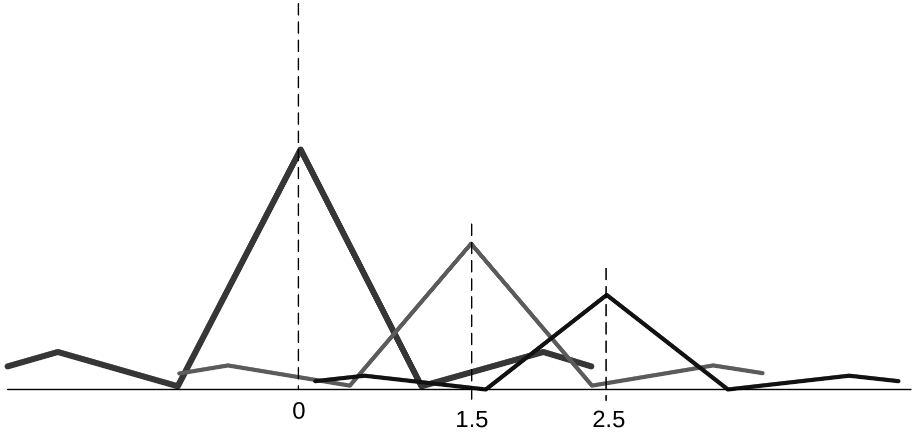
Correlation in the receiver



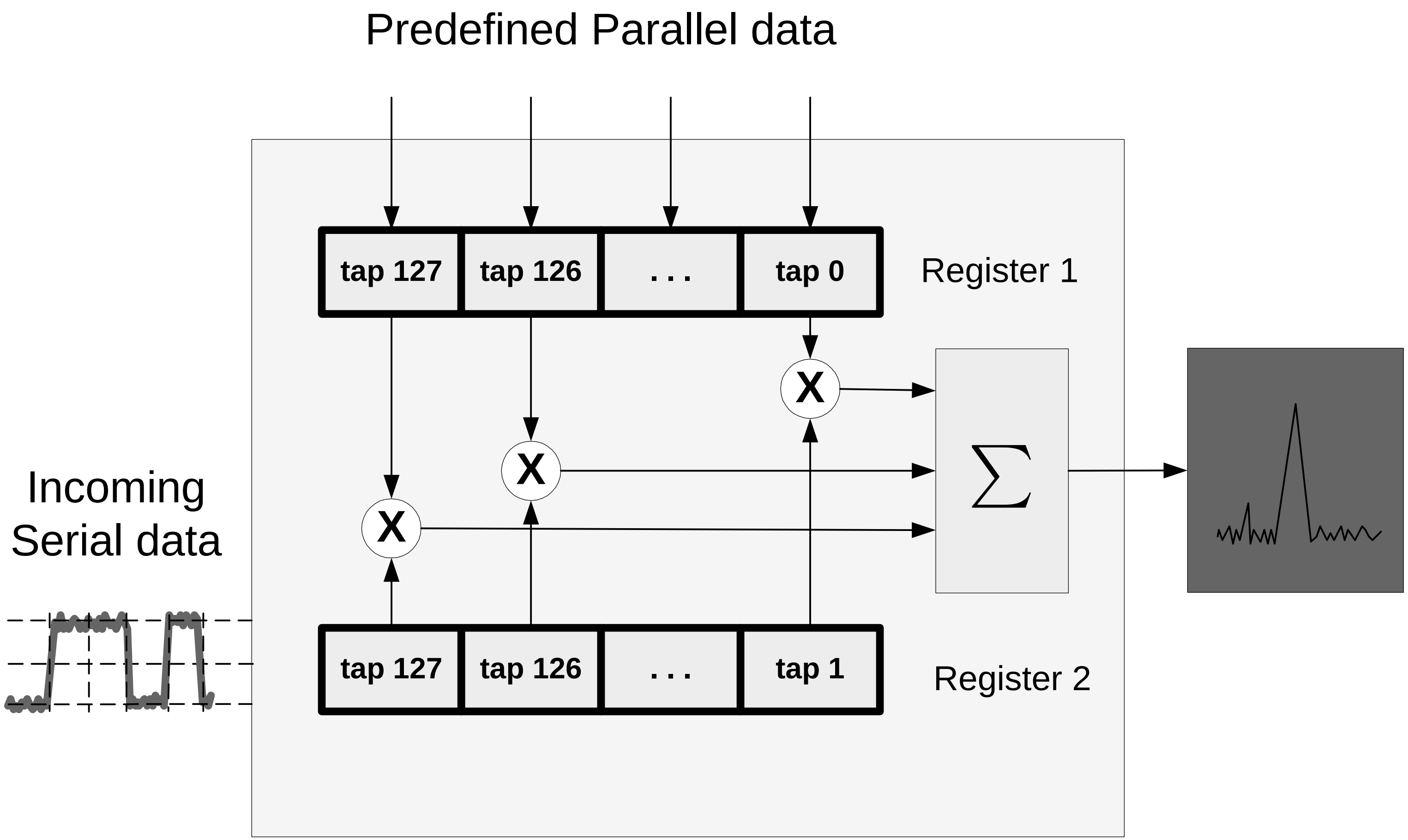


Correlation functions are not delta functions. Correlation functions of neighbouring paths could overlap.

If the channel taps are near enough the correlation functions overlap and create interference.



Matched filter



- RAKE receiver needs data timing.
- When samples of incoming serial data bits are equal to bits of predefined data, there is a maximum at filter output.

Delay profile estimation

- Sum of the signals from different paths.
- Multipath propagation causes several peaks in matched filter output.
- Allocate RAKE fingers to these peaks.
- Later: track and monitor the peaks.

Signal in the channel

$$\sum_{L}\sqrt{P_{k,l}}\,e^{-j\Theta_l}\,m_k s_k\left(t-\tau_l\right)+n\left(t\right)$$

Signal after correlation in receiver

$$z_k(t)=\sum_{L}\left(\begin{array}{l}\displaystyle\int_{T_{-1}}^{u_{n,l}}\left(\sqrt{P_{k,l}}\,e^{-j\Theta_l}\,m_{k,-1}s_k\left(t-u_{k,l}\right)\right)s_k\left(t\right)dt\\ \displaystyle+\int_{u_{n,l}}^{T_0}\left(\sqrt{P_{k,l}}\,e^{-j\Theta_l}\,m_{k,0}s_k\left(t-u_{k,l}\right)\right)s_k(t)dt\end{array}\right)$$

$$+\int_{T}n\left(t\right)s_k\left(t\right)dt$$

The correlation generates multipath interference from other paths.

Performance of a DS-CDMA receiver

Signal in the channel in a channel with multiple users: $\sum_{N}\sum_{L}\sqrt{P_{n,l}}\,m_n s_n(t)+n(t)$

Signal sample at the receiver:

$$z(t)=\sum_{L}\left(\int_{T_{-1}}^{u_{n,l}}\left(\sqrt{P_{k,l}}\,e^{-j\Theta_{k,l}}\,m_{k,-1}s_k\left(t-u_{k,l}\right)\right)s_k(t)\,dt+\int_{u_{n,l}}^{T_0}\left(\sqrt{P_{k,l}}\,e^{-j\Theta_{k,l}}\,m_{k,0}s_k\left(t-u_{k,l}\right)\right)s_k(t)dt\right)$$

$$+\sum_{\substack{N\\ n\neq k}}\left(\sum_{L}\left(\int_{T_{-1}}^{u_{n,l}}\left(\sqrt{P_{n,l}}\,e^{-j\Theta_{n,l}}\,m_{n,-1}s_n\left(t-u_{n,l}\right)\right)s_k(t)\,dt+\int_{u_{n,l}}^{T_0}\left(\sqrt{P_{n,l}}\,e^{-j\Theta_{n,l}}\,m_{n,0}s_n\left(t-u_{n,l}\right)\right)s_k(t)dt\right)\right)$$

$$+\int_{T}n(t)\,s_k(t)\,dt$$

$P_{n,l}$ is the received power of the signal for user *n*.

m_n is the transmitted symbol to user *n*.

$s_n(t)$ is the spreading code of user *n*.

$n(t)$ is the random noise after the carrier demodulator.

$u_{n,l}$ Delay of the user *n* path compared to the user *k* path.

- The first term on the right side represents the desired signal sample of the *k*th user.
- The second term represents the multiple access interference (MAI) and can be modelled as Gaussian.
- The third term represents the random noise.
- Index *k* is used to select the parts from the equation with the user signal.

Performance of a DS-CDMA receiver (2)

- Receiver performance in a Gaussian channel is fully characterised by the first and second moment of the received signal: $P_{be} = Q\left(\sqrt{\frac{E}{\sigma^2}}\right)$

Example.

- Assume:
  - Single symbol transmission with single symbol transmission.
  - Only one multipath component for each user (L=1) and a real channel.
  - Single cell network.
- The received signal can be simplified.
- Variance of the interference is:

$$\sigma^2_{MAI} = E\left\{\left(\sum_{\substack{N\\ n\neq k}} \sqrt{P_n}\, m_i R_{n,k}\left(u_i\right)\right)^2\right\}$$

$$= E\left\{\sum_{\substack{i=0\\ i\neq k}}^{N}\sum_{\substack{j=0\\ j\neq k}}^{N}\sqrt{P_iP_j}\, m_i m_j R_{ik}\left(u_i\right) R_{jk}\left(u_j\right)\right\}$$

$$= \sum_{\substack{i=0\\ i\neq k}}^{N}\sum_{\substack{j=0\\ j\neq k}}^{N}\sqrt{P_iP_j}\, E\left\{m_i m_j\right\} R_{ik}\left(u_i\right) R_{jk}\left(u_j\right) = \sum_{\substack{i=0\\ i\neq k}}^{N} P_i R^2_{ik}\left(u_i\right)$$

$$\sigma^2_n = E\left\{\left(\int_T n_0(t) s_k(t)\right)\right\}$$

$$= \int_T\int_T E\left\{n_0(t) n_0(u)\right\} s_k(t) s_k(u)\, dtdu$$

$$= \int_T\int_T \frac{N_0}{2}\delta(t-u) s_k(t) s_k(u)\, dtdu$$

$$= \frac{N_0}{2}\int_T s_k^2(t)\, dt = \frac{N_0}{2} R_{kk}(0)$$

Performance of a DS-CDMA receiver (3)

By using definition of the autocorrelation:

$$z(t) = \sqrt{P_k}\, m_k R_{kk}(0) + \sum_{\substack{N \\ n\neq k}} \sqrt{P_n}\, m_n R_{nk}(u) + n(T)$$

$R_{kk}(0)$ is the code autocorrelation function of user k.

$R_{nk}(u)$ is the codes crosscorrelation function between spreading codes of user *n* and user *k*.

$n(T)$ is the cross correlation function between the random noise and the spreading code of user *k*.

The performance of the receiver is expressed in terms of the *Q* function:

$$P_{be} = Q\left(\sqrt{\frac{E}{I+\eta}}\right) = Q\left(\sqrt{\frac{P_k R_{kk}^2(0)}{\sum\limits_{\substack{N \\ n\neq k}} P_n R_{nk}^2(u_n) + \frac{N_0}{2} R_{kk}(0)}}\right)$$

In the asynchronous case when the delay *u* is uniformly distributed over the symbol interval, the expected value of the correlation function ratio is about:

$$E\left\{\frac{R_{nk}^2(u_n)}{R_{kk}^2(0)}\right\} \approx \frac{1}{3G_c} \quad \text{where} \quad G_c = N = \frac{R_c}{R_s} = \frac{chip\,rate}{symbol\,rate} = processing\ gain$$

Performance of a DS-CDMA receiver (4)

The average bit error probability can be calculated as a function of number of users:

$$\frac{E}{I+\eta} = \frac{P_k}{\sum\limits_{\substack{N \\ n\neq k}} P_n \frac{R_{nk}^2(u_n)}{R_{kk}^2(0)} + \frac{N_0}{2} R_{kk}(0)} \approx \frac{P_k}{\sum\limits_{\substack{N \\ n\neq k}} P_n \frac{R_s}{3W} + \frac{N_0}{2} R_s}$$

Assume: $P_k = P_n$

If the target SIR ratio given we can estimate the average capacity in the cell.

Assumptions made:

- Powers have the same level:
  - Near far effect.
  - power control suitable for uplink.
- No intracell interference:
  - can be considered by the intracell interference factor.
  - Other cells change the transmission power in the same way than the users cell.
- Orthogonality:
  - In downlink all the codes from one BS synchronous - codes orthogonal - no interference.
  - Multipath channel ruins orthogonality.
  - Can be considered in downlink as orthogonality factor.

CDMA capacity an another approach

- Same assumptions as before. We attempt directly evaluate the equation $\frac{E}{I+\eta}$

$$I_0 = \frac{I}{W} = \text{the noise density in demodulator} = \frac{\text{Total interference}}{\text{entire spread bandwidth}}$$

$$E_b = \frac{P_n}{R_n} = \text{received energy per bit} = \frac{\text{received signal power}}{\text{data rate}}$$

The total interference power is: $I = (N-1)P_n$ where N is number of users.

Total number of users in the system is: $N - 1 = \frac{I}{P_n} = \frac{W/R}{E_b/I_0}$

Compared to analyse in previous slides we assume here that Coding Gain (G) is equal to $\frac{W}{R_n}$. Before we assumed it to be $\frac{3W}{R_n}$. In practice both of these values are only assumptions and the real coding gain depends on the particular codes and multipath delays in the system.

Capacity in multicell environment

Problems:

- We assume that all the powers are the same (suitable only for uplink).
- No other cell interference:

  Other cell interference can be considered by the interference factor *f*. Assume that other cells generate that is added to the own cell interference. Thus capacity in the whole system is reduced.

  $$f+1=\frac{interference\ \ from\, other\ cell}{interference\ \ from\, own\ cell}+1$$

  The new capacity is:

  $$N-1=\frac{I}{P_n}\frac{1}{1+f}=\frac{W/R}{E_b/I_0}\frac{1}{1+f}$$

- Codes that are synchronised are orthogonal:
  - In downlink all the signals are emitted from the same source and propagate along the same path. The spreading codes that are synchronised are orthogonal.
  - Can be considered by the orthogonality factor α. That is a term that describes how much the interference is reduced due to the codes orthogonality.

$$SIR=\frac{W}{R}CIR=\frac{W}{R}\frac{P_k}{\sum\limits_{\substack{N\\ n\neq k}}(1-\alpha)P_n+\eta}$$

Simple equation describing quality of CDMA system

$$CIR = \frac{P_{0,0}}{\sum_{k=1}^{K_0-1} P_{k,0} + \sum_{j=1}^{N} \sum_{k=1}^{K_j-1} P_{k,j} + \eta}$$

where

$P_{k,i}$	signal power for user *k* in cell *I*
η	noise power

Equations for all users

$$-\frac{P_{0,0}}{CIR} + P_{1,0} + \ldots + P_{K_0,0} + \sum_{j=1}^{N} \sum_{k=1}^{K_j-1} P_{k,j} + \eta = 0$$

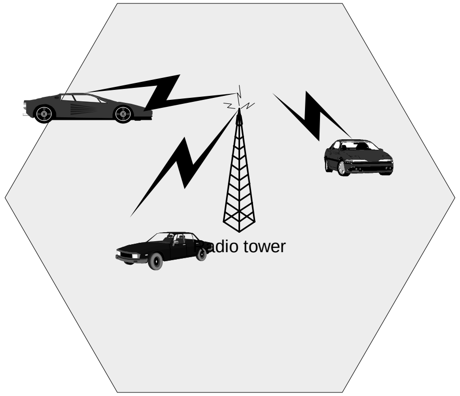
$$P_{0,0} - \frac{P_{1,0}}{CIR} + \ldots + P_{K_0,0} + \sum_{j=1}^{N} \sum_{k=1}^{K_j-1} P_{k,j} + \eta = 0$$

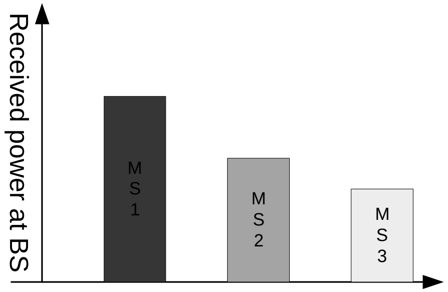
$$\vdots$$

$$P_{0,0} + P_{1,0} + \ldots - \frac{P_{K_0,0}}{CIR} + \sum_{j=1}^{N} \sum_{k=1}^{K_j-1} P_{k,j} + \eta = 0$$

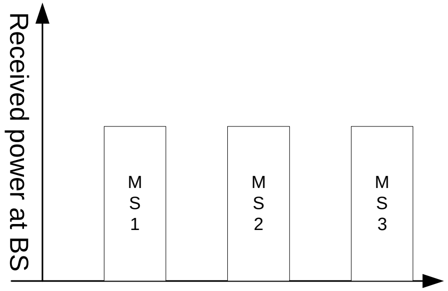
Near far effect

Uplink: Because of different attenuation signals to/from users nearer to BS are stronger than signals to/from further located users.





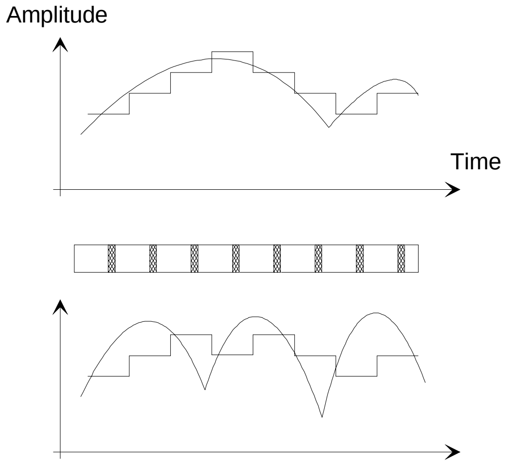
Without Power Control



With Power Control

Downlink: Beacause of the nature of attenuation at the cell border the users experience higher interference that near to the BS. They have high level of interfering signals from own BS and from other BS.

Purpose of Power Control in WCDMA



- Removes near far effect.
- Mitigates fading.
- Compensates changes in propagation conditions.
- In the system level
  - decrease interference from other users
  - increase capacity of the system

- Uplink

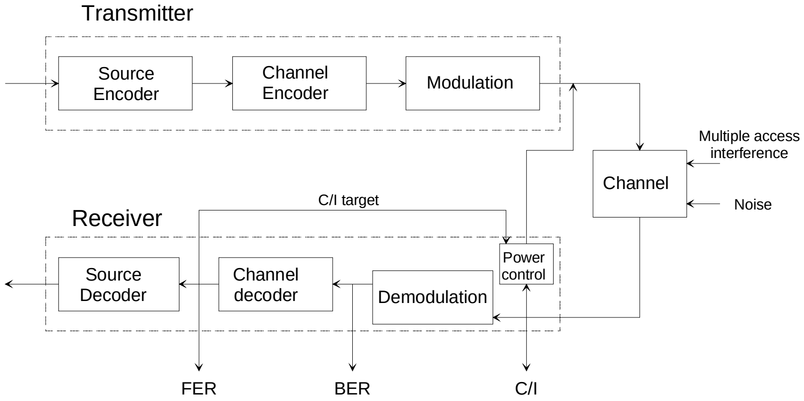
Power control in uplink must make signal powers from different users nearly equal in order to maximise the total capacity in the cell.

- Downlink

In downlink the power control must keep the signal at minimal required level in order to decrease the interference to users in other cells.

Power Control types in WCDMA

- **Open Loop power control**: for initial power setting of MS

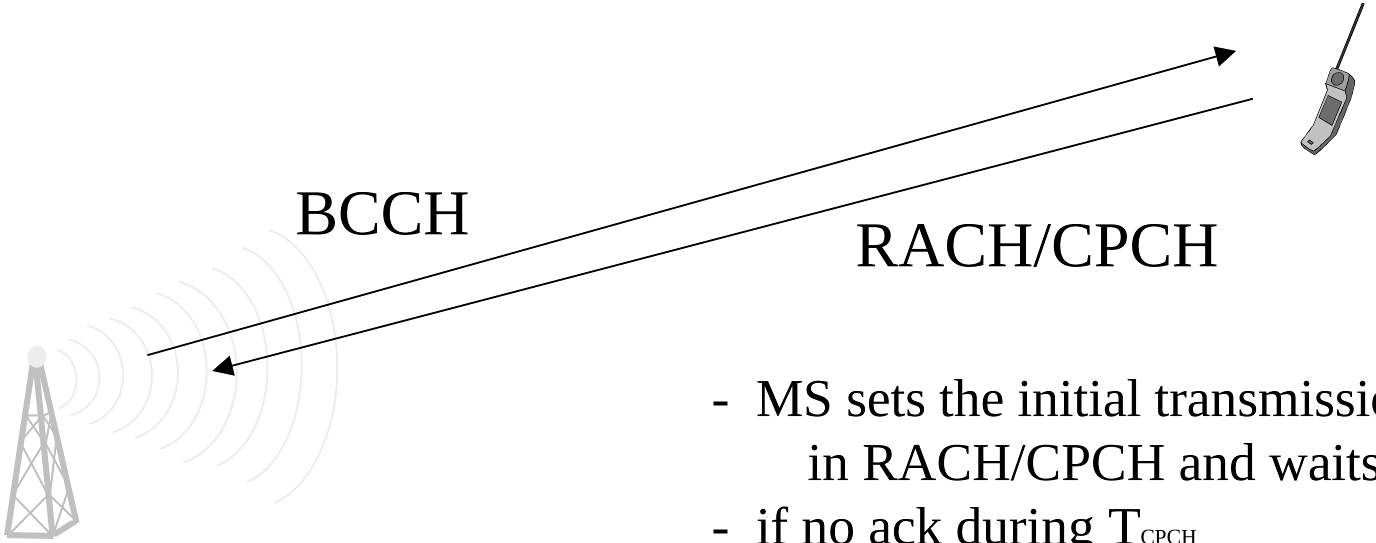


Across the air interface

- **Fast closed loop power control**:
  - Mitigates fast fading rate 1.5 kbps.
  - On UL and DL.
  - Uses a fixed quality target set in MS/BS.
- **Outer loop power control**:
  - Compensates changes in environment.
  - Adjust the SIR target to achieve the required FER/BER/BLER.
  - Depends on: MS speed available, multipath diversity.
  - In the soft handover comes after frame selection.

Open Loop PC

What is initial transmission power?



BCCH

RACH/CPCH

- MS sets the initial transmission power Ptr in RACH/CPCH and waits for ack.
- if no ack during T_{CPCH}

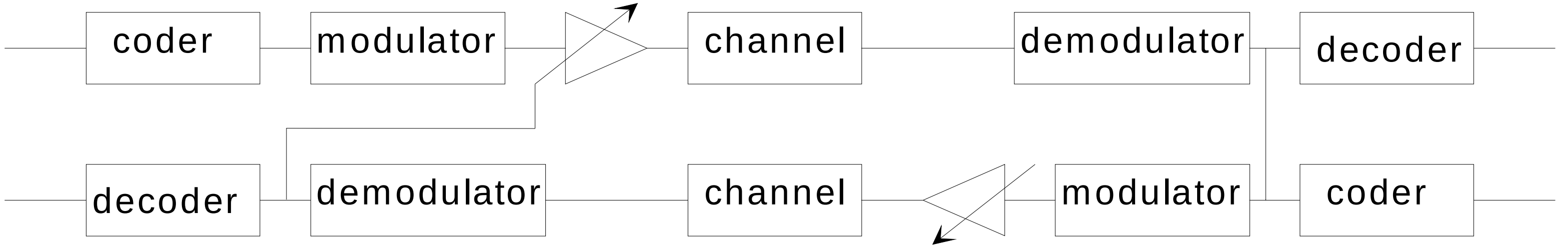
$$Ptr(i+1) = Ptr(i) + \Delta P$$

The BS transmits in BCCH

- power of the PRACH.
- power step ΔP.

Closed Loop Fast PC

- Uses channel in other direction for transmitting the order for power change.



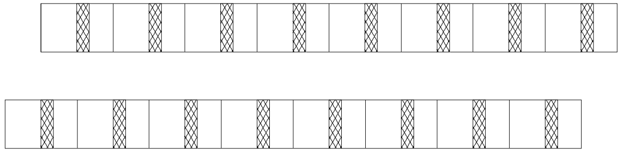
- Applied only to dedicated channels.
- Makes Eb/No requirements lower.
- Introduces peaks into the transmit power.
- PC speed 0.666 ms, compensates the fading for slow and medium speed.
- PC step
  - uplink 1, 2, 3 dB
  - downlink 0.5, 1 dB
- Control range
  - uplink 80 dB
  - downlink 30 dB

Fast PC

Uplink:

Behaviour precisely standardised.

- Equalizes received powers at BS
- BS measures the received CIR and compares to the target CIR value
- BS transmits the TPC command in downlink and orders the MS to increase/decrease the transmission power
- MS change the transmitted power accordingly to the TPC command



Downlink:

Precise algorithm not standardised

- MS estimates the received SIR and compares it with required SIR target
- MS transmits the TPC command in first available TPC field
- In soft handover (diversity transmission)
  - two downlink PC modes
    - MS sends unique PC command in each slot
    - MS repeats the same PC command over 3 slots
- Changes of power are multiplies of the minimum step size
  - it is mandatory for BS to support 0.5 and 1 dB step size

Outer loop PC

- Used for long term quality control
- Controls of the channel by setting target Eb/No
  - the quality requirement is given as long term average of FER/BER
- Uplink
  - SRNC sets the target value
  - Control is located in the Node B for FDD
  - for TDD function is performed by UTRAN but target quality value is sent to the MS
- Downlink
  - located in UE, the initial control parameters are set by UTRAN
  - receives inputs of the quality estimates of the transport channel

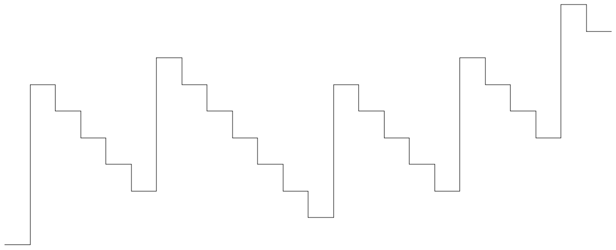
FER and FEP are calculated upon number of frames
Example function for outer loop PC

$$EbNoTarget(t+1) = EbNoTarget(\mathrm{t}) + \Delta\ [dB]$$

where

$$\Delta = fs - Fs$$

f is 1 if frame has error accordingly CRC and 0 if not
F is the wanted FER
s is the step size.



Effectiveness of PC (1)

- The figure of fading from the file.

- Uplink:
  - In uplink an effective power control follows fading as good as possible.
  - In the “own” BS received powers are equal. In other BS high variations.
- Downlink:
  - The power control attempts to estimate the overall interference level in the cell (system).
  - The PC attempts to provide good CIR to the as many users as possible.

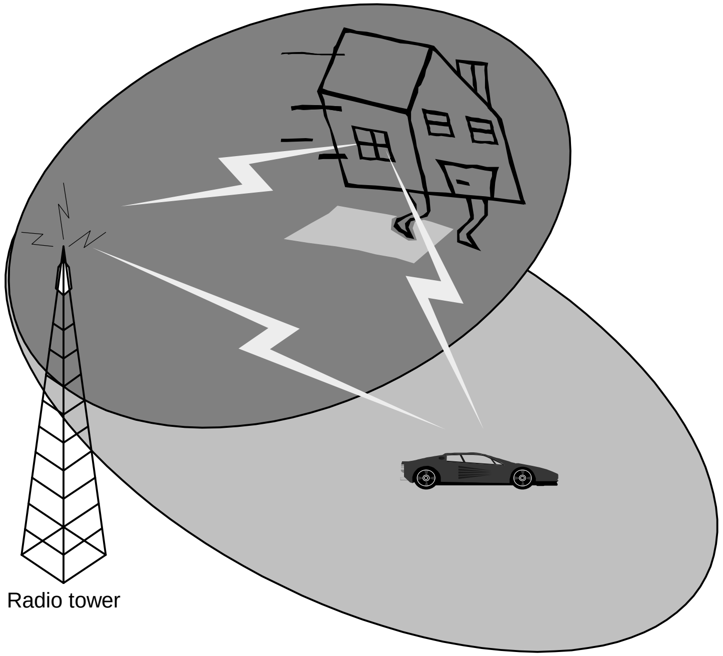
WCDMA handover types.

- Intra-system handovers:
  - Intra-frequency handovers.
    - MS handover within one cell between different sectors: softer
    - MS handover between different BS:
      - Soft.
      - Hard.
  - Inter-frequency handovers.
    - Hard
- Inter-system handovers:
  - Handover between WCDMA <--> GSM900/1800: Hard
  - Handower between WCDMA/FDD <--> TDD: Hard

WCDMA handovers

- Avoidance of near far situation for circuit switched connections
  - for high mobility users shadow fading + (slow) hard handovers would create near far situations.
- Soft/Softer handovers will improve cell capacity (around 40-60 %)
- Soft/Softer provide macrodiversity gain: compared the hard handover larger cell range.
  - Gain against shadow fading (1 -3 dB).
  - Gains against fast fading, typically 0.5 - 2 dB assumed.
- Soft/Softer essential interference mitigating tool.

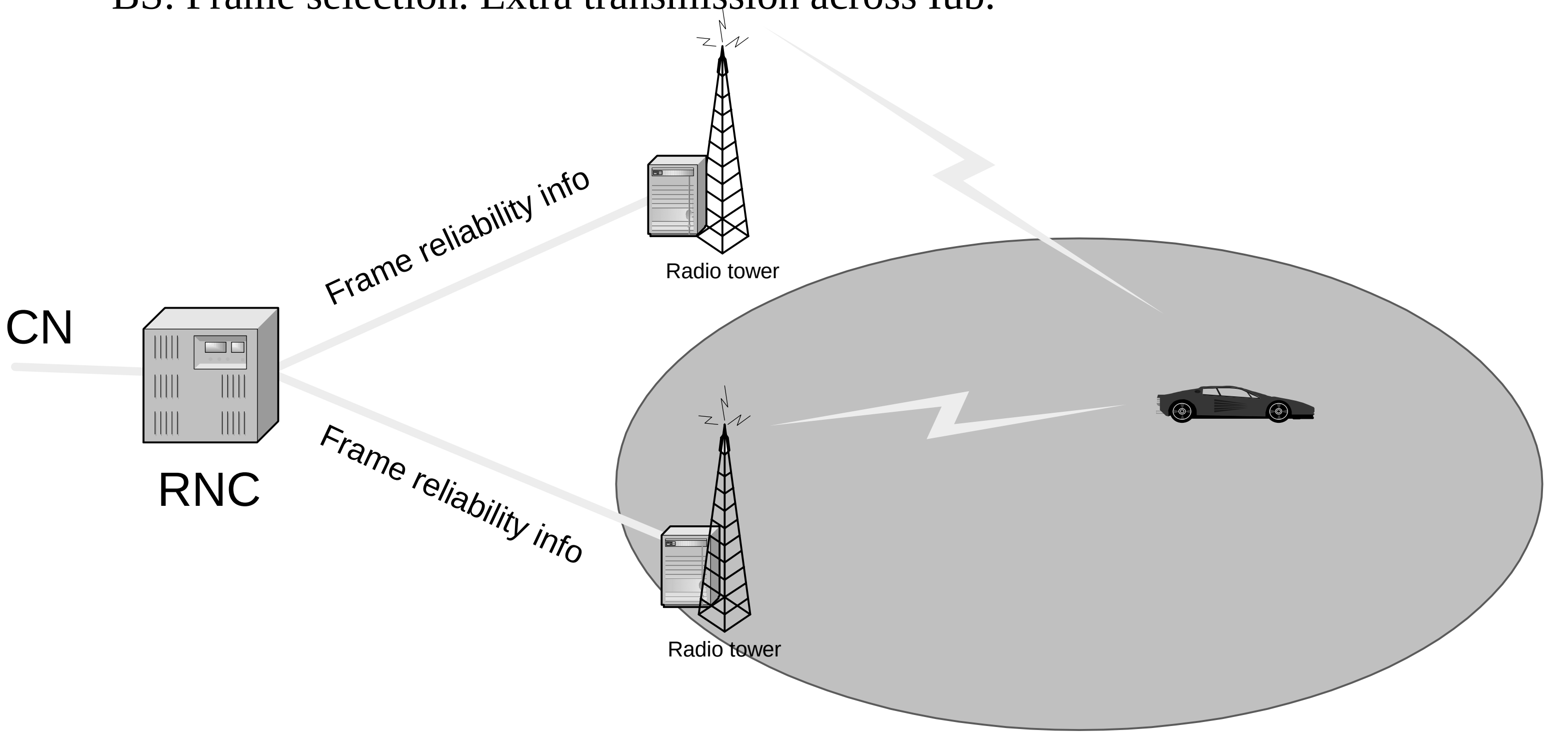
Softer handover



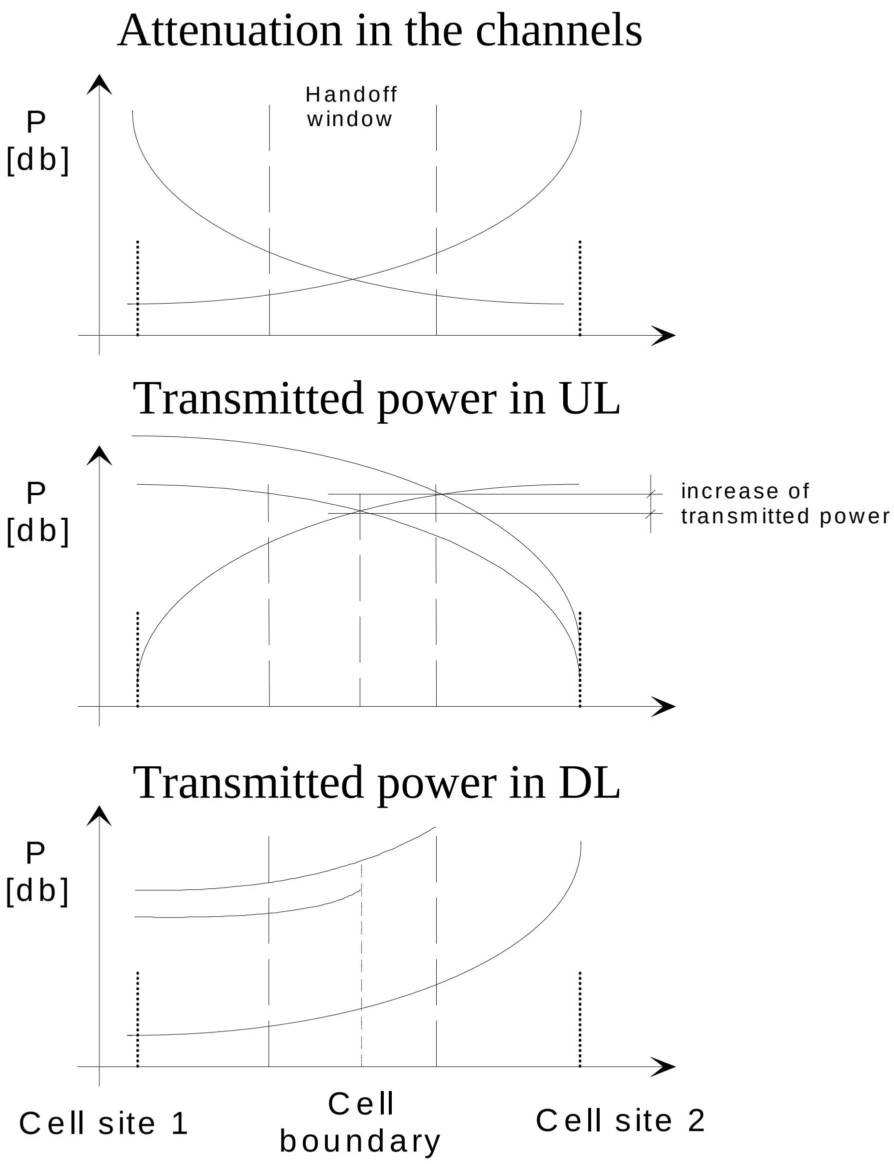
- MS in overlapping cell coverage area of two adjacent sectors of a BS.
- Communication between MS and BS is via two air interface channels (one for each separate sector).
- Different sectors have different scrambling codes.
- UL: MS tunes the RAKE fingers to different sectors and combines the outputs.
- DL: BS receives signals with different antennas and decodes and combines them.

Soft handover

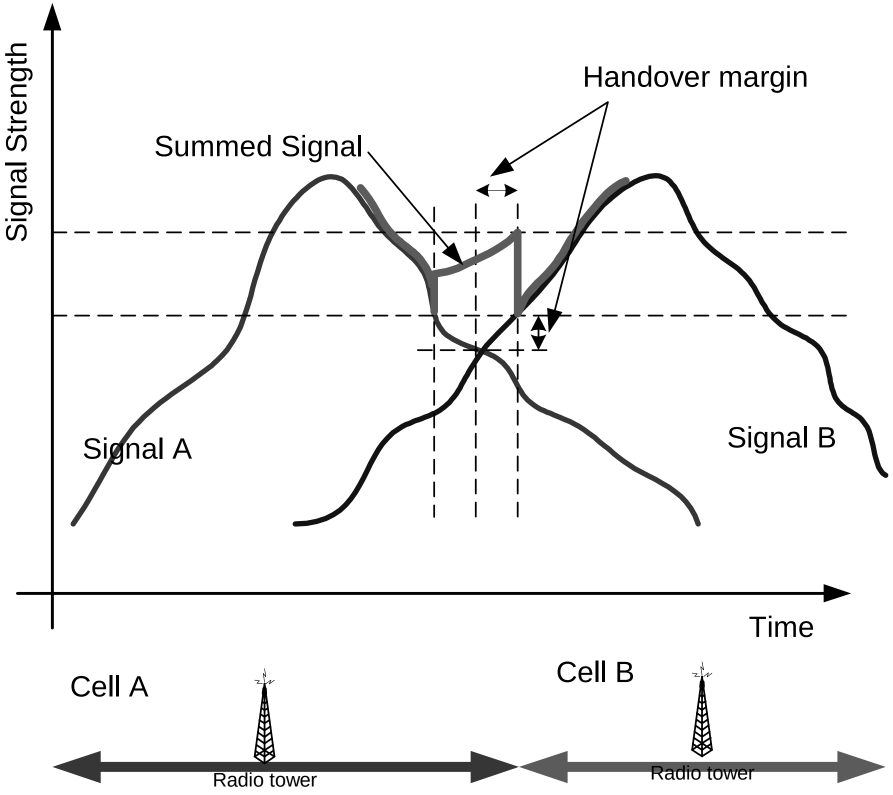
- User has at the same time connection to more than one BS.
- Except PC bits exactly the same information is sent via air interface.
- Soft handover probability 20-40 %.
- UL/DL processing different.
  - MS: At Rake Maximal Ratio Combining of signals from different BS.
  - BS: Frame selection. Extra transmission across Iub.



Handover impact to capacity



Handover procedure



- Strength of the A becomes equal to defined lower threshold. The neighbouring signal has adequate strength. B is added to active set.
- Quality of signal B starts to become better than signal A. The RNC keeps that point as starting point for handover margin calculation.
- The strength of signal B becomes equal or better than the defined lower threshold. Thus its strength is adequate to satisfy the required QoS of the connection. The strength of the summed signal exceeds the predefined upper threshold, causing additional interference to the system. As a result, RNC deletes signal A from the Active Set.

Parameter in the handover algorithm

- Upper threshold: the level at which the signal strength of the connection is at the maximum acceptable level in respect with the requested QoS.
- Lower threshold: is the level at which the signal strength of the connection is at the minimum acceptable level to satisfied the required QoS. Thus the signal strength of the connection should not fall below it.
- Handover margin: is a predefined parameter, which is set at the point where the signal strength of the neighbouring cell (B) has started to exceed the signal strength of current cell (A) by a certain amount and/or for a certain time.
- Active Set: is a set of signal branches (Cells) through which the MS has simultaneously connection to the UTRAN.
- Candidate Set: is a list of cells that are not presently used in the soft handover connection, but whose pilot E/I are strong enough to be added to the active set.
  - Candidate set is not used in WCDMA handover algorithm.
- Neighbour Set: The neighbour set or monitored set is the list of cells that the mobile station continuously measures, but whose pilot E/I are not stron enough to be added to the active set.