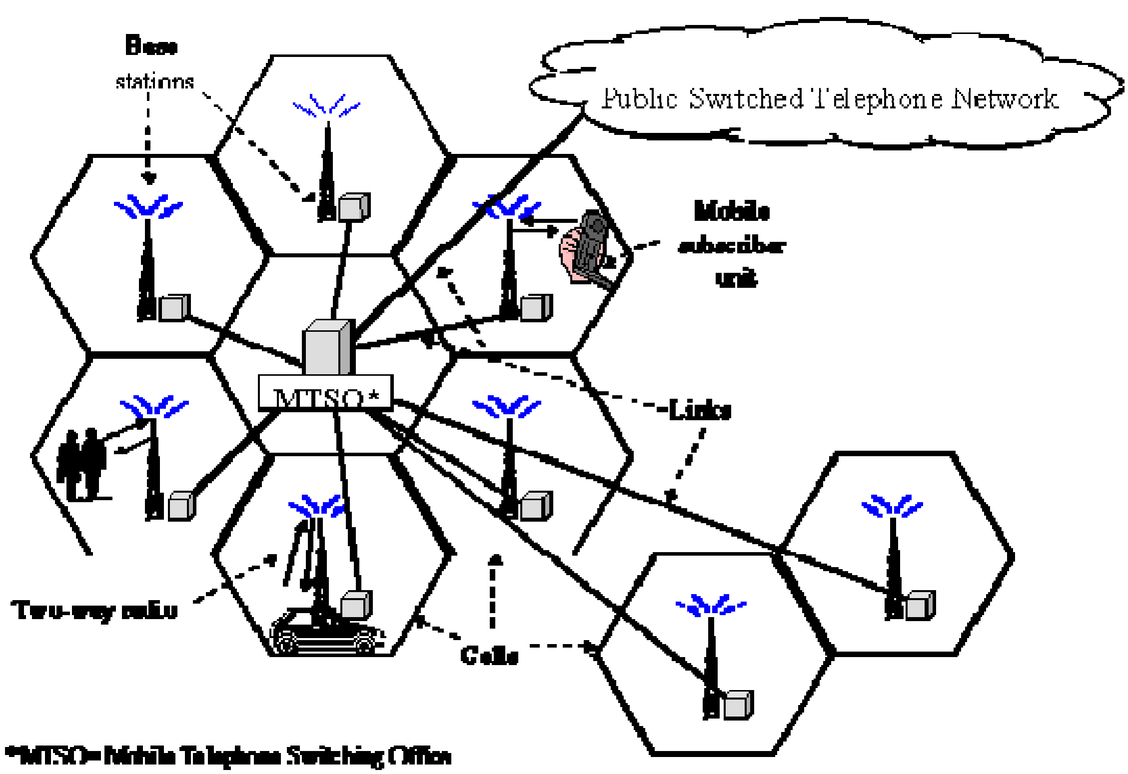
EXAMPLE OF CELLULAR NETWORK

- In a cellular network, cells are generally organized in groups, e.g. seven, to form a cluster.
- There is a "cell site" or " base station" at the centre of each cell, which houses the transmitter/receiver antennae and switching equipment.
- The size of a cell depends on the density of subscribers in an area: for instance, in a densely populated area, the capacity of the network can be improved by reducing the size of a cell or by adding more overlapping cells. This increases the number of channels available without increasing the actual number of frequencies being used.
- All base stations of each cell are connected to a central point, called the Mobile Switching Office (MSO), either by fixed lines or microwave. The MSO is generally connected to the PSTN (Public Switched Telephone Network).



CELLULAR STANDARDS FOR 1G AND 2G

First Generation:

- Advanced Mobile Phone System (AMPS) was first launched in the US. It is the most used analog system analog system, based on FDMA.
- Nordic Mobile Telephone (NMT) was mainly developed in the Nordic countries. (4.5 million in 1998 in some 40 countries including Nordic countries, Asia, Russia, and other Eastern European Countries)
- Total Access Communications System (TACS) was first used in the UK in 1985. It was based on the AMPS technology.
- There were also a number of other proprietary systems, rarely sold outside the home country.

Second Generation:

- Global System for Mobile Communications (GSM) was the first commercially operated digital TDMA cellular system, first developed in the 1980s through a pan-European initiative, involving the Eureopean Commission, telecommunications operators and equipment manufacturers. The European Telecommunications Standards Institute was responsible for GSM standardization. used by all European countries, and in other continents, with over 45% of the world's subscribers as April 1999.
- TDMA IS-136 is the digital enhancement of the analog AMPS technology (called D-AMPS, fist introduced in late 1991) and its main objective was to protect the substantial investment that service providers had been made in AMPS technology. Digital AMPS services have been launched in some 70 countries worldwide with almost 22 million TDMA handsets in circulation, the dominant markets being the Americas, and parts of Asia, in March 1999.
- CDMA IS-95: South Korea is the largest single CDMA IS-95 market in the world.
- Personal Digital Cellular (PDC), based on TDMA is the second largest digital mobile standard (introduced in 1994 in Japan with about 66.39 million users in Japan, November 2001).
- Personal Handyphone System (PHS) is a digital system first launched in 1995 in Japan (5.68 million subscribers in November 2001), as a cheaper alternative to cellular systems: between a cellular and a cordless technology. It has inferior coverage area and limited usage in moving vehicles.

3G:

- Voice: stream-type and Data: bursty,
- 3G "widens the data pipe": 384 Kbps.
- Standard based on wideband CDMA
- Packet-based switching for both voice and data
- 3G cellular struggling in Europe and Asia
- Evolution of existing systems (2.5G,2.6798G):
    - GSM+EDGE
    - IS-95(CDMA)+HDR
    - What is beyond 3G?

RADIO CAPACITY IN MULTICELL TDMA/FDMA SYSTEMS

The motivation behind implementing a cellular system is to improve the **utilization of spectrum efficiency**. **Frequency reuse** can drastically increase the spectrum efficiency. Co-channel interference is a major concern.

The frequency reuse distance, D, (i.e., the distance between the two adjacent co-channel cells of radius R) is related to the number of cells in a frequency reuse pattern K by the following CCI reduction factor: $[D/R]^2=3K$. K^{-1}: **frequency reuse efficiency**.

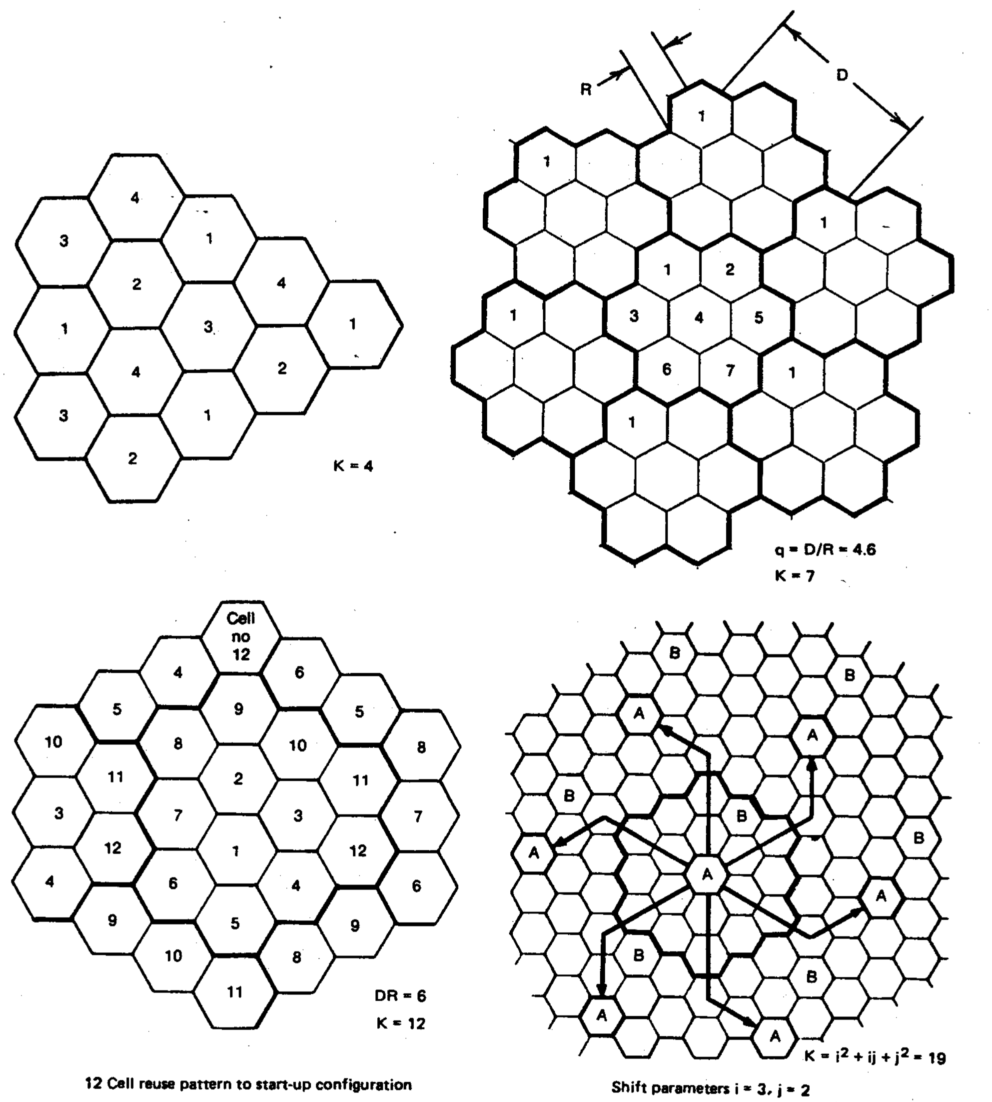


Figure 2.3 ***N*-cell reuse pattern.**

(Figures from W.C.Y. Lee, *Mobile Cellular Telecommunications Systems* , McGraw-Hill, 1989.)

RADIO CAPACITY IN MULTICELL TDMA/FDMA SYSTEMS

Radio capacity: $M_{TDMA} \approx M_{FDMA} \approx M/K = (B/f_b)\, e_M/K$.

Consider interference in a worst-case from 6 dominant interferers

$$\frac{C}{I} = \frac{C}{N + \sum_{j=1}^{6} I_j}, \text{ for equal distance: } \frac{C}{I} \approx \frac{R^{-\alpha}}{6D^{-\alpha}} \approx \frac{\left[3K\right]^{\alpha/2}}{6} \rightarrow K \approx \frac{1}{3}\left[6\frac{C}{I}\right]^{2/\alpha}$$

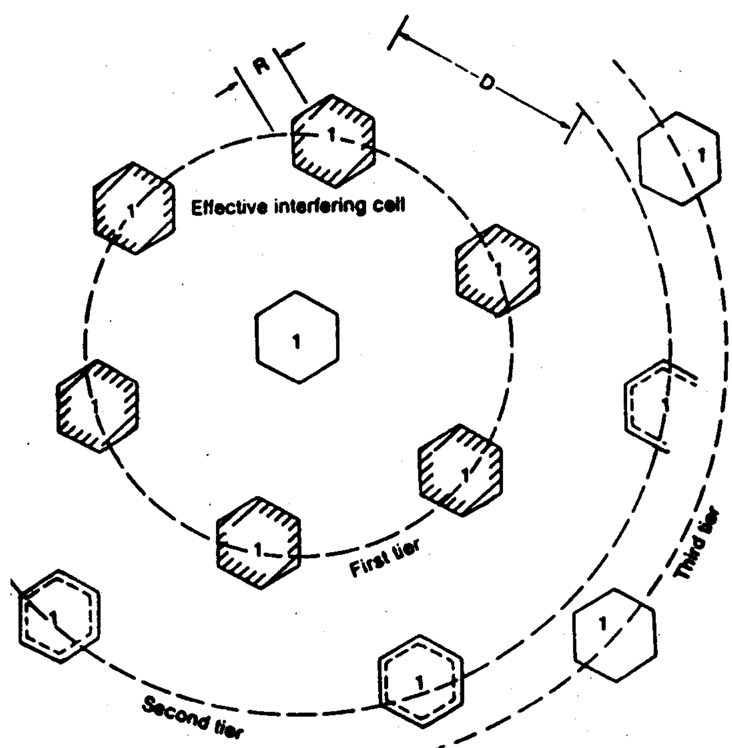
where N is the noise power; α is the path loss slope (or exponent, or decay law index).

In a mobile environment, a 4th power path loss is often used.

$$\alpha = 4 \rightarrow K \approx \sqrt{\frac{2}{3}\frac{C}{I}} \rightarrow M_{FDMA} \approx M_{TDMA} \approx \frac{Be_M}{f_b}\left[\frac{2}{3}\frac{C}{I}\right]^{-1/2}$$

limited by the required **minimum** required C/I.

Example: mobile systems, with a **minimum** C/I **=18dB** is required at the cell boundary for handoff in order to have toll-quality voice. This leads to $K \approx 7$



RADIO CAPACITY IN MULTICELL CDMA SYSTEMS

Consider a cell with M simultaneous calls with individual (equal) power C, and total interference power I_s generated from surrounding cells.

Effective noise power spectral density: $[N_o+I_o]=N_o+(M-1)C/B+ I_s/B$

Effective $E_s/(I_o+N_o)$ after despreading is

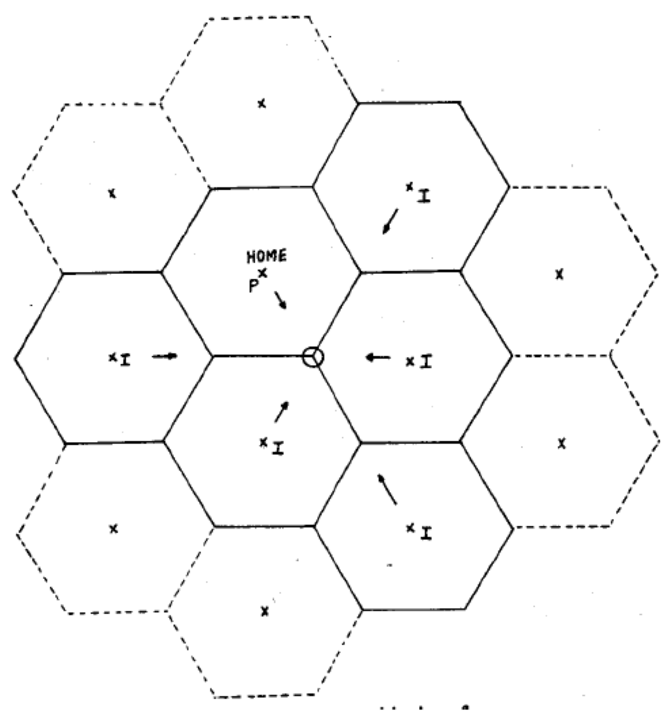
$$E_s/(I_o+N_o)= e_M(B/f_b)[(M-1) + I_s/C + N_oB/C]^{-1}$$

for $M>>1$ and $1>>C/(N_oB)$, $E_s/(I_o+N_o) \approx e_M(B/f_b)[M(1+I_s/MC)]^{-1}$
$M_{CDMA}=M\approx e_M(B/f_b)[E_s/(I_o+N_o)]^{-1}[1+I_s/MC]^{-1}$

$K_{CDMA}=1+I_s/MC$

Comparison: $M_{CDMA}/M_{FDMA}=[E_s/(I_o+N_o)]^{-1}[K_{CDMA} / K_{FDMA}]^{-1}$

Example 1: fourth-order path loss (α=4), cell radius: R, M: equal number of channels/cell, $K_{FDMA} \approx 7$



Without power control, i.e., same Tx power, $MC= R^{-4}$,

$I_s=2R^{-4}+3(2R)^{-4}+(2.633R)^{-4}$
$\rightarrow K_{CDMA}=1+I_s/MC=3.31$

By using power control at the forward link of each cell to reduce the interference to other adjacent cells. Ideally, $I_s=0$ and $K_{CDMA}=1$

For a required $E_s/(I_o+N_o)=7$dB,

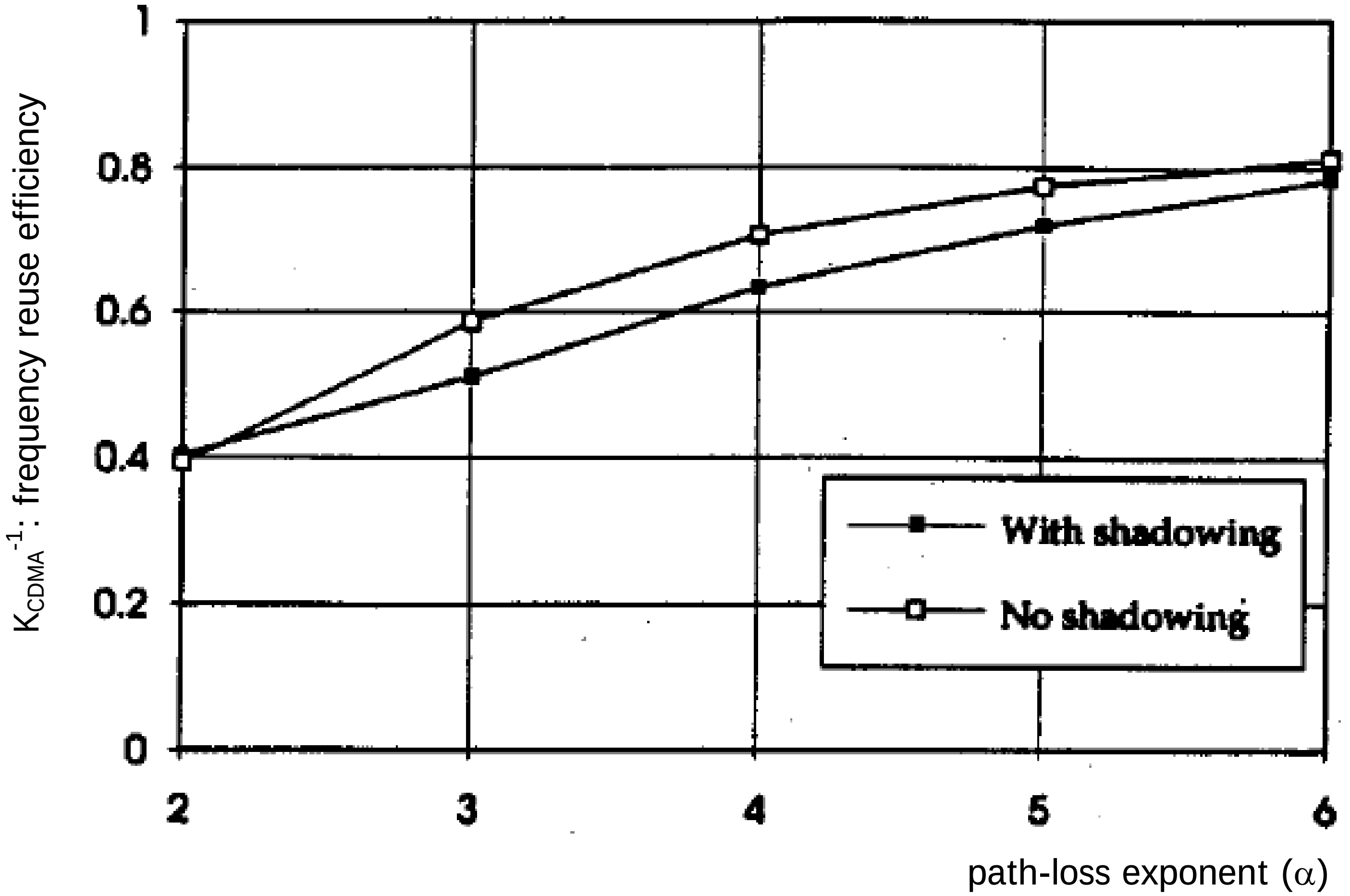
$M_{CDMA}/M_{FDMA}=0.42$ without power control, and $M_{CDMA}/M_{FDMA}=1.4$ with ideal power control

Example 2: log-normal shadowing with σ=8dB

$K_{FDMA} \approx 7$, $K_{CDMA} \approx 1.67$ for α=4, or 2.5 for α=2

$M_{CDMA}/M_{FDMA}\geq 1$ if required $E_s/(I_o+N_o)\leq 6.2$dB for α=4, or 4.3dB for α=2

(from P. Newson, M.R. Health, "The Capacity of a Spread Spectrum CDMA System for Cellular Mobile Radio with Consideration of System Imperfections", *IEEE JSAC,* May 1994, pp. 673-684.)



CDMA CAPACITY ENHANCEMENT

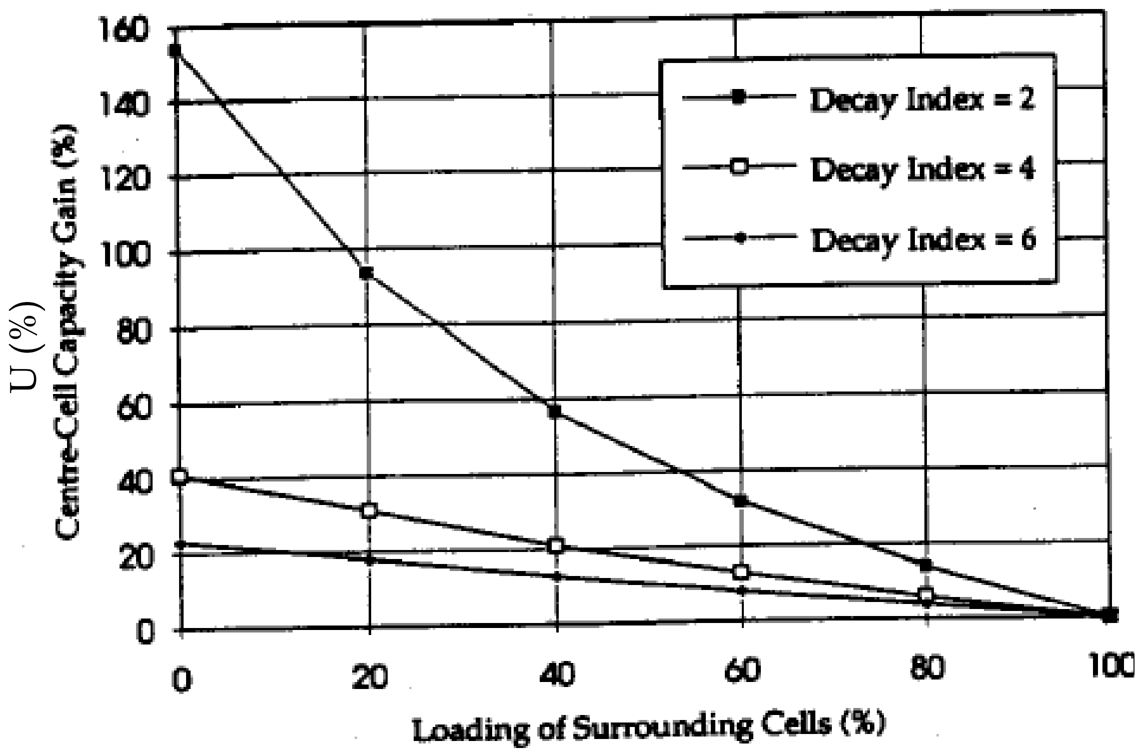
Voice activity factor: Duty cycle of speech is about 35% - 42%. Therefore level of interference is, in average, reduced to the activity factor A_v and the capacity is increased to

$$M_{CDMA} \approx e_M(B/f_b)[E_s/(I_o+N_o)]^{-1}[A_v\ K_{CDMA}]^{-1}$$

where A_v^{-1} is the gain due to voice activity: 2.63.

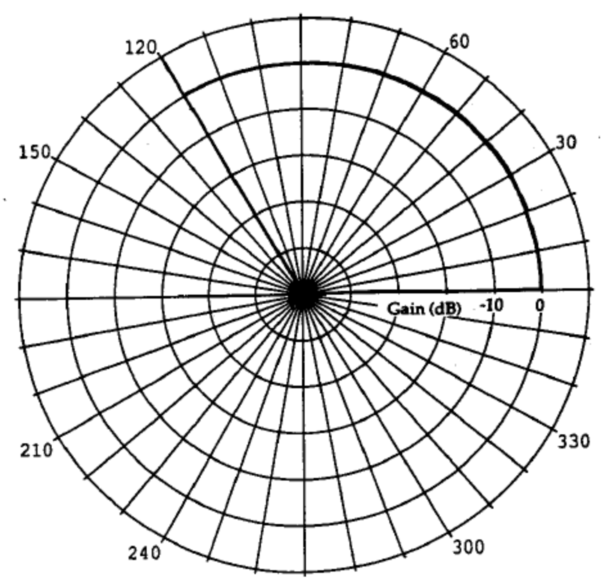
Unequal Cell Loading: With unequal loading of cells, the capacity of more heavily loaded cells may be increased because less interference is received from lightly loaded neighbouring cells.

Example: Center cell is heavily loaded while surrounding cells are equally loaded → Center cell: M_{CDMA} (1+U)

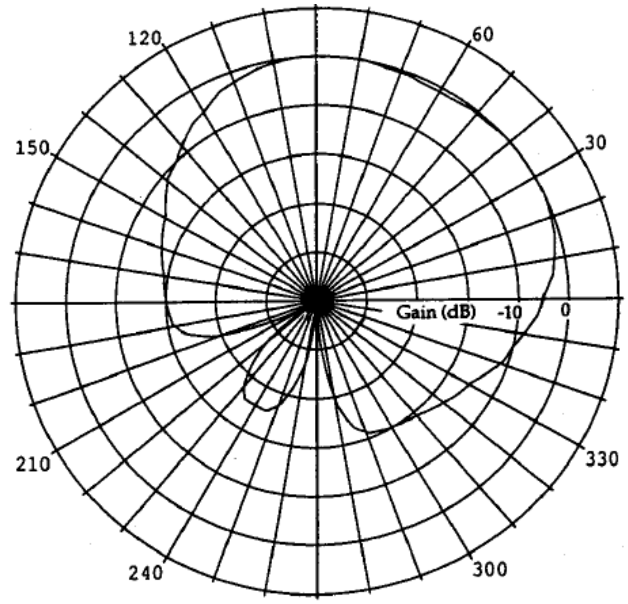


Sectorization: Level of interference may be reduced by the use of sectored antennas at each base station. Ideally, the capacity gain is $360B_W^{-1}$ where B_W^{-1} is the beamwidth of the sectored antenna in degrees. However, the capacity gain may be significantly reduced from this ideal value if more realistic antenna patterns are considered.

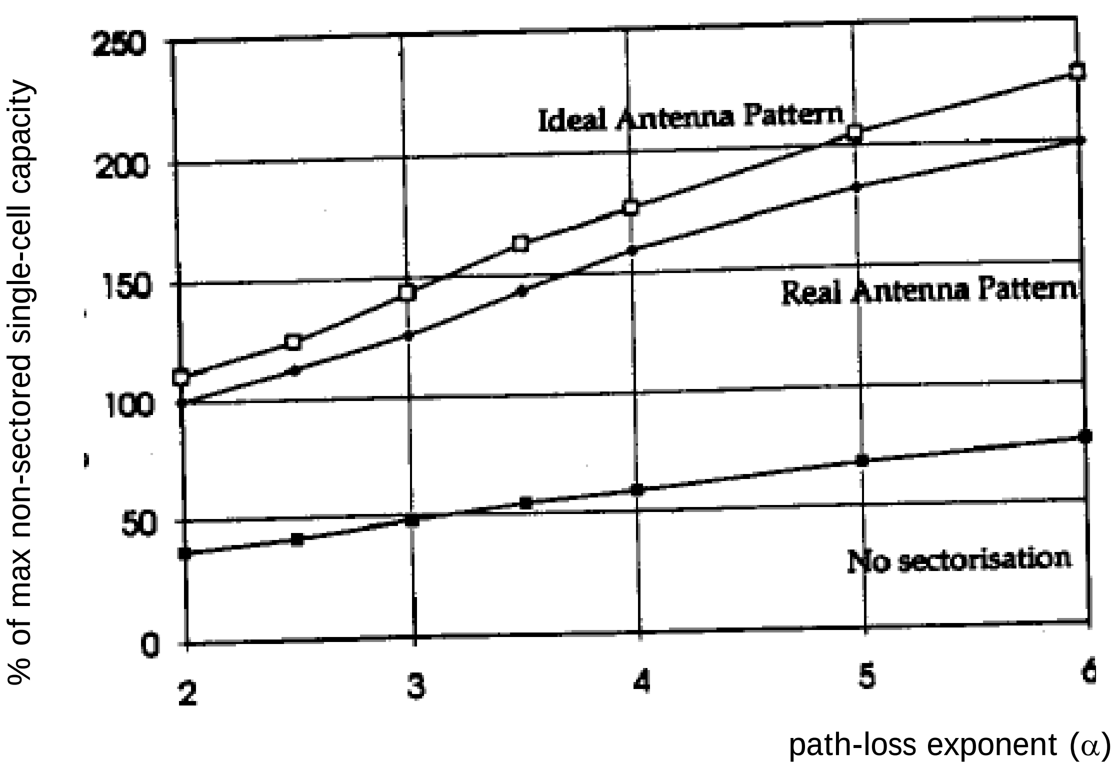
Sectorization: Example of 120-degree antenna beam patterns



ideal



realistic



(from P. Newson, M.R. Health, "The Capacity of a Spread Spectrum CDMA System for Cellular Mobile Radio with Consideration of System Imperfections", *IEEE JSAC,* May 1994, pp. 673-684.)

FDMA OR TDMA SYSTEMS:
HARD BLOCKING & ERLANG CAPACITY

Hard blocking occurs when all channels are occupied.

Erlang-B formula (introduced by A. K. Erlang, a Danish mathematician and telephone traffic engineer, in the 1920's) is widely used.

B(ρ,M): Probability that all M lines are busy at the time of the call for an offered average traffic load under the assumption of Poisson-distributed arrivals and exponential service (holding) time.

B(ρ,M): called **blocking rate (probability)** representing the *Grade of Service* in terms of fraction of incoming calls turned away.

$$B(\rho,M)=\frac{\rho^M}{M!}\left[\sum_{k=0}^{M}\frac{\rho^k}{k!}\right]^{-1}\rightarrow B^{-1}(\rho,M)=\sum_{k=1}^{M}\frac{M!}{k!\rho^{M-k}}=1+\frac{M}{\rho}\sum_{k=1}^{M-1}\frac{(M-1)!}{k!\rho^{(M-1)-k}}$$

$$\rightarrow B^{-1}(\rho,0)=1,\quad B^{-1}(\rho,M)=1+\frac{M}{\rho}B^{-1}(\rho,[M-1]),\ for\ M=1,2,\ldots$$

(used for numerical computation to avoid possible overflow errors due to large ρ^k, $k!$)

M: number of channels (capacity), $\rho=\lambda/\mu$: offered average traffic load (in Erlangs)

λ: arrival (call) rate, λ^{-1}: avg. inter-arrival time; μ: service rate, μ^{-1}: avg. holding time

$$\rightarrow B^{-1}(\rho,M)>B^{-1}(\rho,M')\ for\ M>M';\quad B^{-1}(\rho,M)>B^{-1}(\rho',M)\ for\ \rho>\rho'$$

Example:

AMPS (FM) system: total system bandwidth: B=12.5 MHz
Channel bandwidth: 30 kHz channels
Frequency reuse pattern (factor): k=7
and 3 sectors.

→ total number of available channels: 12.5 MHz/30kHz=416

→ $M_{AMPS(FM)}$ =(416/7)/3=19 channels/sector

D-AMPS system: 3-slot TDMA with the same parameters

→ $M_{D\text{-}AMPS}$ =19 X 3 = 57 channels/sector

For a blocking rate of 2%, $\rho_{AMPS(FM)}$ =12.34 E $\rho_{D\text{-}AMPS}$= 46.8 E

CDMA SYSTEMS:
SOFT BLOCKING & ERLANG CAPACITY

Adding one more channel just increases the interference level by (M+1)/M≈1 (i.e., negligible for large M) and hence slightly degrades the voice quality.

→ **Soft-Blocking** in CDMA can be represented by a **performance outage** event when the active users create an interference power density level, I, exceeding a threshold I_o for a threshold $E_s/[I_o+N_o]$ required to maintain an acceptable voice quality represented by a threshold error rate, i.e.,

$$P_{sb} = \Pr\{I > I_o\},\ I = \left[\sum_{i=1}^{k_0-1} a_{i0}C_{i0} + \sum_{j=1}^{J}\sum_{i=1}^{k_j} a_{ij}C_{ij}\right] / B$$

where a_{ij}: binary random variable representing voice activity with $\Pr\{a_{ij}=1\}= A_v$(voice activity factor)

j=0: cell of interest, j=1,2,...,J: other interfering cells

k_j: number of active users in cell j; it is a Poisson random variable with mean ρ_{CDMA}.

C_{ij} : power for interfering user i in cell j received by the user of interest.

ERLANG CAPACITY OF CDMA SYSTEMS

Erlang capacity: $\rho_{CDMA}(P_{sb})$ for a target P_{sb}.

(The following analysis and results are extracted from

A.M. Viterbi, A.J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System", *IEEE JSAC*, Aug. 1993, pp. 892-900.)

- For simplicity, assume that all cells are equally loaded with the same number of users, all k_j=k and $\Pr\{k\}=[\rho_{CDMA}(P_{sb})]^k \exp[-\rho_{CDMA}(P_{sb})]/k!$
- Under **power control**,

- The ratio of total inter-cell (i.e., from other cells) interference to intra-cell (i.e., within the cell of interest) interference is $a_{\text{int}} \approx 0.55$.

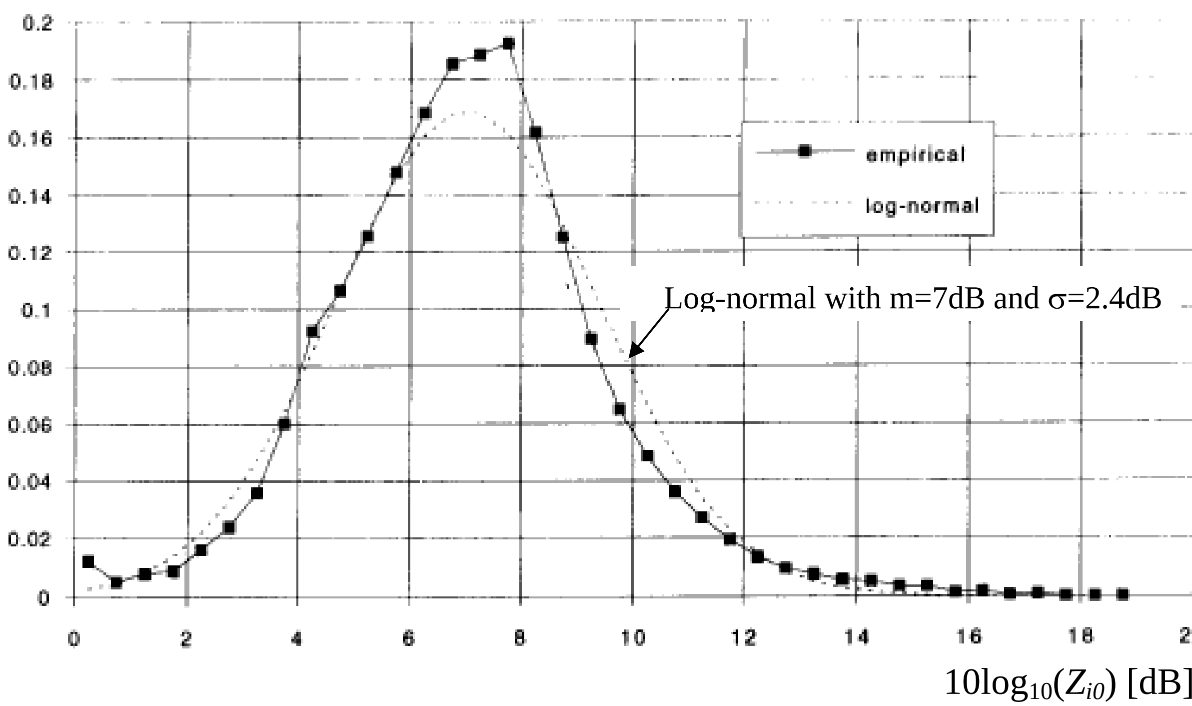
$$I = \left[\sum_{i=1}^{k-1} a_{i0} C_{i0} + \sum_{j=1}^{J} \sum_{i=1}^{k} a_{ij} C_{ij} \right] / B \approx \left(1 + a_{\text{int}}\right) B^{-1} \sum_{i=1}^{k-1} a_{i0} C_{i0}$$

$$\rightarrow P_{sb} = \Pr\{I > I_o\} = \Pr\{Z > B[e_M / f_b][1-\eta]\},$$

$$\text{where } Z = IB[e_M / f_b]/[I_o + N_o] = \left(1 + a_{\text{int}}\right) \sum_{i=1}^{k-1} a_{i0} Z_{i0},$$

$$Z_{i0} = E_{si0} / [I_o + N_o], E_{si0} = [e_M C_{i0} / f_b], \eta = N_o / [I_o + N_o]$$

- Z_{i0}: approximated as a log-normal random variable, i.e., $10\log_{10}(Z_{i0})$ is Gaussian with mean m [dB] and standard deviation σ [dB]; $E\{Z_{i0}\} = \exp\left(\beta m + \beta^2 \sigma^2 / 2\right), E\{Z_{i0}^2\} = \exp\left(2\beta m + 2\beta^2 \sigma^2\right), \beta = (\ln 10)/10$.

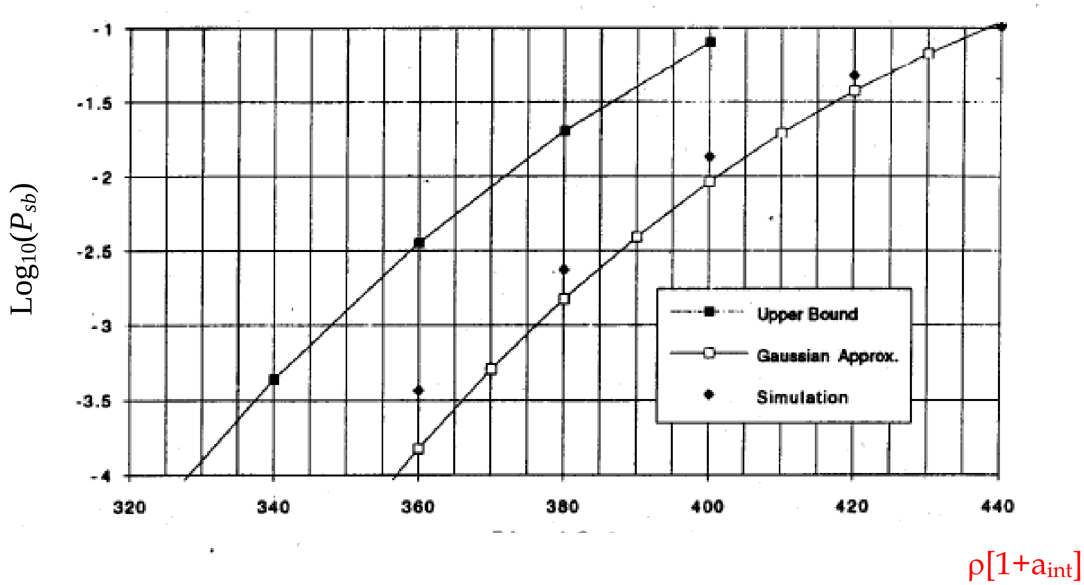


- Z is sum of k log-normal random variables and k is a Poisson random variable with load ρ (=ρ_{CDMA}). Using a central limit theorem approximation, Z can be assumed to be Gaussian with

$$\overline{Z} = E\{Z\} = x\exp\left(\beta m + \beta^2\sigma^2/2\right), x = \left(1 + a_{\text{int}}\right)\rho_{CDMA}A_v$$

$$\sigma_Z^2 = E\left\{\left[Z - \overline{Z}\right]^2\right\} = x\exp\left(2\beta m + 2\beta^2\sigma^2\right)$$

$$\rightarrow P_{sb} = \Pr\{Z > B\left[e_M/f_b\right][1-\eta]\} \approx Q\left(\left[Z_o - \overline{Z}\right]/\sigma_Z\right), Z_o = B\left[e_M/f_b\right][1-\eta]$$



$$\rightarrow \overline{Z}^2 - \sigma_Z^2\left[Q^{-1}(P_{sb})\right]^2 - 2Z_o\overline{Z} + Z_o^2 = 0$$

$$\rightarrow a^2x^2 + bx + c^2 = 0, \text{ solution: } x = \left[-b + \sqrt{b^2 - 4a^2c^2}\right]/\left(2a^2\right)$$

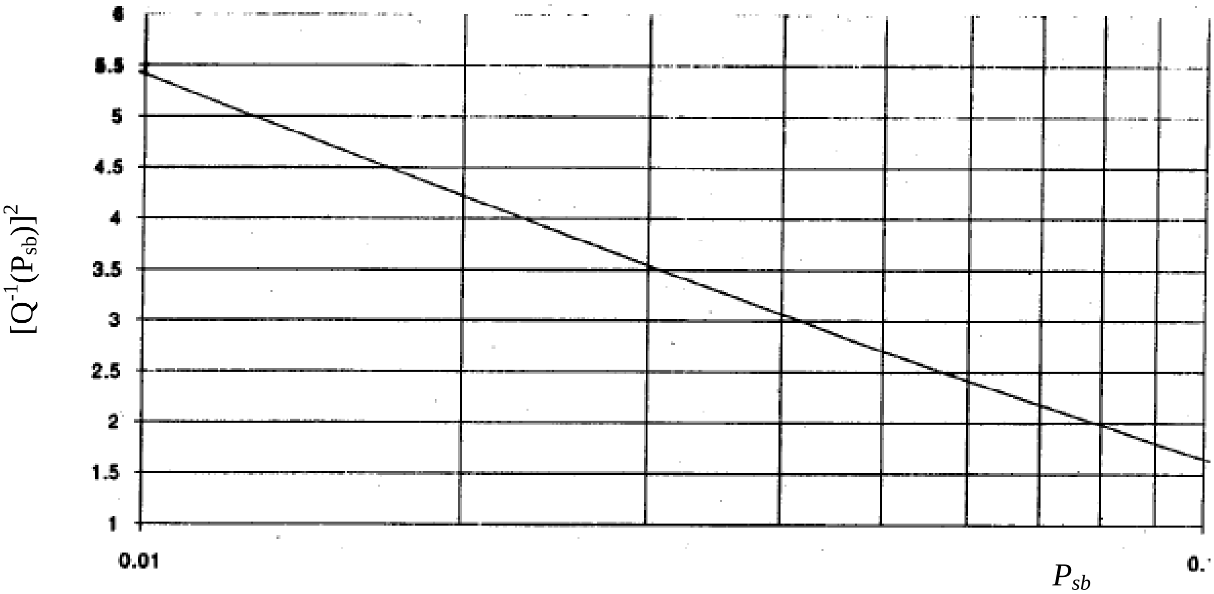
$$a = \exp\left(\beta^2\sigma^2/2\right), c = Z_o\exp\left(-\beta m\right) = Z_o(10^{-m/10}),$$

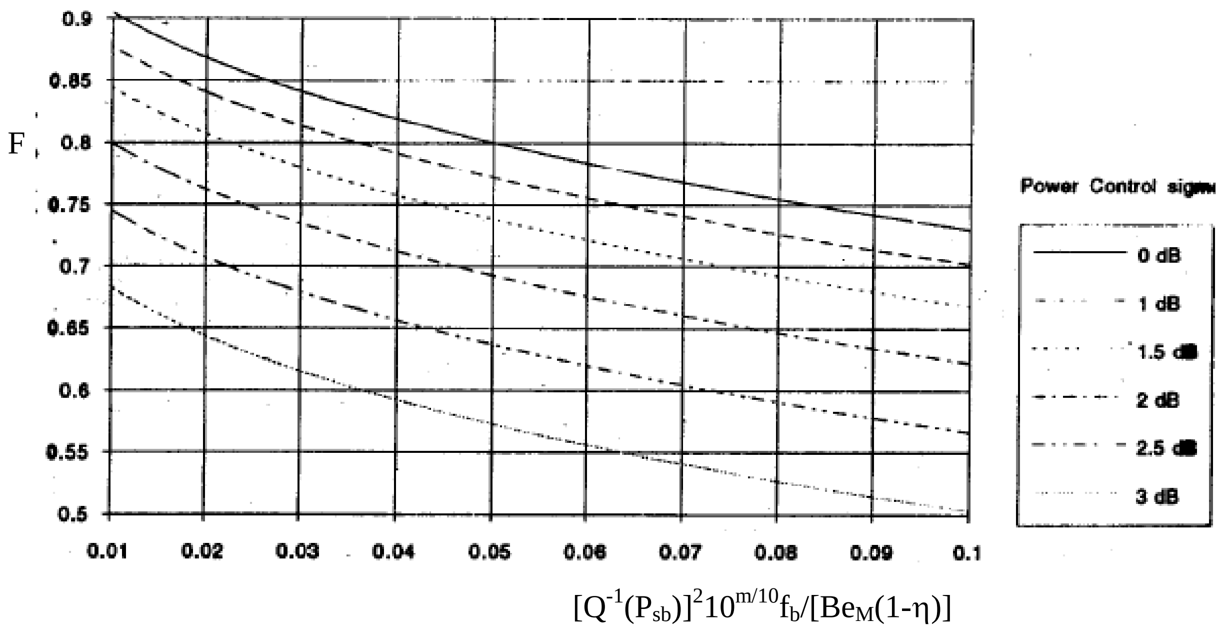
$$b = -\left\{\left[a^2Q^{-1}(P_{sb})\right]^2 + 2ac\right\}$$

$$\sqrt{b^2 - 4a^2c^2} = \left[a^2Q^{-1}(P_{sb})\right]\sqrt{\left[a^2Q^{-1}(P_{sb})\right]^2 + 4ac}$$

$$\rightarrow \rho_{CDMA} = \frac{e_M B}{f_b}\frac{(10^{-m/10})[1-\eta]}{\left(1 + a_{\text{int}}\right)A_v}F, F = a^{-1}\left[1 + \frac{a^3Q^{-1}(P_{sb})}{2c}\left(1 + \sqrt{1 + \frac{4c}{a^3Q^{-1}(P_{sb})}}\right)\right]$$

recall: $M_{CDMA} \approx e_M(B/f_b)[E_s/(I_o+N_o)]^{-1}[A_v\ K_{CDMA}]^{-1}$





Example: For spreading factor Be_M/f_b=1280, η=0.1, $a_{\text{int}}\approx 0.55$, A_v=0.4, m=7dB, σ=2.5dB, P_{sb}=0.01,

From graph: $P_{\text{sb}}=0.01 \rightarrow [Q^{-1}(P_{\text{sb}})]^2=5.45$,

$[Q^{-1}(P_{\text{sb}})]^2 10^{m/10} f_b/[Be_M(1-\eta)]=0.023711$

From graph: $[Q^{-1}(P_{\text{sb}})]^2 10^{m/10} f_b/[Be_M(1-\eta)]=0.023711$, σ=2.5dB $\rightarrow F=0.695$,

$\rho_{CDMA}= 10^{-m/10}(Be_M/f_b)[1-\eta]F/[(1+ a_{\text{int}})\, A_v]= 258E$

CDMA FOR MOBILE CELLULAR SYSTEMS

Advantages:

- interference and multipath resistance by using codes with low cross correlation and low auto-correlation
- inherent privacy due to noise-like signals
- Soft-capacity: system only gradually (gracefully) degrades as more users access the system:Higher capacity
- Improves voice quality (new coder)
- Less power consumption (6-7 mW)
- Choice for 3G systems

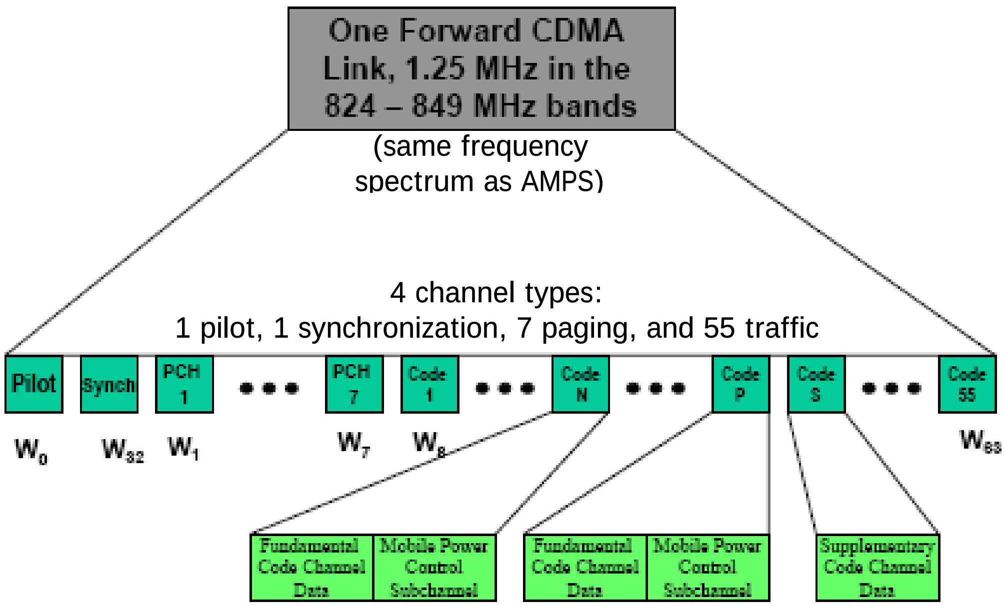
Drawbacks:

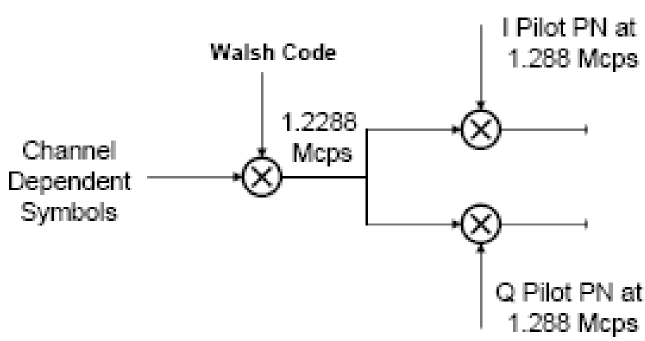
- Self-jamming due to transmissions from multiple imperfectly synchronized users
- Near-far problem: signals closer to the receiver are received with less attenuation than signals farther away
- Soft handoff: the mobile needs to acquire the new cell before it relinquishes the old:
  - mobile temporarily connected to more than one bases simultaneously
  - more complex than hard handoff used in FDMA/TDMA
- Complex unsymmetrical air-interface:
  - Forward channel uses orthogonal spreading codes
  - Reverse channel transmissions are not synchronized

EXAMPLE OF CDMA CELLULAR SYSTEM: IS-95

- Uses DSSS and ECC
- Frequency reuse factor is 1
- 3 systems: IS-95 2G, W-CDMA, and CDMA2000

IS-95 CDMA Forward Channel:



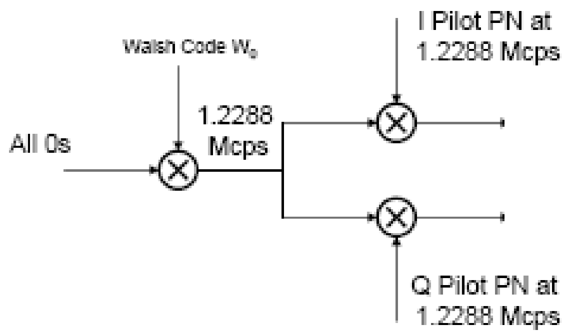


modulation: QPSK
Channel spreading: using 2 codes:

- Orthogonal Walsh codes (64 total)
- further spread by short PN spreading to differentiate intra-cell transmissions (M codes of length 15, i.e., period of 32768 chips), used to isolate different cells (BSs). The same PN sequence is used in all BSs with different offset for each BS (i.e., requires synchronization achieved by GPS).

IS-95 CDMA Forward Channel:

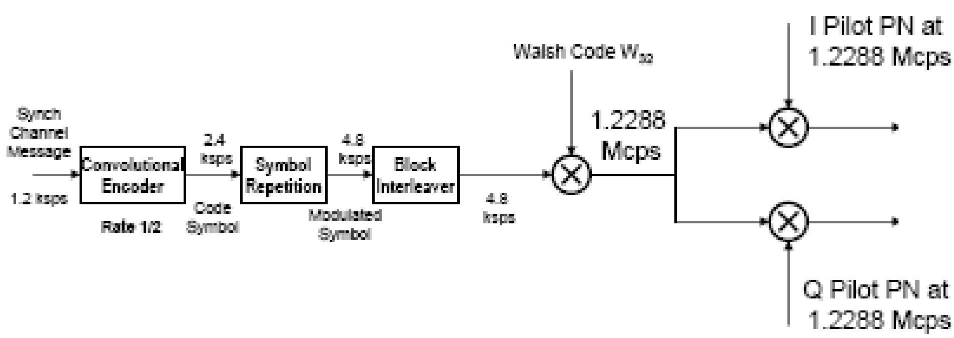
Pilot channel:



- uses all-zero Walsh code for single-tone RF carrier provides a phase reference signal for all mobiles for COHERENT demodulation
- 4-6 dB stronger than all other channels without power control.
- Spread using the PN spreading code to identify the Base. (512 different BS*64 offsets)

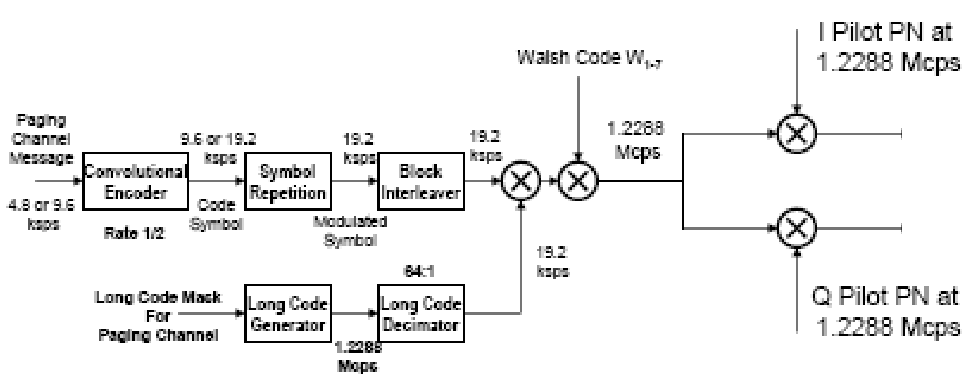
Sync channel:

- Used to acquire initial time synchronization: system ID (SID), network ID (NID), the offset of the PN short code, the state of the PN-long code, and the paging channel data rate (4.8/9.6 Kbps)
- Uses W32 for spreading
- Operates at 1200 bps



Paging channel:

Used to page the MS for an incoming call, or to carry the control messages for call set-up
Uses W1-W7 and additionally scrambled by PN long M-code of length 42
no power control
rate: 4.8 Kbps or 9.6Kbps



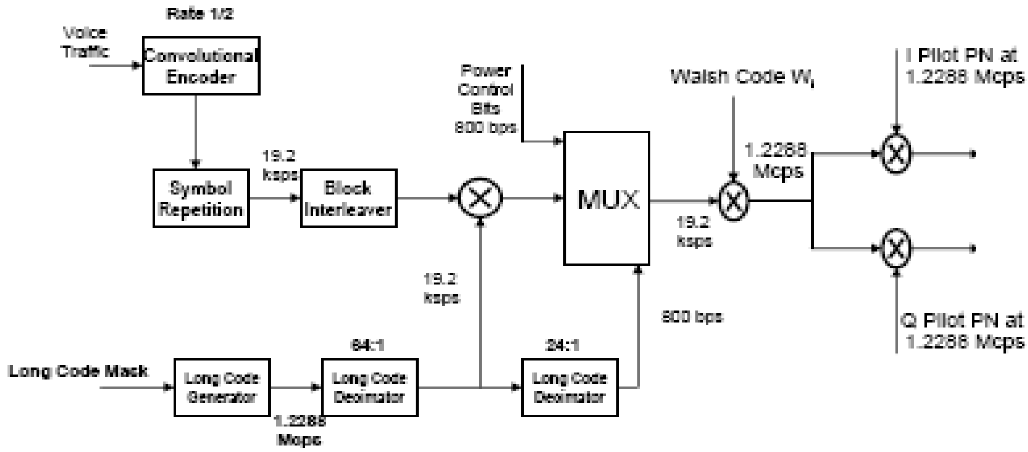
IS-95 CDMA Forward Channel:

Traffic channel:

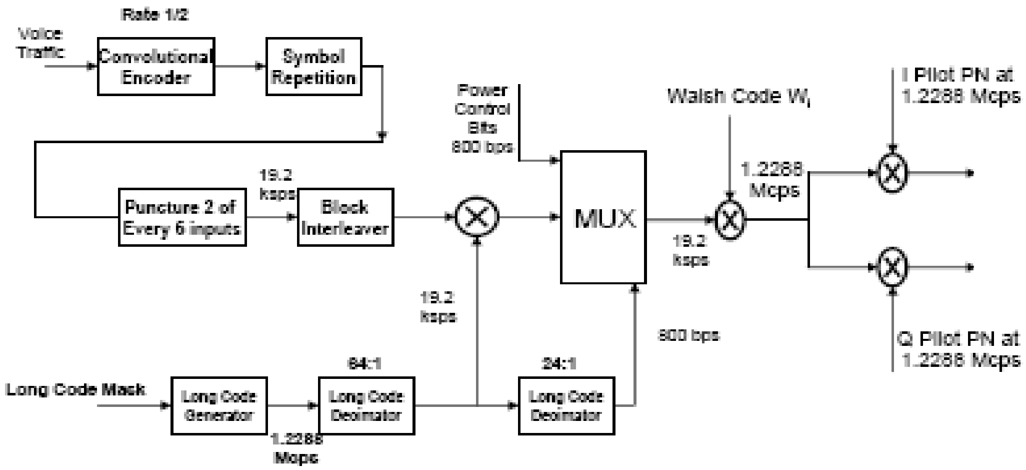
carries user information and power control bits for the reverse channel

Two possible sets of date rates:

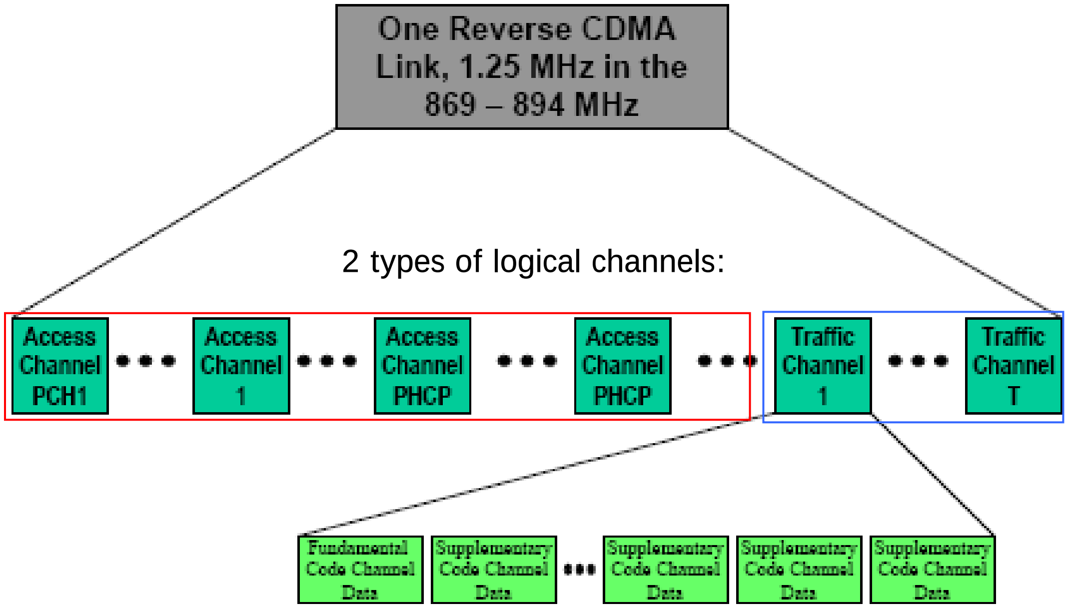
- RS1 (mandatory): 9.6, 4.8, 2.4, 1.2 Kbps

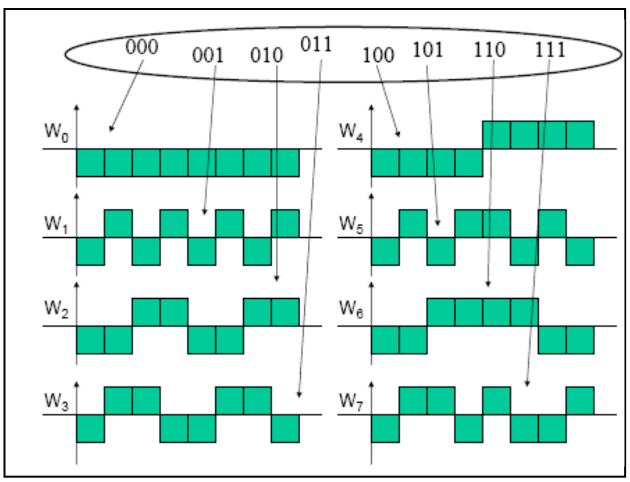


- RS2 (optional): 14.4, 7.2, 3.6, 1.8 Kbps

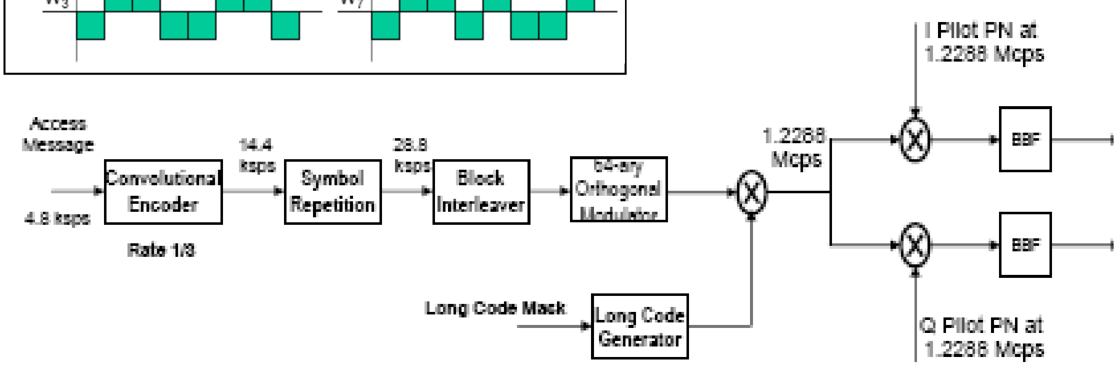


IS-95 CDMA Reverse Channel





Uses OQPSK for power efficiency different from the forward channels data uses orthogonal Walsh codes only (i.e., no further PN spreading) for symbol encoding



Access Channel Processing