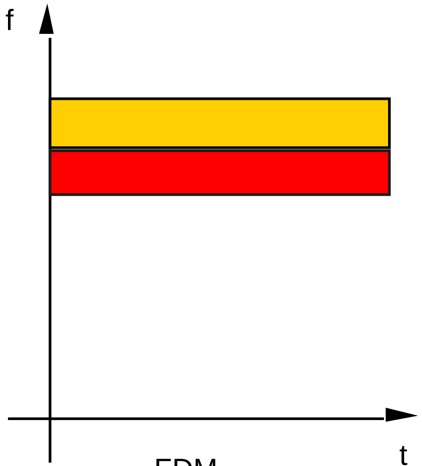
DS-CDMA in Wireless Networks

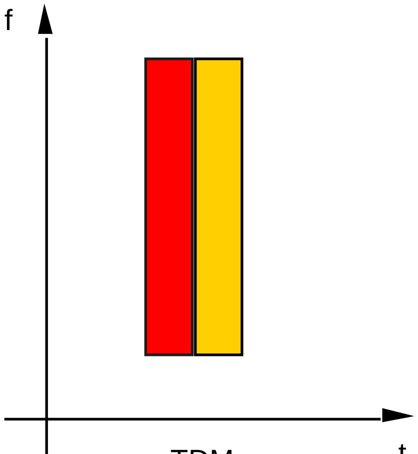
DS-CDMA Wireless Networks

- Introduction to cellular DS-CDMA.
- Spreading sequences for DS-CDMA cellular systems.
- DS-CDMA digital cellular networks.
- Capacity calculations of DS-CDMA cellular systems.
- Coverage-load tradeoff in DS-CDMA cellular networks.
- Traffic-based capacity calculations of DS-CDMA systems.
- Multi-rate DS-CDMA systems.
- Power control in DS-CDMA cellular systems.
- DS-CDMA reverse/forward link power control.
- Soft handoff in DS-CDMA cellular systems.
- Soft handoff and cell coverage in DS-CDMA cellular systems.
- Soft handoff and capacity in DS-CDMA cellular systems.
- Summary.

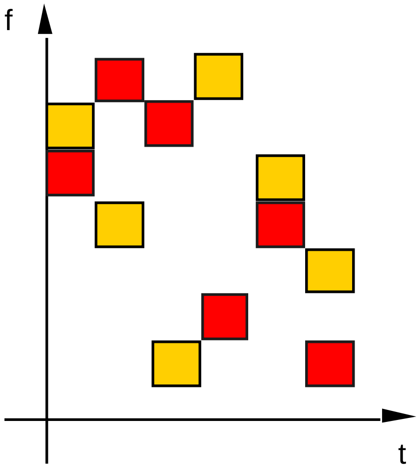
Orthogonal waveforms



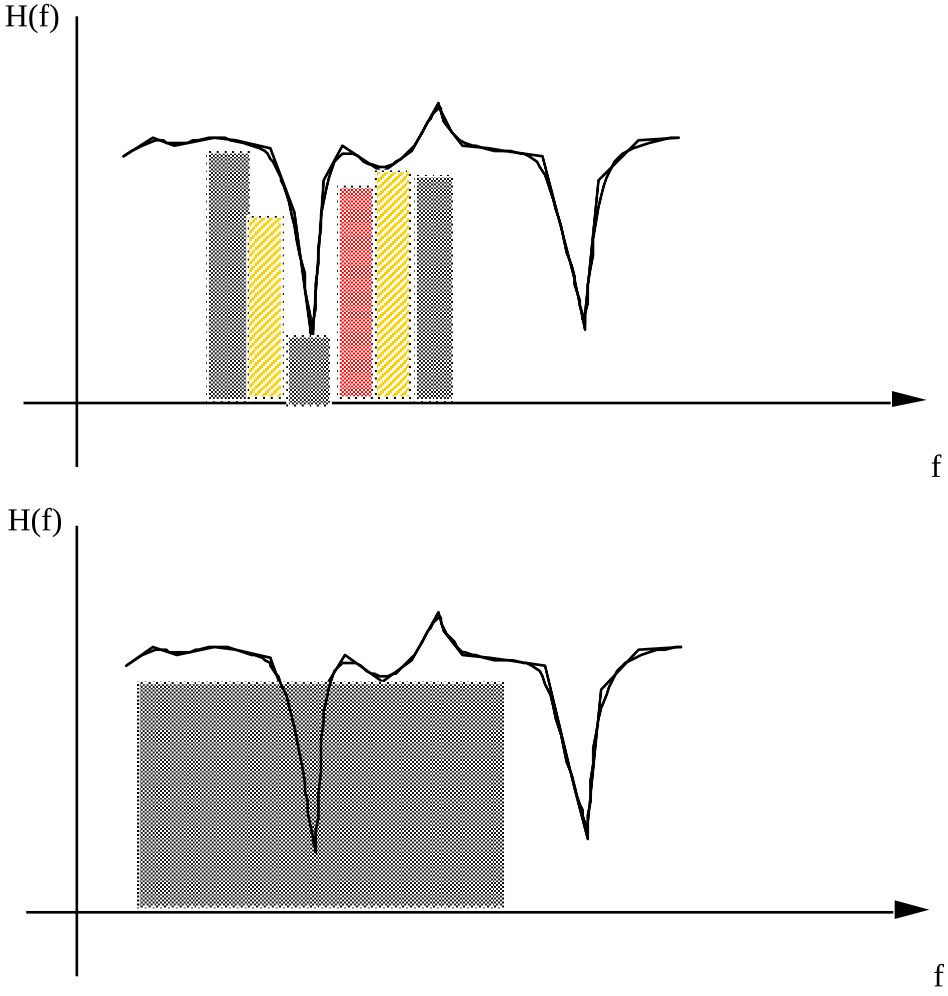
FDM



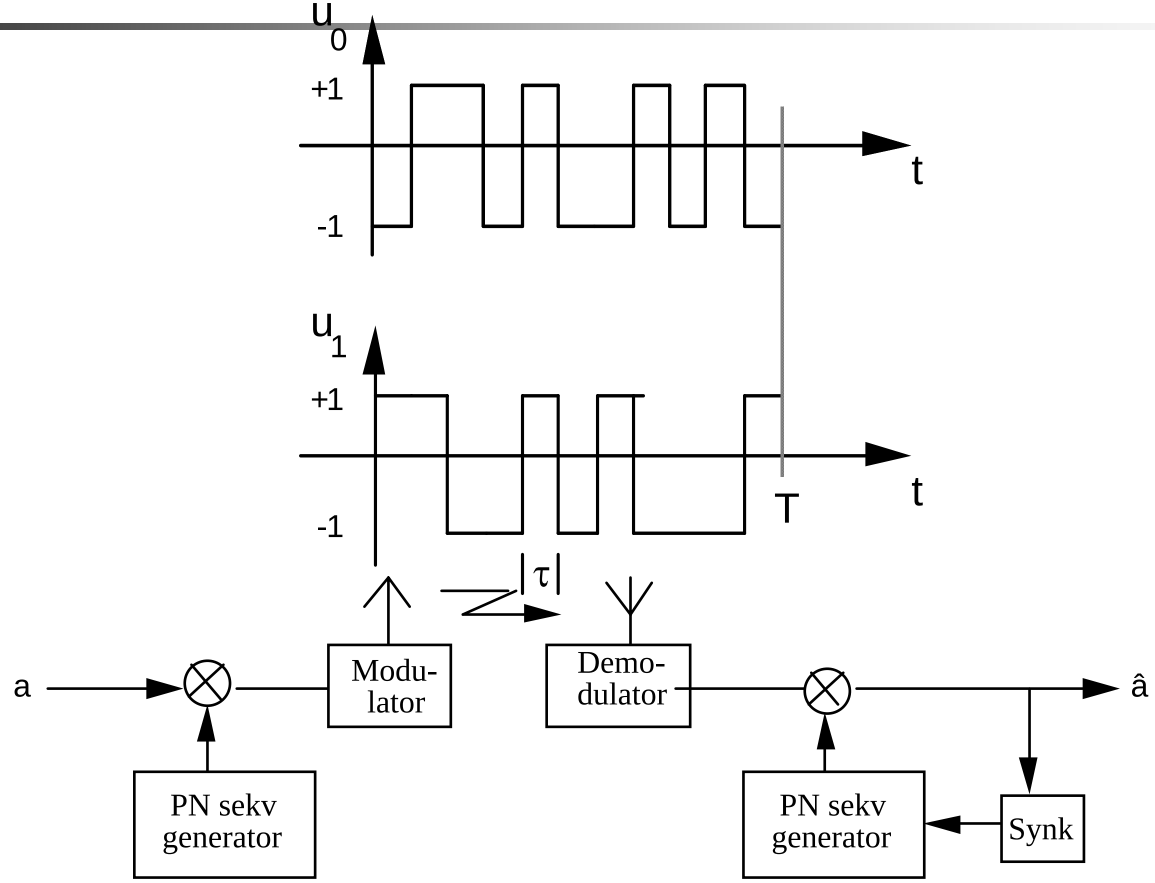
TDM



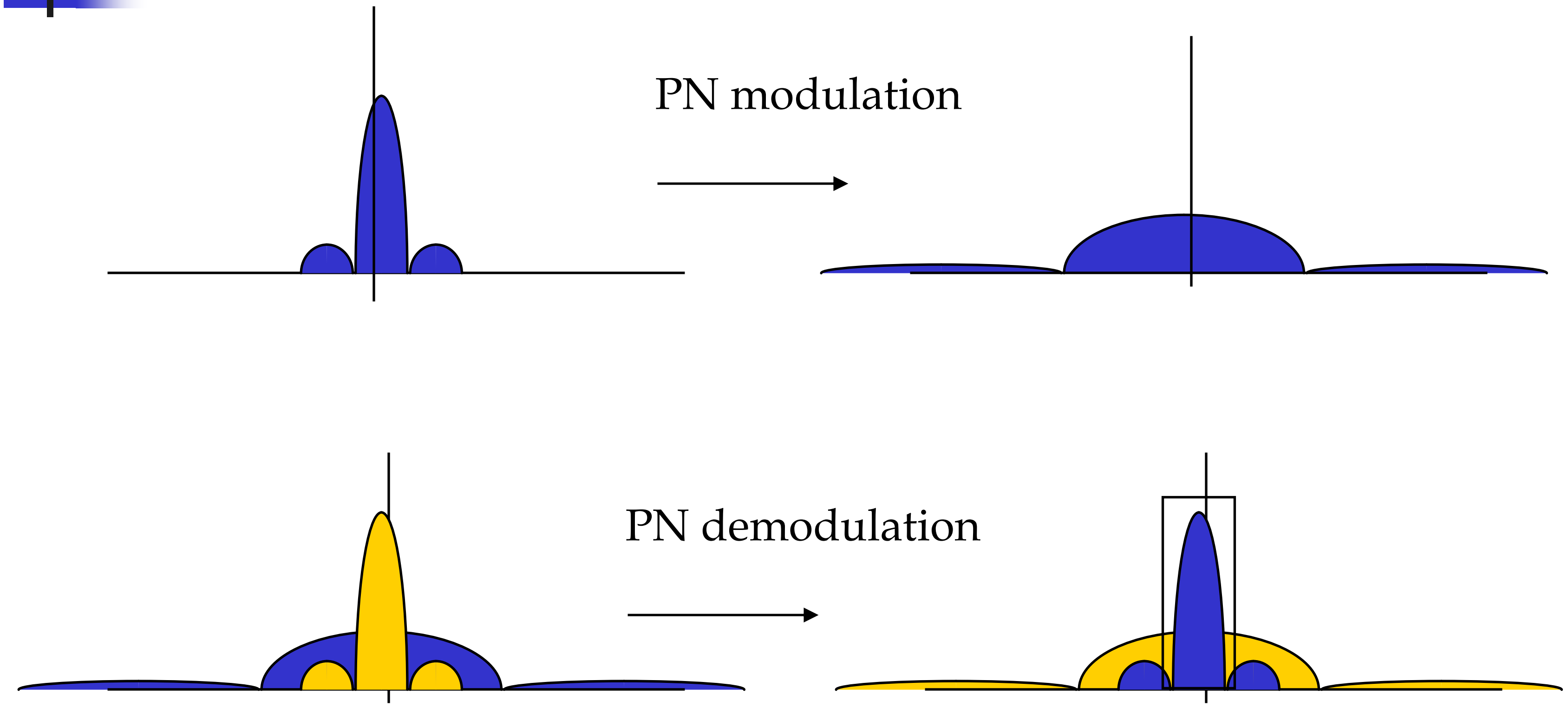
Why spreading ?



Direct sequence modulation



Spreading - Despreading



PN modulation

PN demodulation

Spreading and Scrambling Codes

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

Synchronization

- Autocorrelation properties

$$a_i(k) = a_i(k+N) \qquad i=1,2,\ldots M$$

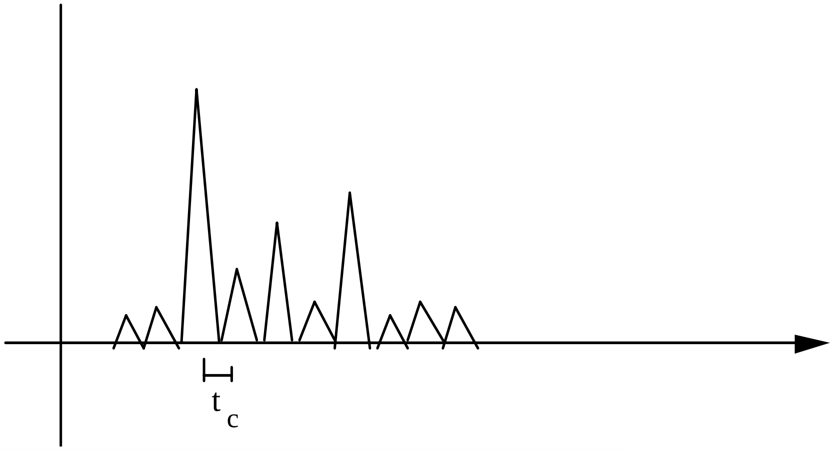
$$a_i(k) = \pm 1$$

$$C_{ii}(\tau) = \frac{1}{N}\sum_{k=0}^{N-1} a_i(k)a_i(k+\tau)$$

Ideal: "Self-orthogonal" sequences

$$C_{ii}(\tau) = 0; \quad \tau \circ 0$$

Cross-correlation



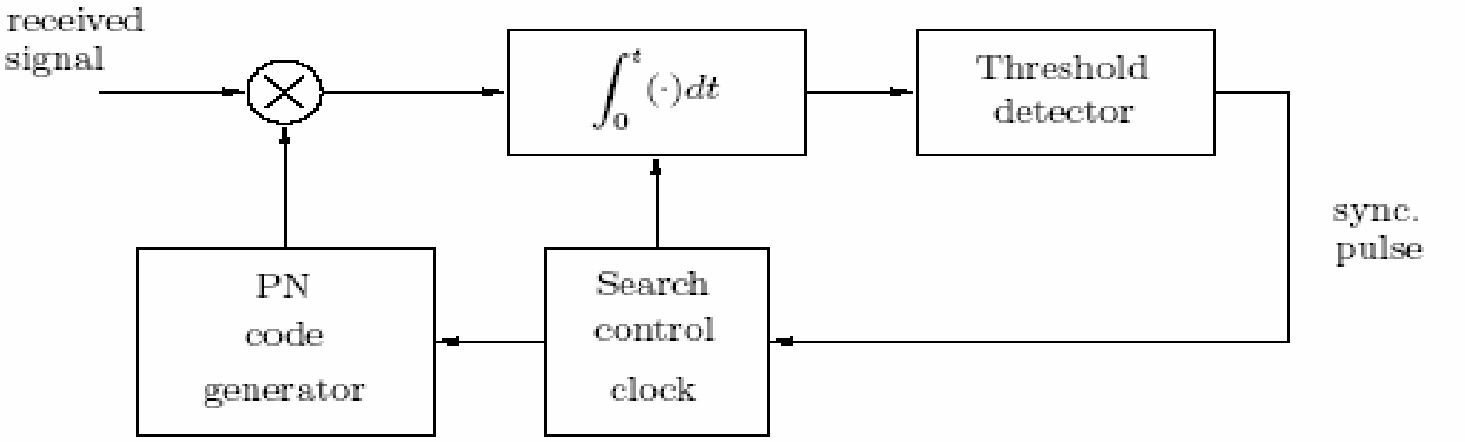


Figure 4: A sliding correlator for DS signals acquisition.

Cross-correlation properties

$$C_{ij}(\tau) = \frac{1}{N}\sum_{k=0}^{N-1} a_i(k)\,a_j(k+\tau)$$

Crosscorrelation

$$C_{\max} \geq \sqrt{\frac{M-1}{MN-1}} \approx \frac{1}{\sqrt{N}}$$

Welch bound

$$C_{avg} \approx \frac{1}{\sqrt{N}}$$

Average Crosscorrelation

Maximum-Length Sequence (m-sequence)

- M-sequence are generated using LFSR based on the following recursion
- Maximum length because they have the maximum possible period N = 2^n-1

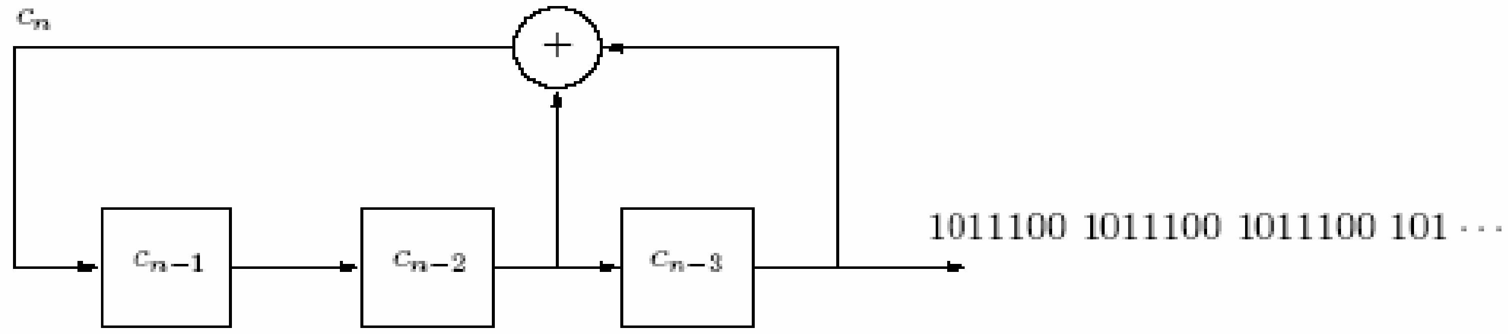
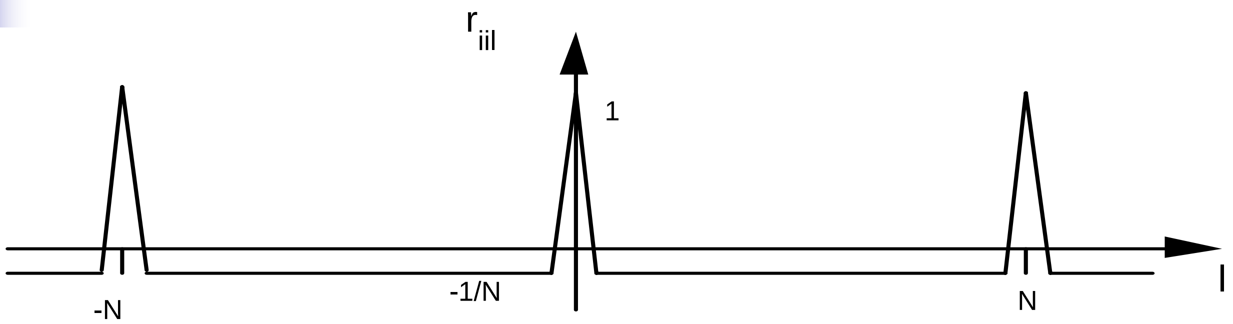
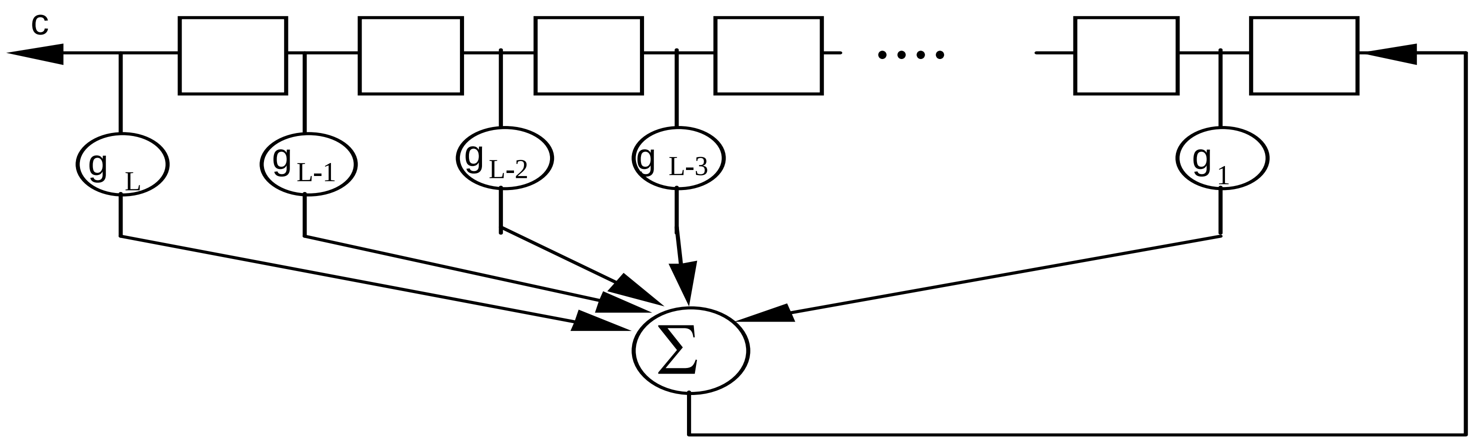


Figure 2: Example of an m-sequence with period $N = 2^3 - 1 = 7$

- The autocorrelation function of an m-sequence is a two-valued function, that is -1/N,1

m-sequences





Gold Sequence

- Gold sequences are generated using two m-sequences of the same period.
- This set consists of Ns = N + 2 sequences of period N = 2^n-1
- The cross-correlation of any pair is a three valued function

$$\frac{-1}{N}, \frac{1+\sqrt{2N+2}}{N}, \frac{1+\sqrt{2N+2}}{N} - 2$$

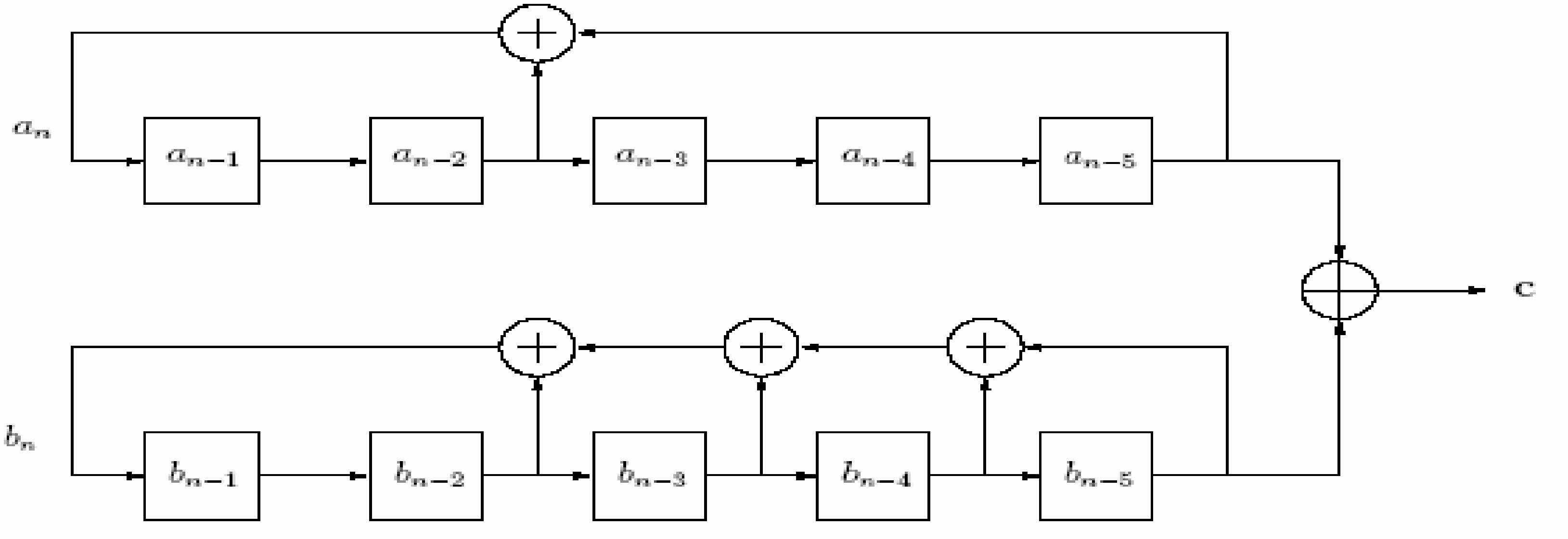


Figure 3: Example of a Gold sequence with $N = 2^5 - 1 = 31$.

Kasami Sequences

- Small set of Kasami sequences:
  - Generated using two m-sequences of period N = 2^n-1
  - Contains a total of M=$2^{n/2}$ binary sequences
  - The cross-correlation of any pair is a three valued function

$$\frac{-1}{N}, \frac{1+\sqrt{N+1}}{N}, \frac{1+\sqrt{N+1}-1}{N}$$

  - Generate a sequence of length N = 2^n-1
- Large set of Kasami sequences:
  - Generated using three m-sequences of period N = 2^n-1
  - Contains a total of M=$2^{n/2}$ binary sequences
  - The cross-correlation of any pair is a three valued function

$$\frac{-1}{N}, \frac{-1\pm\sqrt{N+1}}{N}, \frac{-1\pm 2\sqrt{N+1}}{N}$$

Walsh and Hadamard Sequences

- Walsh and Hadamard are orthogonal sequences
- These sequences have a period of N= 2^n
- They can be generated through the recursive procedure

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & -1 & 1 \end{bmatrix},$$

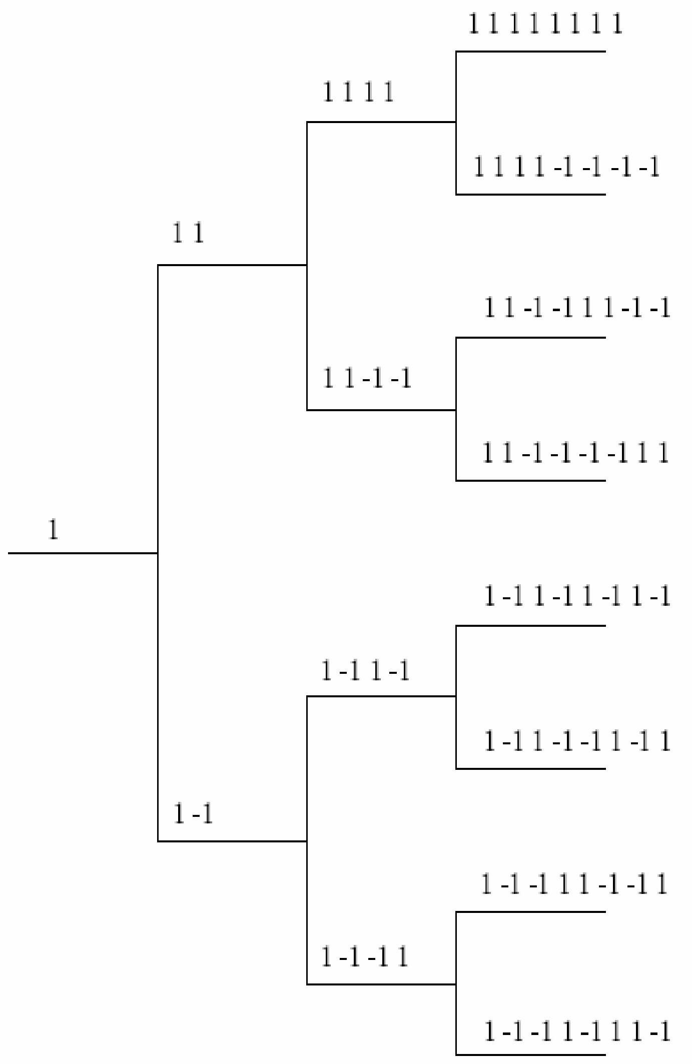
$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & -H_N \end{bmatrix}$$

Orthogonal Variable Length (OVL) Spreading Sequences

- It can be extracted from Walsh and Hadamard sequences
- Orthogonal short codes will only be useful if channel can be synchronized in the symbol level.
  - Mainly used in DL.

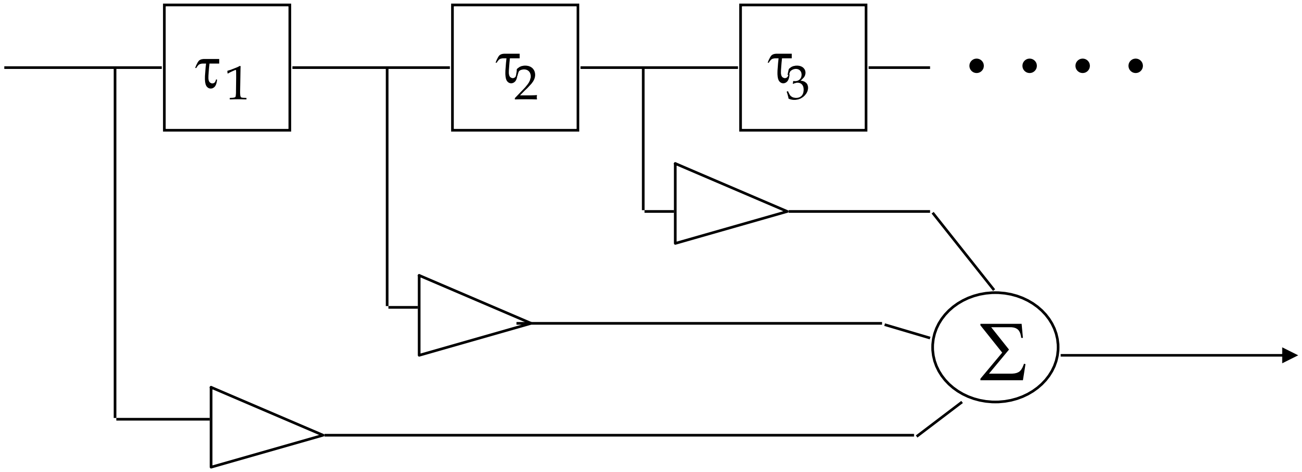
Orthogonal Variable Length (OVL) Spreading Sequences

- 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.

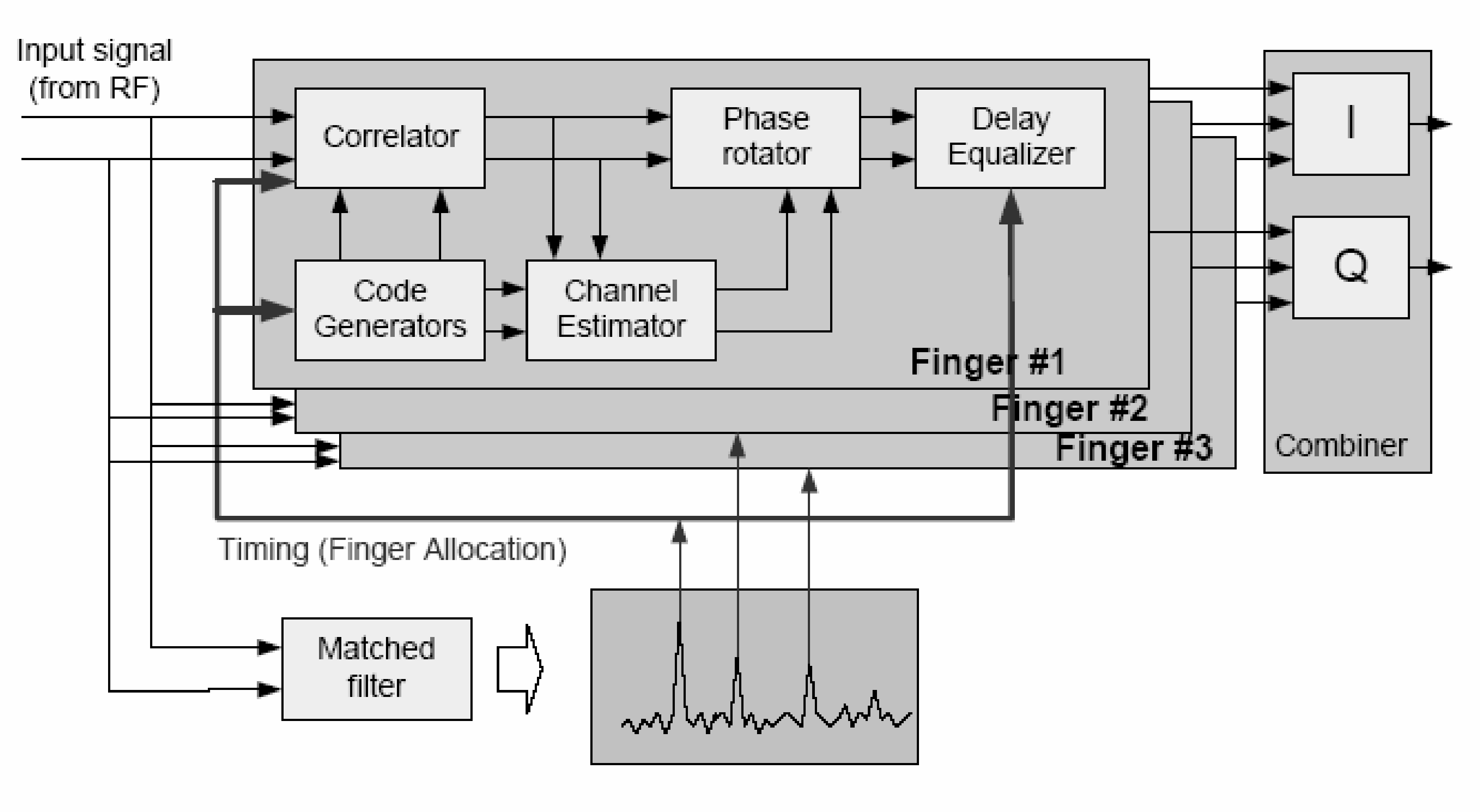


The need for “Rake” -Receiver

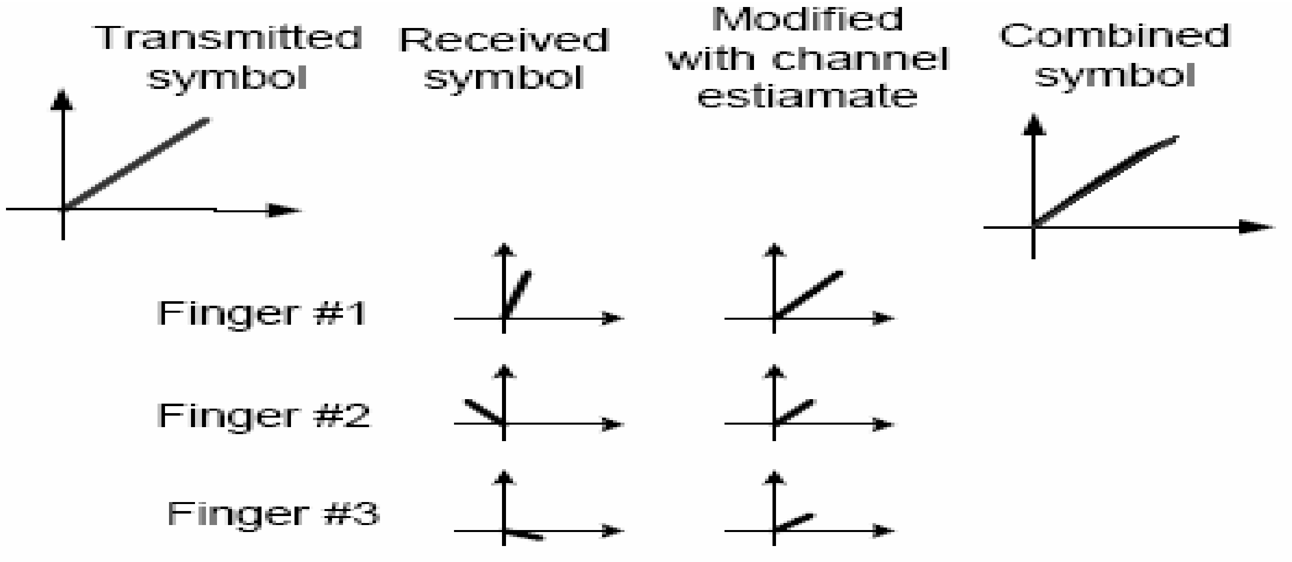
- Channel can rotate the signal to any phase and to any amplitude.
- QPSK symbols carry information in phase.
- Energy spitted to many finger -> combining.



RAKE Diversity Receiver



- 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)



DS-CDMA Cellular systems

- Power control is a basic requirement in DS-CDMA systems.
  - Constant Received Power (CRP) in the uplink.
  - Power allocation type in the downlink.
- Soft and softer handoffs.
- DS-CDMA systems use a two-layered spreading code allocation.
  - Short orthogonal codes (channelization codes).
    - Increase system capacity.
  - Long PN sequences (scrambling codes)
    - Reduce interference between different cells.
    - Reduce uplink interference.

DS-CDMA Cellular systems

- North American DS-CDMA Digital Cellular System (IS-95), 1993
  - Bandwidth: W = 1.25 MHz.
  - Information (speech) data rate: Rs = 9.6 kbps.
  - Processing gain of L_c = PG = 128.
- 3rd Generation: W-CDMA, 2001
  - Bandwidth: W = 5 MHz.
  - Variable data rate: Rs = 9.6; 144; 384; 2048 kbps.
  - Variable processing gain: 4-256.

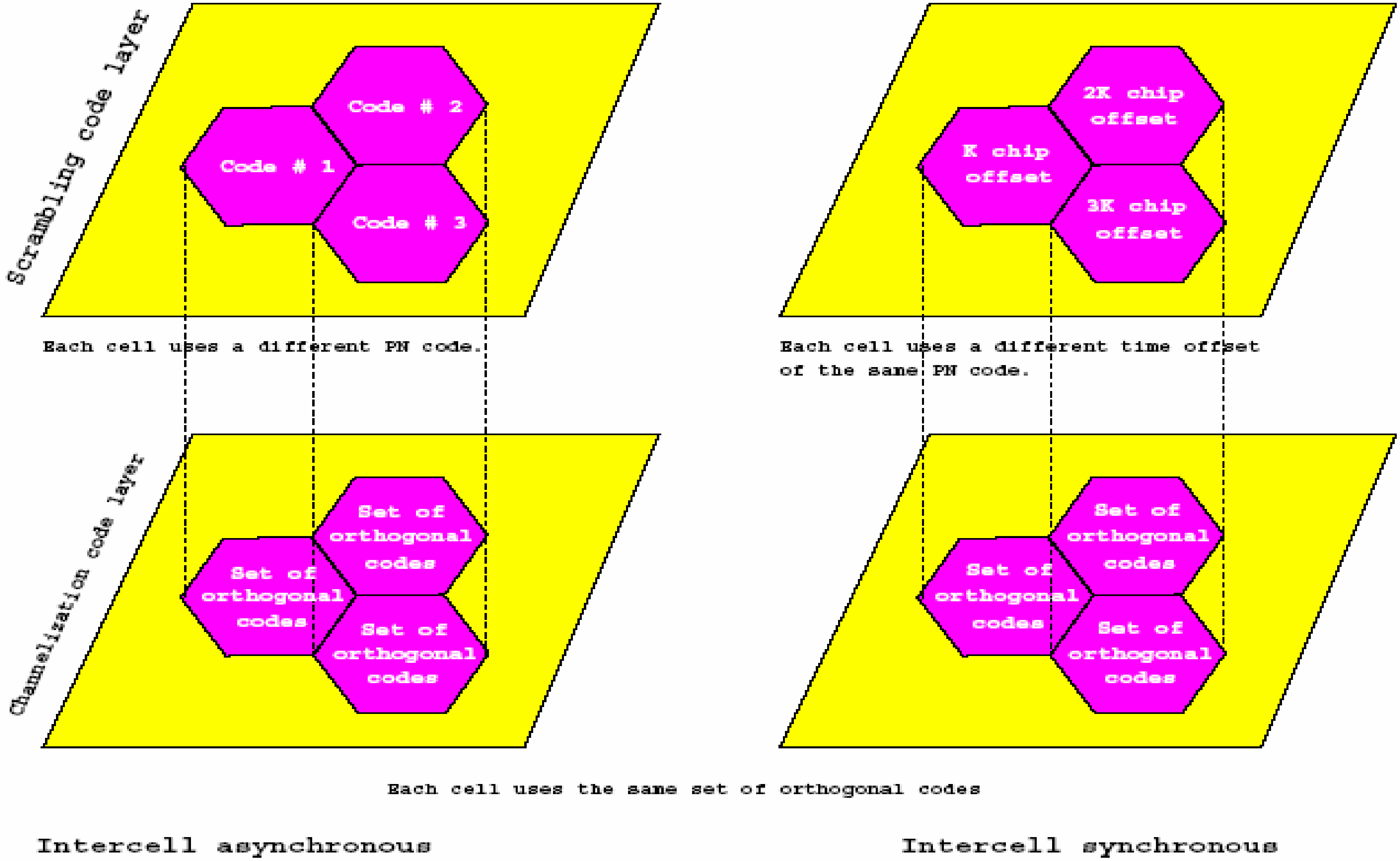
Sequences in IS-95 and WCDMA Cellular Networks

	CDMA (IS-95)	
	Forward Link	**Reverse Link**
Channelization code	Walsh sequences of length 64	
Scrambling code	Different offsets of an m-sequence with N = 2^{15}-1 chips A common PN for all users of a cell.	Different offset of an m-sequence with N = 2^{42}-1 chips. A distinct offset for each user.

Sequences in IS-95 and WCDMA Cellular Networks

	WCDMA	
	Forward Link	**Reverse Link**
Channelization code	OVL sequences	OVL sequences
Scrambling code	Gold sequence with N = 2^{18}-1 chips. A common PN for all users of a cell.	Very large set of Kasami sequences. Optional: Gold sequence with N = 2^{41}-1 chips

Sequences in IS-95 and WCDMA Cellular Networks



Each cell uses a different PN code.

Each cell uses a different time offset of the same PN code.

Each cell uses the same set of orthogonal codes

Intercell asynchronous

Intercell synchronous

Example of DS-CDMA transmitter

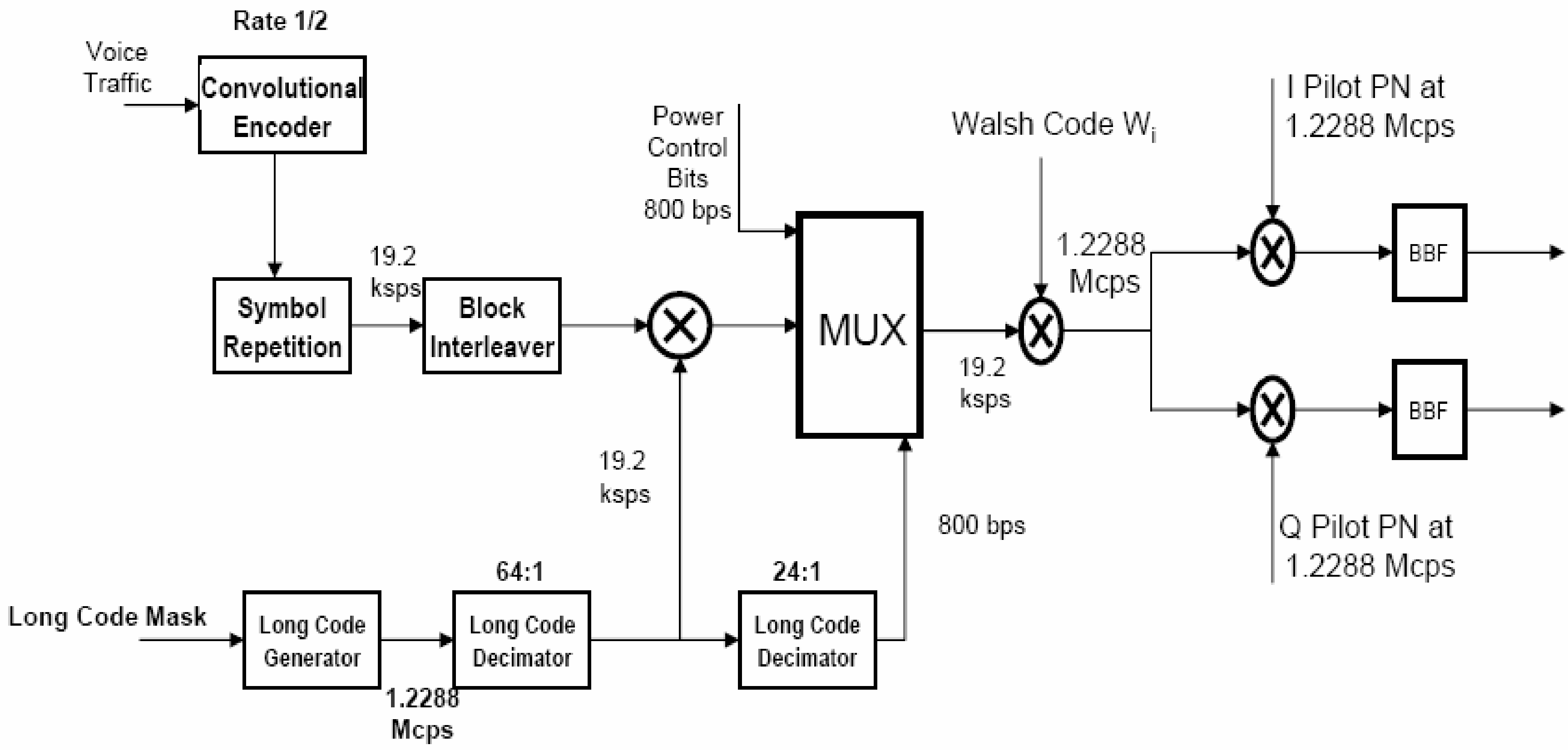


Figure 8.8: Forward Traffic Channel Processing in IS –95 (Rate Set 1)

Uplink of DS-CDMA systems

- The received signal at the base station can be written as follows:

$$r(t) = \sum_{i=1}^{M} y_i(t) + \sum_{k=1}^{L} z_k(t) + n(t)$$

$y_i(t)$ received signal from mobile i within the same cell.
$Z_k(t)$ received signal from mobile k in a neighbor cell.

- The SINR at the base station for user m is written as:

$$\Gamma_m = \frac{W}{R_s} \frac{P_m}{\sum_{i=1,}^{M} P_i + \sum_{k=1}^{L} P_k + N_o W} > \gamma_t, \quad m = 1,2, \cdots, M$$

P_i is the received power from mobile i.
R_s is the user data rate.
W is the system bandwidth.
γ_t is the required threshold.

Single Cell Capacity of DS-CDMA Systems

- For a single cell, the SINR becomes

$$\Gamma_m = \frac{W}{R_s} \frac{P_m}{\sum_{i=1,}^{M} P_i + N_o W} > \gamma_t, \quad m = 1,2, \cdots, M$$

- With perfect Constant Received Power (CRP), we get

$$\Gamma_m = \frac{W}{R_s} \frac{P}{(M-1)P + N_o W} > \gamma_t$$

- The capacity is estimated as

$$M < 1 + \frac{W}{R_s}\left(\frac{1}{\gamma_t} - \frac{1}{\gamma_o}\right), \quad \gamma_o = \frac{P}{N_o R_s}$$

Example 1

- Compute the single cell capacity of IS-95 CDMA and compare it to that of FDMA(AMPS system).

Multiple Cell Capacity of DS-CDMA Systems

- The signal-to-interference ratio at the base station is given by

$$\Gamma_m = \frac{W}{R_s}\frac{P_m}{\sum_{i=1,}^{M} P_i + \sum_{k=1}^{L} P_k + N_o W} > \gamma_t, \quad m = 1,2, \cdots, M$$

$$= \frac{W}{R_s}\frac{P_m}{I_{\text{intra}} + I_{\text{inter}} + N_o W} \geq \gamma_t$$

Multiple Cell Capacity of DS-CDMA

- The capacity is obtained by computing the time availability

$$\Pr(\Gamma \geq \gamma_t) = x\%$$

M users/cell:

- The capacity can approximated from the average SNR as

$$\overline{\Gamma} > \frac{W}{R_s}\frac{P}{(M-1)P+E\{I_{\mathrm{inter}}\}+N_oW} = \frac{W}{R_s}\frac{P}{(M-1)P+f(M-1)P+N_oW}$$

  - (We define the frequency reuse factor as:

$$F = 1 + f = \frac{\text{Total interfernce power}}{\text{Own cell interfernce power}}$$

- The capacity of multi-cell DS-CDMA systems becomes:

$$M \approx 1 + \frac{1}{F}\frac{W}{R_s}\left(\frac{1}{\gamma_t} - \frac{1}{\gamma_o}\right)$$

- The external interference is about 60% of the internal interference, i.e.,

Example 2

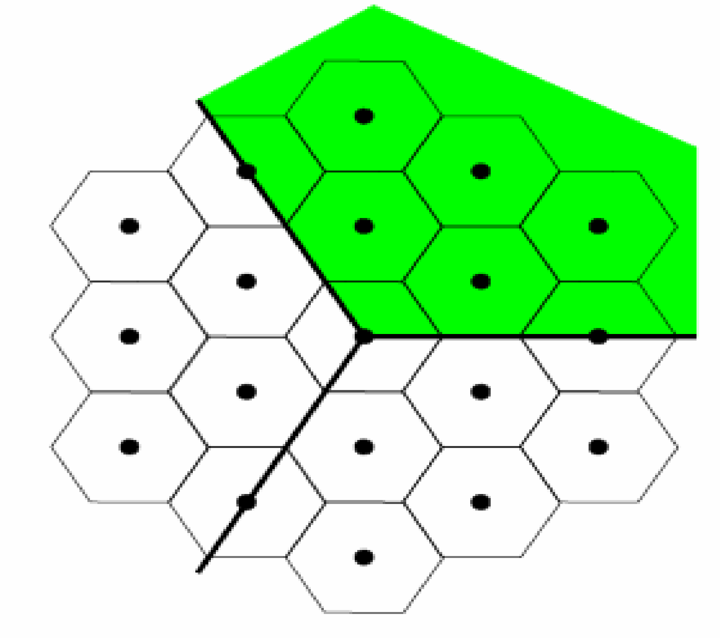
- Let us consider the IS-95 CDMA system with PG = 128 and t = 7 dB.

Sectorization in DS-CDMA Cellular systems

- The capacity of DS-CDMA system can be improved by reducing the interference
  - Sector antennas improve the capacity of DS-CDMA

$$M \approx 1 + \frac{n_{\sec}}{f} \frac{W}{R_s} \left(\frac{1}{\gamma_t} - \frac{1}{\gamma_o} \right)$$

$n_{\sec}$ is the number of antennas per cell.



Voice Activity Detection in DS-CDMA Systems

- Voice activity monitoring can improve the capacity of DS-CDMA.
  - Modeling the talk spurt and silence as exponential with means τ_1 and τ_2 s, respectively. The voice activity factor can be written as

$$q = \frac{\tau_1}{\tau_1 + \tau_2} \leq 1$$

- The transmission rate of a given mobile i can be modeled as a stochastic process with average transmission rate

$$R = qR_{ts} + (1 - q)R_{ss}$$

- The average received power from such user is qP_i.
- The multicell capacity of DS-CDMA becomes

$$M \approx 1 + \frac{n_{\sec}}{Fq}\frac{W}{R_s}\left(\frac{1}{\gamma_t} - \frac{1}{\gamma_o}\right)$$

Example 3

- Let us reconsider the IS-95 CDMA system with PG = 128 and γ_t = 7 dB.

Pole Capacity of DS-CDMA Systems

- The pole capacity is obtained when the user stations power approaches infinity

$$M_{pole} = 1 + \frac{n_{\sec}}{F}\frac{W}{R_s}\frac{1}{\gamma_t}$$

Real systems operate below the pole capacity.

- We define the dimension less load as follows:

$$L = \frac{M}{M_{pole}}$$

- The relationship between power and loading becomes

$$Z \overset{def}{=} \frac{1}{1 - L}$$

- This analysis neglects the effects of imperfect power control and the dynamics of the system.
- To account for these variations, a system should not run too close to the capacity pole.

Coverage-Capacity Tradeoff in the Reverse Link

- When the mobile users are transmitting at maximum power, loading should not be permitted to increase.
- Conversely, if the loading is allowed to increase, then the mobile users can no longer reach the required target γ_t.
  - The cell shrinks due to loading.
- This phenomenon couples coverage and loading.
- Loadings of 50% to 75% (Z = 3 to 6 dB) are an appropriate compromise between loading and coverage.

Traffic-Based Capacity Evaluation of DS-CDMA Systems

- The number of channels (codes) in CDMA is very large.
- Blocking occurs due to bad SINR and not to lack of available channels.
- In CDMA cellular networks, each cell can be modeled as an M/G/∞ queue.
- For a single cell, the number of users is modeled as a Poisson random variable having mean equal to the cell offered traffic, $\rho = \lambda/\mu$.

$$\Pr(M_c = n) = \frac{(\lambda/\mu)^n}{n!} e^{-\lambda/\mu}$$

- With voice activity detection, the number of users is still Poisson but with reduced traffic load

$$\Pr(M_c = n) = \frac{(q\lambda/\mu)^n}{n!} e^{-q\lambda/\mu}$$

- The multiple cell case can also be seen as a single cell with a higher traffic load. The number of active mobiles is modeled as Poisson RV with

$$\Pr(M_c = n) = \frac{[(1+f)q\lambda/\mu]^n}{n!} e^{-(1+f)q\lambda/\mu}$$

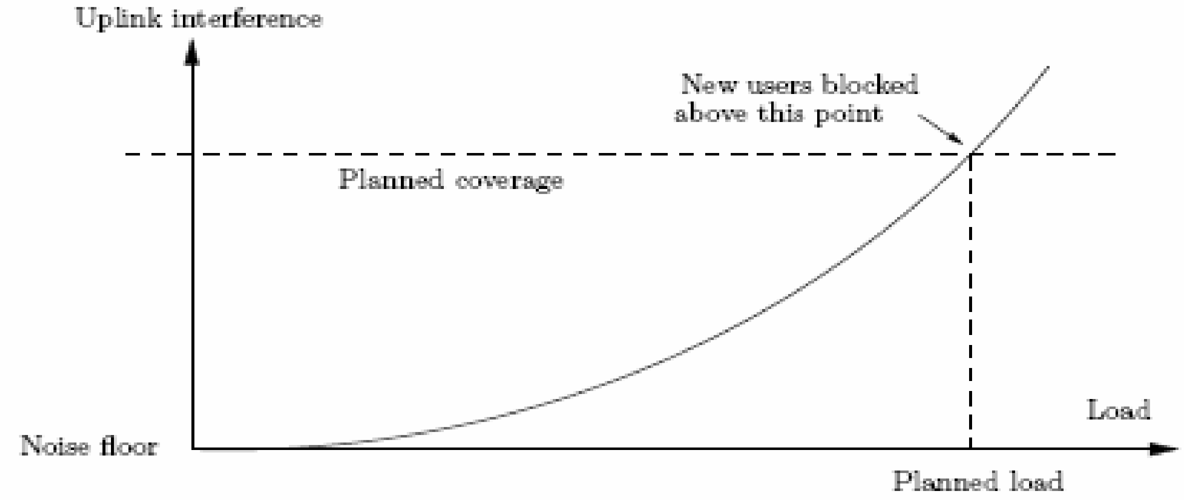
Traffic Variations-Erlang Capacity of DS-CDMA

- With M_c users, the SINR at a given base station for user m can be written as

$$\Gamma_i = \frac{W}{R_s} \frac{P}{(M_c - 1)P + N_o W} \geq \gamma_t$$

- The assignment failures in DS-CDMA is defined to occur when the total interference experienced by any user exceeds the background noise by an amount

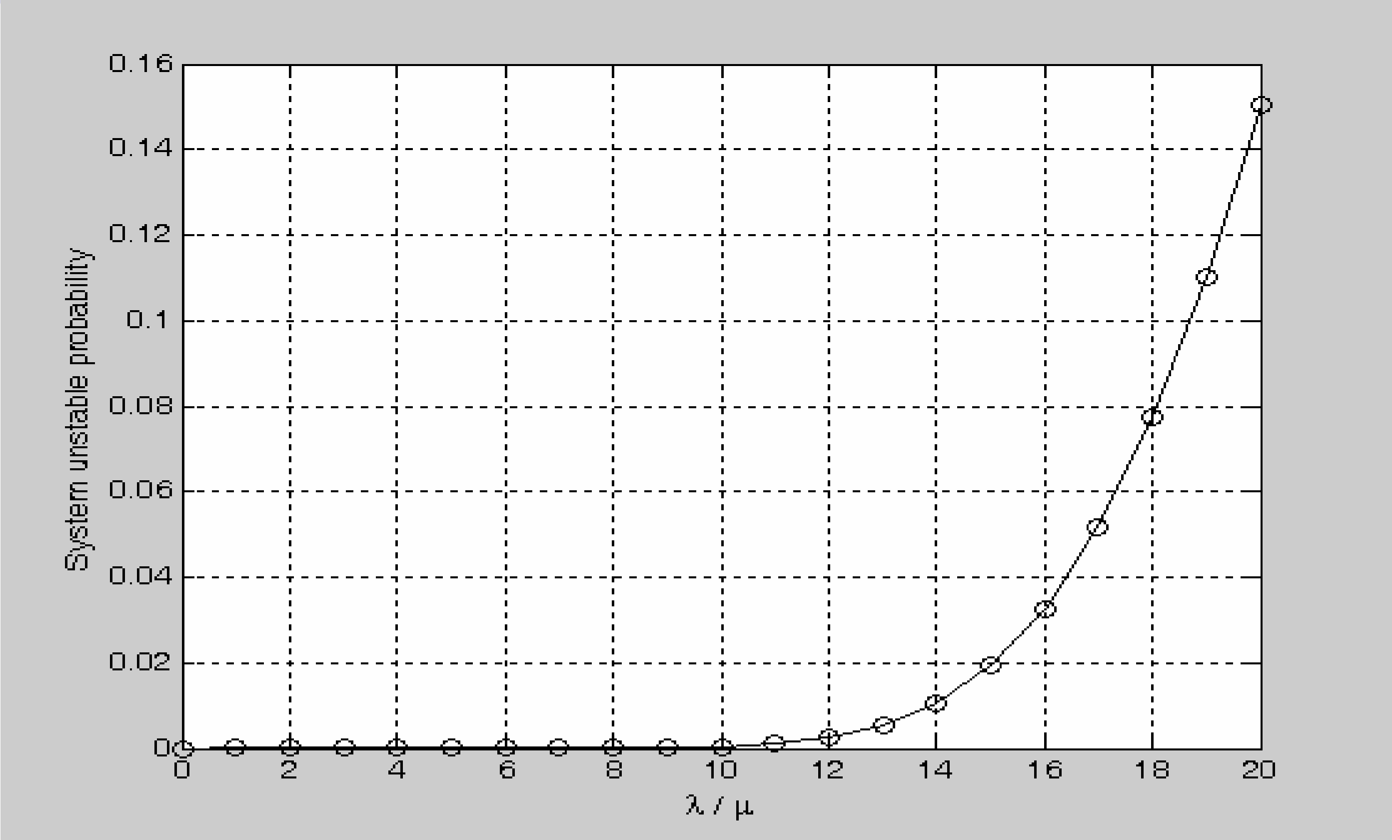
$$\nu = \Pr(M_c \geq K_o) = e^{-(1+f)q\lambda/\mu} \sum_{n=K_o}^{\infty} \frac{(1+f)q\lambda/\mu}{n!}, \quad K_o = \left\lfloor \frac{(W/R_S)(1-\eta)}{E_b/I_o} \right\rfloor$$



Example 9.2

- Consider uplink DS-CDMA system with
  - processing gain is 20 dB
  - Traffic follows Poisson distribution with activity factor is 0.4
  - Target E_b/I_o = 7 dB
  - Intercell interference factor is 0.6
  - System stability threshold is 0.1
  - Determine the maximum load per cell that gives system unstable probability less than 2%

System unstable probability



- Find the effect of different target E_b/I_o values

Downlink of DS-CDMA systems

- Each base station allocate the fraction power needed for every user within the cell
- For a DS-CDMA system with M users per cell

$$\sum_{m=1}^{M} \phi_m \leq 1$$

ϕ_m is the fraction of power assigned to user m.

- The SINR ratio at some mobile *m* is written as

$$\Gamma_m = \frac{W}{R_s} \frac{\phi_m P_{1,m}}{\theta_m (1-\phi_m) P_{1,m} + \sum_{k=2}^{B} P_{k,m} + N_o W} \geq \gamma_t$$

$\theta_m \, (0 \leq \theta_m \leq 1)$ is the Orthogonality factor between the downlink users.

B is the number of base stations.

$P_{k,m}$ is the received power from base station *k*.

- The fraction power needed for mobile m is then obtained as

$$\phi_m \geq \frac{1}{\theta_m + \frac{W}{R_s} \frac{1}{\gamma_t}} \left[\theta_m + \sum_{k=2}^{B} \frac{P_{k,m}}{P_{1,m}} + \frac{N_o W}{P_{1,m}} \right]$$

Downlink Capacity of DS-CDMA systems - Single Cell Case

- The fraction power needed for some mobile m, in this case, is obtained as

$$\phi_m \geq \frac{1}{\theta_m + \frac{W}{R_s}\frac{1}{\gamma_t}}\left[\theta_m + \sum_{k=2}^{B}\frac{P_{k,m}}{P_{1,m}} + \frac{N_o W}{P_{1,m}}\right] = \frac{1}{\theta_m + \frac{W}{R_s}\frac{1}{\gamma_t}}\left[\theta_m + \sum G_m\left(\frac{r_m}{R}\right)^{\alpha} + \frac{W}{R_s}\frac{1}{\gamma_o}\right], \quad \gamma_o = \frac{cP}{R^{\alpha} N_o R_s}$$

γ_o is the median SNR at the border of the cell.

- When the base station power approaches infinity, the single cell downlink capacity becomes

$$M_{sp} = 1 + \frac{1}{\theta}\frac{W}{R_s}\frac{1}{\gamma_t}$$

- With limited power, the downlink single cell capacity is approximated as

$$M \approx \frac{M_{sp}}{1 + \frac{2}{\theta_m(\alpha+1)}\frac{W}{R_s}\frac{1}{\gamma_o}} = 1 + \frac{1}{\theta_m}\frac{W}{R_s}\left(\frac{1}{\gamma_t} - \frac{2}{(\alpha+1)}\frac{1}{\gamma_u}\right), \quad \gamma_u = \phi_m \gamma_o = \frac{\gamma_o}{M}$$

γ_u with is the median user SNR at the border of the cell.

Downlink Capacity of DS-CDMA systems - Multiple Cell Case

- Without shadowing, the fraction of power allocated to user m is obtained as

$$\theta_m \geq \frac{1}{\theta_m + \frac{W}{R_s}\frac{1}{\gamma_t}}\left[\theta_m + \sum_{n=1}^{\infty} 6n\left(\frac{r_m}{nD}\right)^{\alpha} + \frac{W}{R_s}\frac{1}{\gamma_o}\left(\frac{r_m}{R}\right)^{\alpha}\right]$$

Multiple cell components

- The capacity of the multiple cell case is approximated as

$$M \approx \frac{1}{\theta_m + \frac{12}{3^{\alpha/2}(\alpha+1)}\zeta(\alpha+1)}\left[\theta + \frac{W}{R_s}\left(\frac{1}{\gamma_t} - \frac{2}{\alpha+1}\frac{1}{\gamma_u}\right)\right]$$

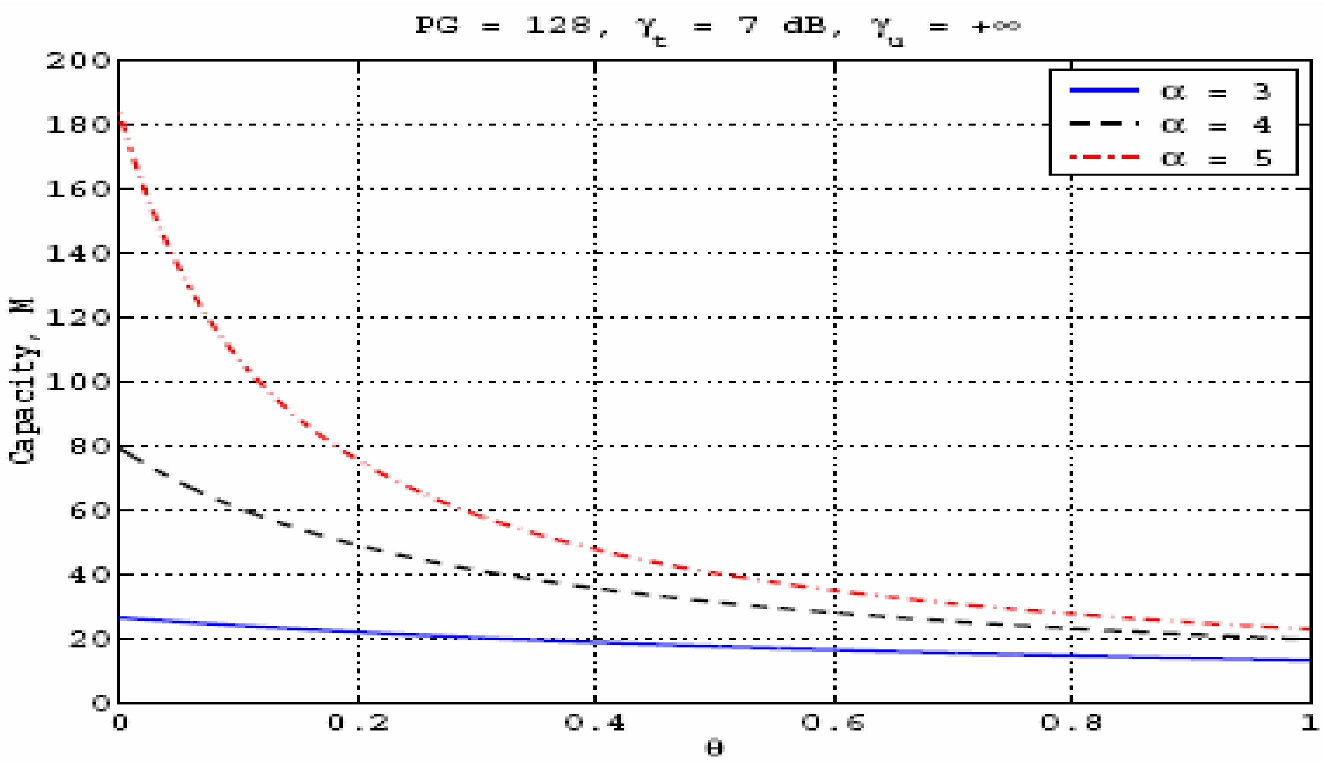
- ζ(.) is the Riemann zeta function , which has the values

$$\zeta(\alpha-1) = \sum_{n=1}^{\infty}\frac{1}{n^{\alpha-1}} = \begin{cases} +\infty, & \alpha = 2 \\ \frac{\pi^2}{6} = 1.6449, & \alpha = 3 \\ 1.2021, & \alpha = 4 \\ \frac{\pi^4}{90} = 1.0823, & \alpha = 5 \end{cases}$$

Example 4

- Let us consider the IS-95 CDMA system with PG = 128 and γ_t = 7 dB.
- The downlink multicell capacity of this system can be approximated as

$$M \approx \frac{1}{\theta_m + \frac{12}{3^{\alpha/2}(\alpha+1)}\zeta(\alpha+1)}\left[\theta + \frac{W}{R_s}\frac{1}{\gamma_t}\right], \qquad \text{users/cell}$$



Multi-Rate DS-CDMA systems

- DS-CDMA can provide multimedia services by using variable rate spreading codes.
- The processing gain for user m is given by $PG_m = \frac{W}{R_m}$
- The **SINR** for user m is written as follows:

$$\Gamma_m = \frac{W}{R_m}\frac{P_m}{\sum_{i=1,i\neq m}^{M} P_i + I_{\text{inter}} + N_o W} > \gamma_m$$

- The required power for user m is then given by

$$P_m = \frac{1}{1 + \frac{W}{R_m}\frac{1}{\gamma_m}} \frac{I_{\text{inter}} + N_o W}{1 - \sum_{i=1}^{M} \frac{1}{1 + \frac{W}{R_m}\frac{1}{\gamma_m}}} > \gamma_m$$

- The capacity of multi-rate DS-CDMA systems is feasible if

$$\sum_{i=1}^{M} \frac{1}{1 + \left(\frac{W}{R_m}\frac{1}{\gamma_m}\right)} < 1$$

Example 9.3

- Consider uplink DS-CDMA system with
  - System bandwidth = 5 MHz
  - Two available date rates: 10, 20 kbps
    - 50% of active users require R_1 and the other 50% requires R_2
  - Target E_b/I_o = 7 dB for data rates
  - Intercell interference is fixed
  - No limitation on transmitter power
  - Determine the maximum supportable number of active terminals in the cell

Power-constrained case

- What if the terminal is power-limited?

$$0 < P_m = \frac{1}{1+\frac{W}{R_m}\frac{1}{\gamma_m}} \frac{I_{\text{inter}} + N_o W}{1-\sum_{i=1}^{M} \frac{1}{1+\frac{W}{R_m}\frac{1}{\gamma_m}}} \le \overline{P_m}, \quad \forall m$$

- If the target rate (SIR) of each terminal is achieved within each terminal power limit, then

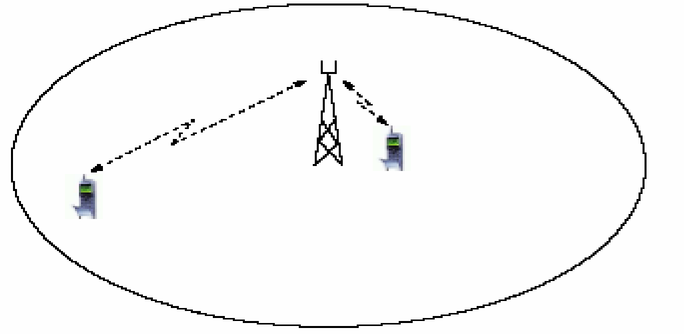
$$\sum_{i=1}^{M} \frac{1}{1+\frac{W}{R_i}\frac{1}{\gamma_i}} \le 1 - \frac{I_{\text{inter}} + N_o W}{\min\limits_{1\le i\le M}\left[\overline{P_m}\left(1+\frac{W}{R_i}\frac{1}{\gamma_i}\right)\right]}$$

Power Control in DS-CDMA Systems

- DS-CDMA cellular systems require good and accurate power management.
  - Bandwidth allocation ; power allocation.
  - Power control ensures that each user receives and transmits enough energy to properly convey information while interfering with other users no more than necessary.
- Power control reduces the required transmitted power
  - Better battery life.
  - Less interference.
- Power control increases the capacity of DS-CDMA cellular systems.
- Uplink and downlink power control are required (lack of reciprocity).

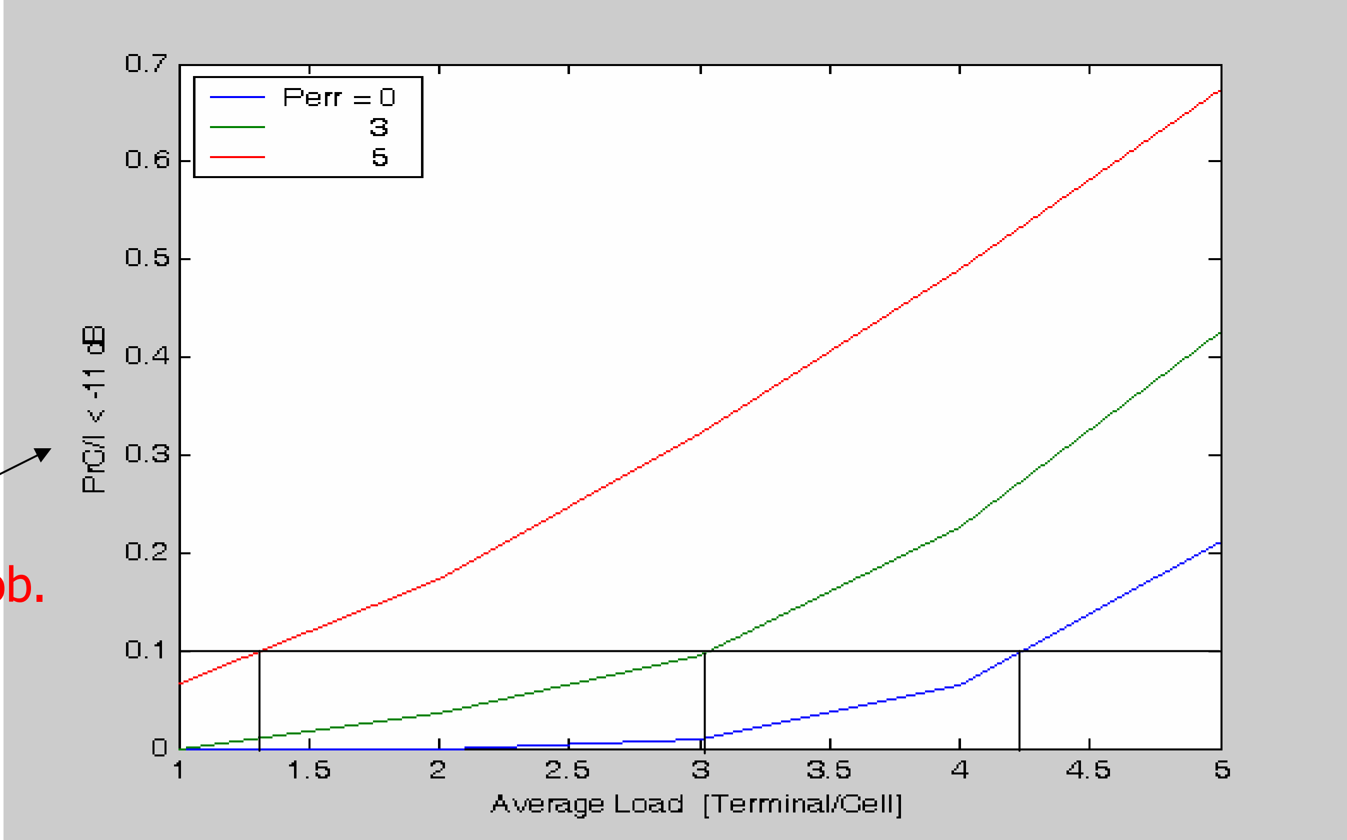
Reverse Link Power Control

- Power control is very critical for DS-CDMA cellular systems.
- Path loss effects (dynamic range in the order of 80 dB).
- Fading multipath effects (fluctuations of 20 to 30 dB).
- The reverse link power in DS-CDMA constitutes of three loops
  - Open-loop power control.
  - Fast closed loop power control.
  - Outer loop power control.



When both users are transmitting with same power, the far away user will be jammed by the near by user

Imperfect power control and DS-CDMA system capacity



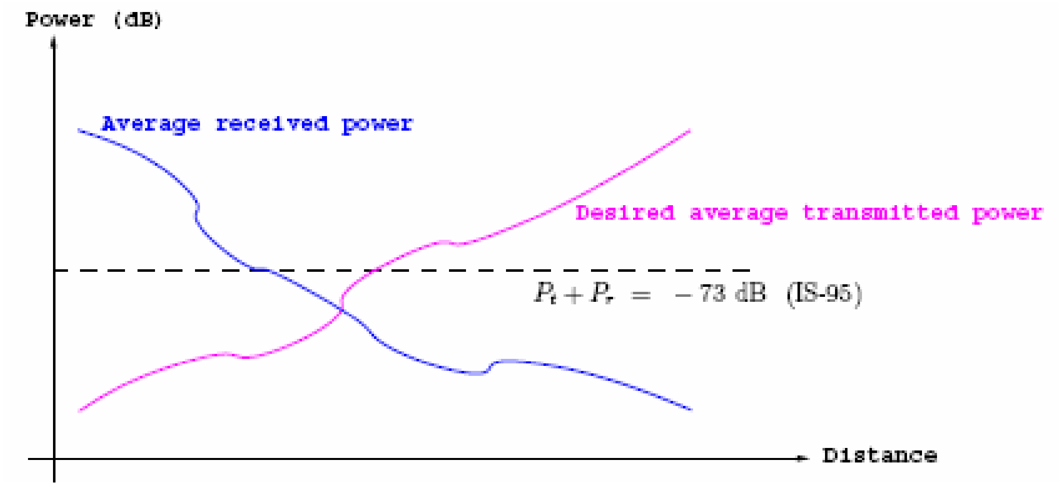
Outage Prob.

Open Loop Power Control

- The mobile estimates the path loss to the base station by measuring the received signal level (e.g. pilot signal).
- Measurements based on an analog AGC voltage.
- The mobile unit adjusts its transmitted power according to

$$P_{\text{transmitted}}\ (\text{dB}) + P_{\text{received}}\ (\text{dB}) = \text{Constant}$$

- Required accuracy of about ±9 dB in normal conditions.

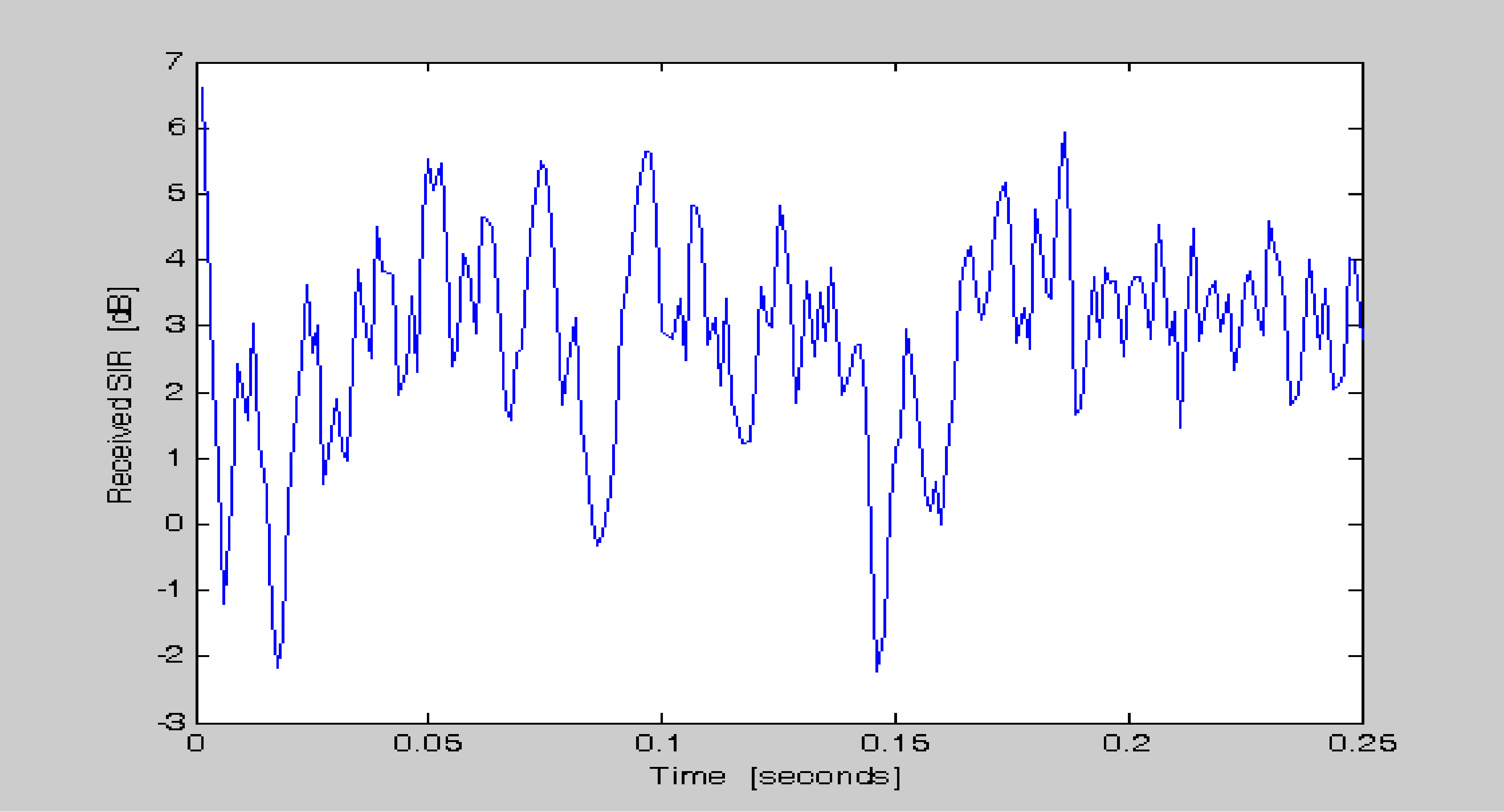


- Problem of reciprocity in FDD cellular networks (what about TDD?).

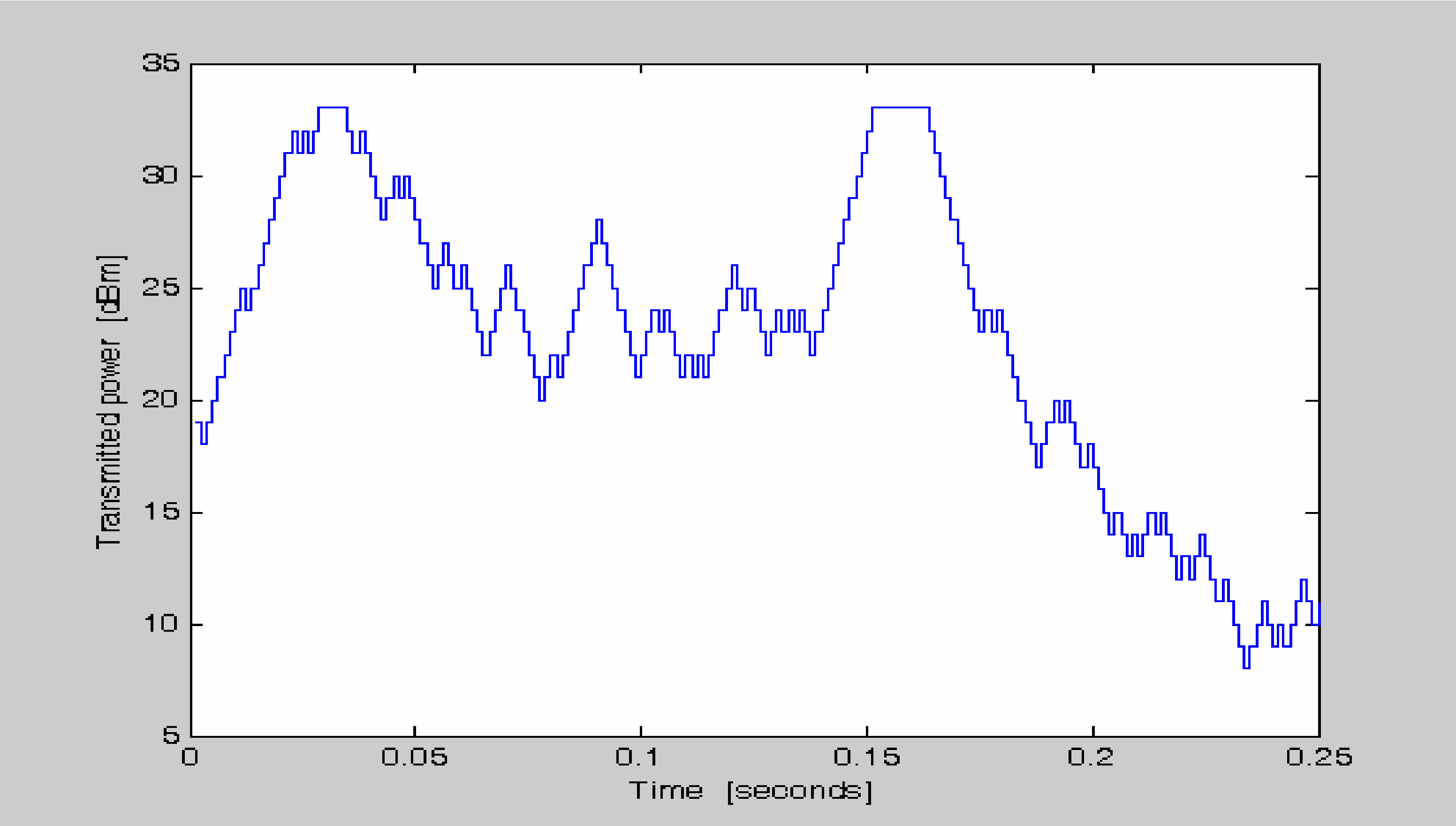
Closed Loop Power Control

- Closed loop power control is a sort of “fine tuning" to the open loop power control.
  - The base station measures the received E_b/I_o, Γ_ι for each mobile.
  - Compares this estimate to the desired threshold, γ_t.
  - If $\Gamma_\iota > \gamma_t$, a “down" command is sent to the mobile.
  - If $\Gamma_\iota < \gamma_t$, an “up" command is sent to the mobile.
    - Power control frequency: 800 Hz, 1600 Hz.
    - Power up/down “step size": 0.5 - 1 dB.
  - There is no “do nothing" command (to reduce overhead).

Uplink power control in IS-95

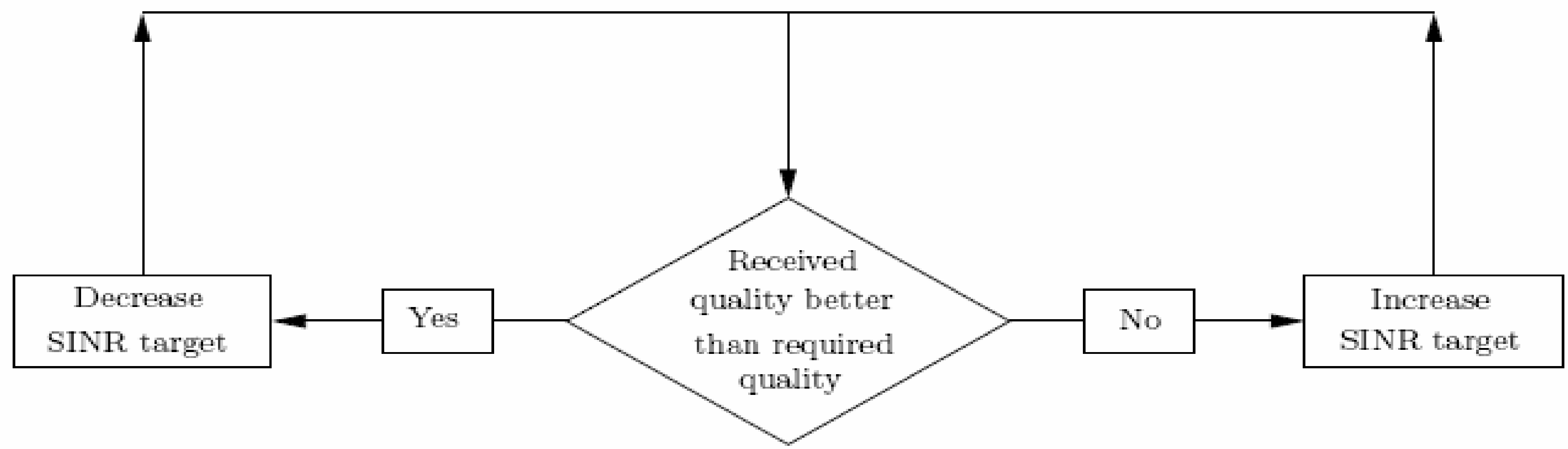


Uplink power control in IS-95



Outer Loop Power Control

- The outer loop power control aims at providing the required quality: no worse, no better.
  - Adjust target γ_t to the required FER (or BER).
- This loop ensures that the fast power control strategy is operating correctly.
  - Uplink only in IS-95.
  - Both uplink and downlink in WCDMA.

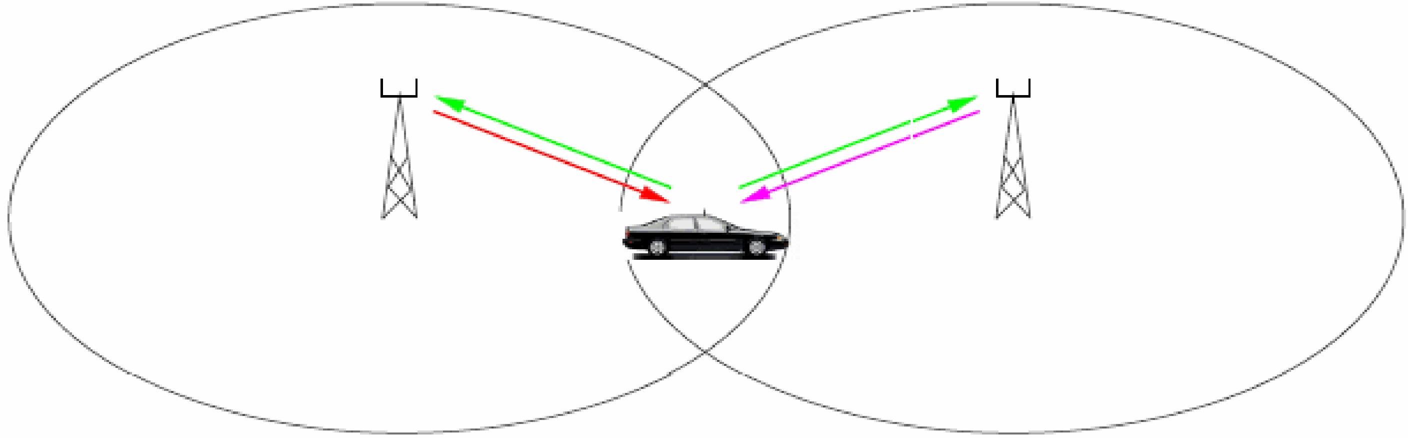


Forward Link Power Control

- The forward link may be subject to poor reception conditions.
  - Mobile near the border of the cell.
  - Mobile located where several strong multipath signals arrive.
- The mobile can request an increase/decrease in the power transmitted to it by the base station.
  - Mobile has the capability to measure received signal-to-total interference ratio.
- Slow rate of forward link power adjustment:
  - Once per 15-20 ms.
- Limited dynamic range:
  - About ±6 dB around the nominal power.

Soft Handoff in DS-CDMA Cellular Systems

- Soft handoff is a technique whereby mobile units in transition between one cell and its neighbor transmit to and receive the same signal from both base stations simultaneously.



- On the downlink, the RAKE receiver at the mobile can achieve MRC of the two coming signals.
- On the uplink, the mobile switching center must resolve which base station is receiving the stronger signal and hence better replica and decide in its favor (selection diversity).

Soft Handoff Increases CDMA Uplink Capacity

- With perfect power control, the received E_b/I_o at base station 0, for a given user, is given by

P is the received power

$$\Gamma_0 = \frac{W}{R_s}\frac{P}{(M-1)P + \sum_{b=1}^{B}\sum_{k=1}^{M}\left(\frac{G_{k,0}}{d_{k,0}^{\alpha}}\right)\left(\frac{d_{k,b}^{\alpha}}{G_{k,b}}\right)P + N_o W}$$

B is the number of base stations.

M is the number of users per cell.

- With a candidate set for soft handoff of N_c cells, we have

$$\frac{G_{k,b}}{d_{k,b}^{\alpha}} = \max\left\{\frac{G_{k,1}}{d_{k,1}^{\alpha}}, \frac{G_{k,2}}{d_{k,2}^{\alpha}}, \cdots, \frac{G_{k,N_c}}{d_{k,N_c}^{\alpha}}\right\} > \frac{G_{k,0}}{d_{k,0}^{\alpha}}$$

- The capacity can approximated from the average E_b/I_o as follows:

$$\overline{\Gamma}_i = \frac{W}{R_s}\frac{P}{(M-1)P + E\{I_{\text{inter}}\} + N_o W} = \frac{W}{R_s}\frac{P}{(1+F_{N_c})(M-1)P + N_o W}$$

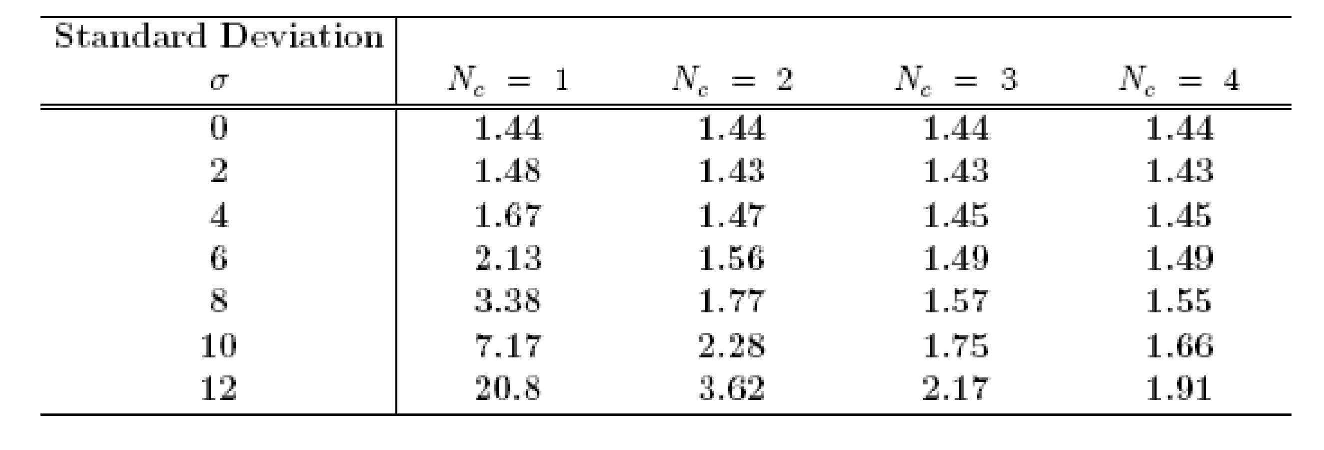
- A frequency reuse factor is dependent on the number of cells in the candidate set for handoff

Soft Handoff Increases CDMA Uplink Capacity

- The uplink capacity of DS-CDMA cellular systems with soft handoff becomes:

$$M \approx 1 + \frac{1}{F_{N_c}} \frac{W}{R_s} \left(\frac{1}{\gamma_t} - \frac{1}{\gamma_o} \right)$$

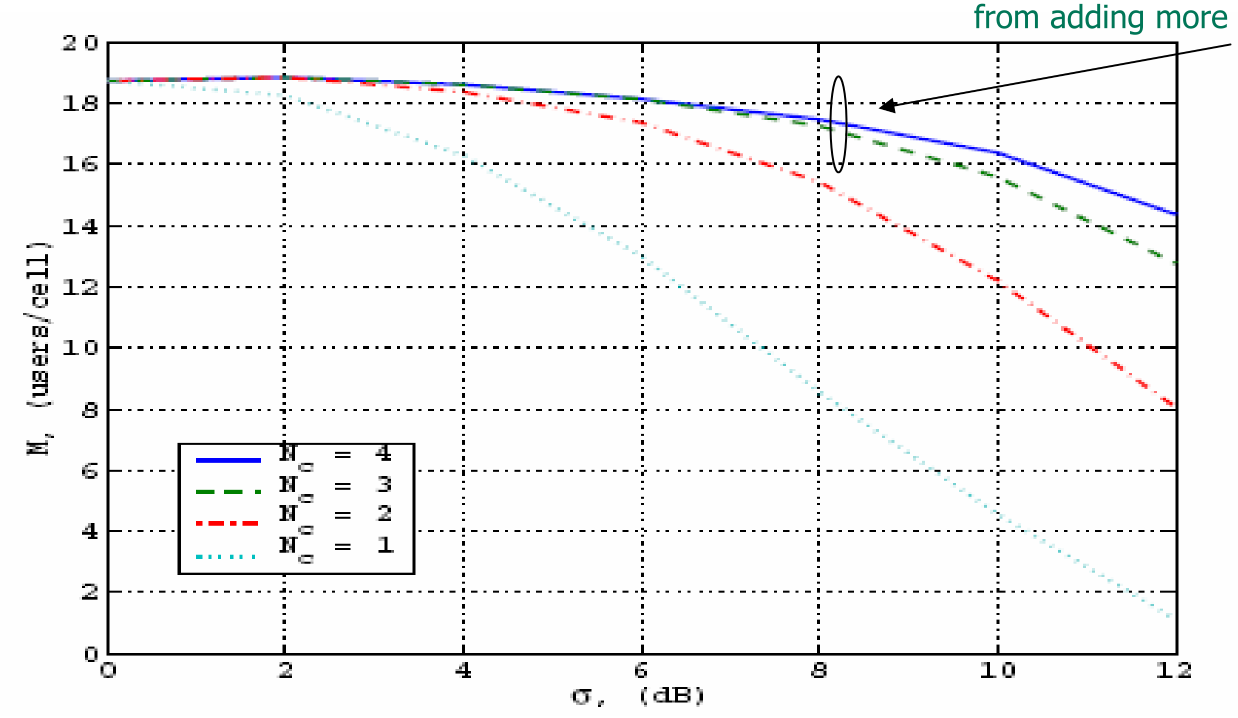
- The frequency reuse factor, F_{Nc}, for different values of Nc and $\alpha = 4$



Standard Deviation σ	$N_c = 1$	$N_c = 2$	$N_c = 3$	$N_c = 4$
0	1.44	1.44	1.44	1.44
2	1.48	1.43	1.43	1.43
4	1.67	1.47	1.45	1.45
6	2.13	1.56	1.49	1.49
8	3.38	1.77	1.57	1.55
10	7.17	2.28	1.75	1.66
12	20.8	3.62	2.17	1.91

Example

- Let us consider the IS-95 CDMA system with PG = 128 and γ_t = 7 dB
- Compute the capacity for different values of Nc as a function of the standard deviation σ! Neglect the noise.



There is a limitation on the obtained gain from adding more base station

Soft Handoff in the Downlink of DS-CDMA Systems

- A mobile in soft handoff requires a traffic channel from each base station involved in the soft handoff process.
- The number of available traffic channels on the forward link decreases as the number of mobiles in soft handoff increases.
- The received Eb/I0 ratio at some mobile m is written as

$$\Gamma_m = \frac{W}{R_s}\frac{\phi_m P_{1,m}}{\theta_m(1-\phi_m)P_{1,m} + \sum_{k=2}^{B} P_{k,m} + N_o W} \geq \gamma_t$$

$\theta_m\,(0 \leq \theta_m \leq 1)$ is the Orthogonality factor between the downlink users.

B is the number of base stations.

$P_{k,m}$ is the received power from base station k.

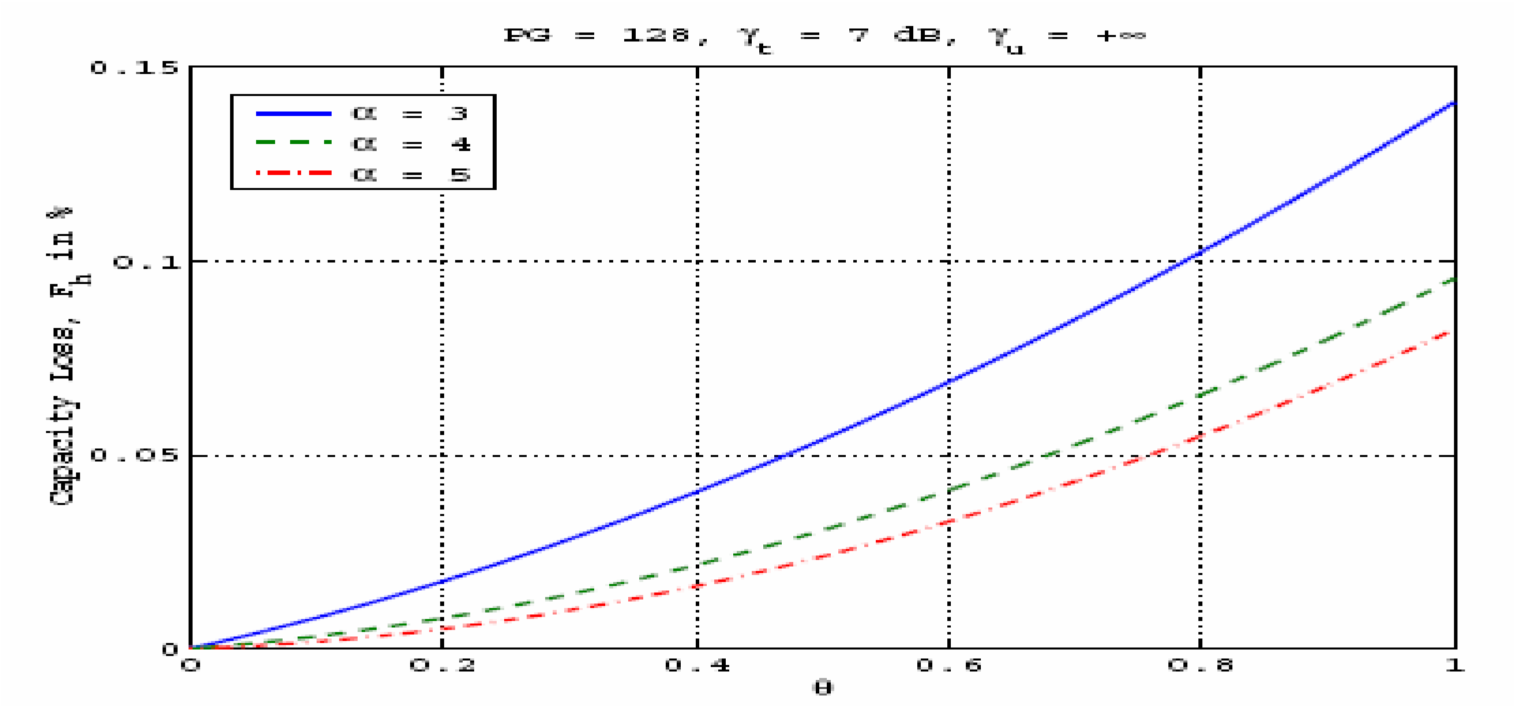
- When mobile m is in soft handoff, with Nc base stations involved in the process, its combined E_b/I_o can be written as:

$$\Gamma_m = \sum_{i=0}^{N_c-1} [\Gamma_m]_i$$

Example

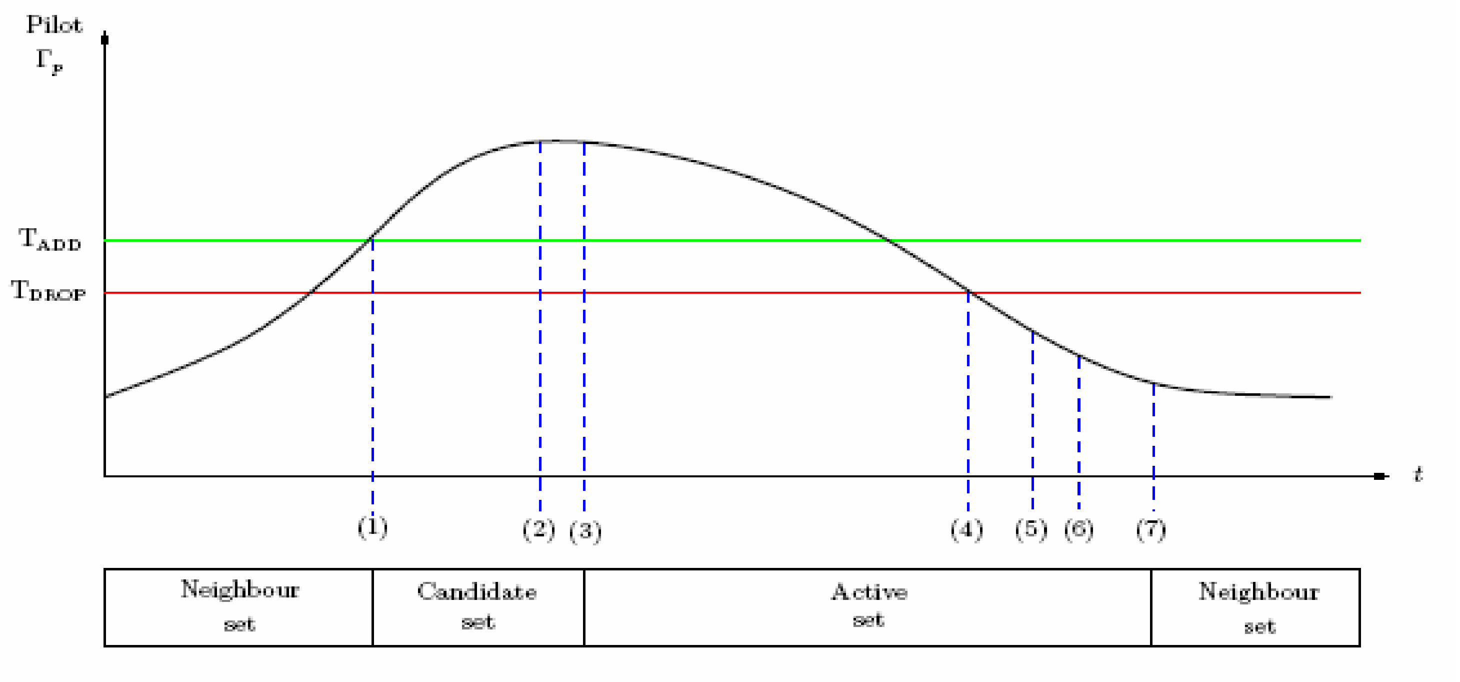
- Let us consider the IS-95 CDMA system with PG = 128 and t = 7dB.
- The effect of soft handoff on the downlink capacity of this system, when one user is in soft handoff, can be illustrated by

$$F_h \approx \frac{1}{1 + \frac{2}{\theta}\frac{W}{R_s}\frac{1}{\gamma_t}}$$



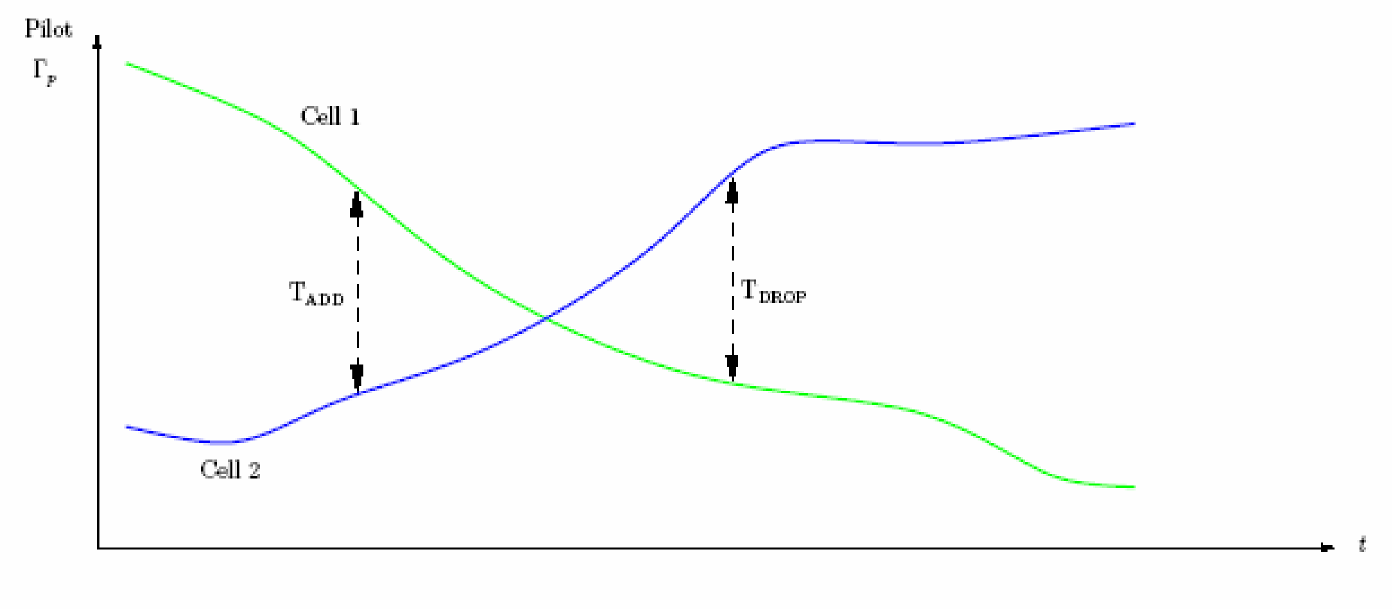
Soft Handoff in IS-95

- Soft handoff in IS-95 is based on Pilot set maintenance:
  - Mobile continuously monitors pilot channel signals.
  - Active set, Candidate set, Neighbor set, remaining set.
- Soft handoff in IS-95 is based on absolute values of received pilots.
  - Load dependent active set updating.



Soft Handoff in WCDMA

- Soft handoff in WCDMA is based on relative handover thresholds between received pilots.
  - Load independent active set updating.



Soft Handoff in WCDMA

- Pilot strength exceeds TADD: Mobile station sends a Pilot Strength Measurement Message and transfers pilot to the candidate set.
- Base station sends a Handover Direction Message.
- Mobile station transfer pilot to the active set and sets a Handover Completion Message.
- Pilot strength drops below TDROP: Mobile station starts the handover drop timer.
- Handover drop timer expires: Mobile station sends a Pilot Strength Measurement Message.
- Base station sends a Handover Direction Message.
- Mobile station moves pilot from the active set to the neighbor set and sends a Handover Completion Message.

Summary

- DS-CDMA cellular networks are interference limited systems.
- DS-CDMA cellular networks require very accurate power management especially in the uplink.
- DS-CDMA cellular networks have the possibility to trade coverage for capacity and vice versa.
- Assignment failures in DS-CDMA cellular networks are due to signal outage and not the lack of available channels.

Summary

- Power control allows DS-CDMA to properly convey information while interfering with other users no more than necessary.
- Uplink and downlink power control are necessary in DS-CDMA cellular systems.
- Soft handoff extends DS-CDMA cell coverage.
- Soft handoff increases DS-CDMA uplink capacity (base station diversity).
- Soft handoff improves signal quality for mobiles in bad positions but causes slight loss in downlink capacity.