# Cellular mobile radio systems

Part of the material from:
- O.Andrisano, D.Dardari, *Appunti di Sistemi di Telecomunicazioni – Elementi di progetto di sistemi radiomobili*, Società Editrice Esculapio
- M.Chiani, A.Conti, *Fundamentals of Mobile Radio Communications*, Teledoc2 course, CNIT

Other suggested books:
- William C. Jakes, Jr., “Microwave Mobile Communications”, First Ed., John Wiley & Sons, Toronto, Canada, 1974.
- Gordon L. Stüber, “Priciples of Mobile Communication”, First Ed., Kluwer Academic Publishers, Massachusetts 0261 USA, 2001.
- Sergio Benedetto, Ezio Biglieri, “Principles of Digital Transmission – with wireless applications”, First Ed., Kluwer Academic / Plenum Publisher, 10013 NY, 1999.
- John G. Proakis, “Digital Communications”, Fourth Ed., McGraw-Hill International Edition, NY 10020, USA, 2001.
- Marvin K. Simon, Mohamed-Slim Alouini, “Digital Communication over Fading Channels – A Unifed Approach to Performance Analysis”, First Ed., Wiley-Interscience, Danvers, MA 01923, USA, 2000.
- Leonard Kleinrock, “Sistemi a coda – Introduzione alla teoria delle code”, Hoepli Ed., 20121 Milan, Italy, 1996.

- ❑ overview on mobile radio systems
- ❑ cellular concepts
- ❑ key case: GSM-like network
- ❑ cell design
- ❑ cluster design

# Generalities on Cellular Systems

Design of cellular systems has to take into account different aspects affecting system performance.

Only the main impairments in the link and cell design will be considered.

Operator point of view:
minimize the number of base stations for for a given coverage and QoS → analysis of the offered traffic per area and service penetration.

Area coverage and link-budget evaluation → propagation modeling validated by measurements (e.g., Rayleigh fading and log-normal shadowing).

# Cellular Basics

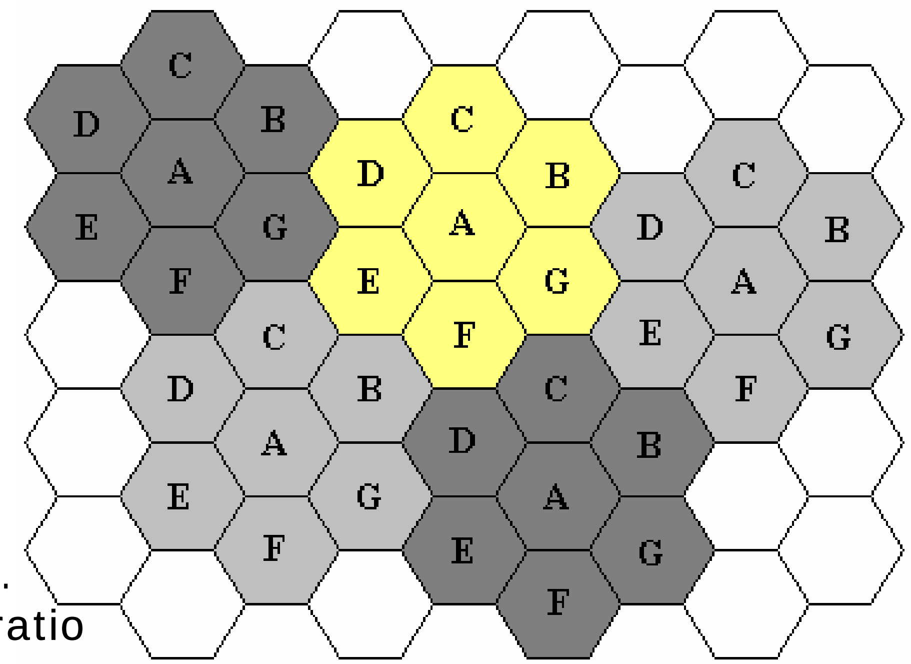
The territory is divided in cells, each one radio-covered by a base station.

Cell dimension depends on propagation characteristics, link-budget, capacity, ...

Radio resources are limited!

❑ reuse in cells at a proper distance

❑ cluster of cells




**Design criteria focal points:**

- PHY layer:
coding&modulation, (smart) antennas,...
→ link-budget, Interference protection ratio

- Network planning

- Radio resource management: power control, handover,...

- Interaction with PSTN

# Public Cellular Systems in Italy and in the world

In Italy:

E-TACS: European Total Access Cellular System,
from 1990, analog - 900MHz

GSM: Global System for Mobile communications,
from 1993, digital - 900, 1800 MHz

GPRS, EDGE, UMTS,... 4G is coming

**Advantages of Digital vs. Analog**

Voice + data transmission → more services
More robustness to disturbs (coding) → capacity increase
Security

2G digital systems in the world:

| | |
|---|---|
| GSM: | Europe, parts of South America and Asia |
| IS-54/136: | USA |
| IS-95: | USA, Korea |
| PDC: | Japan |

# Evolution of Cellular Systems

packet radio

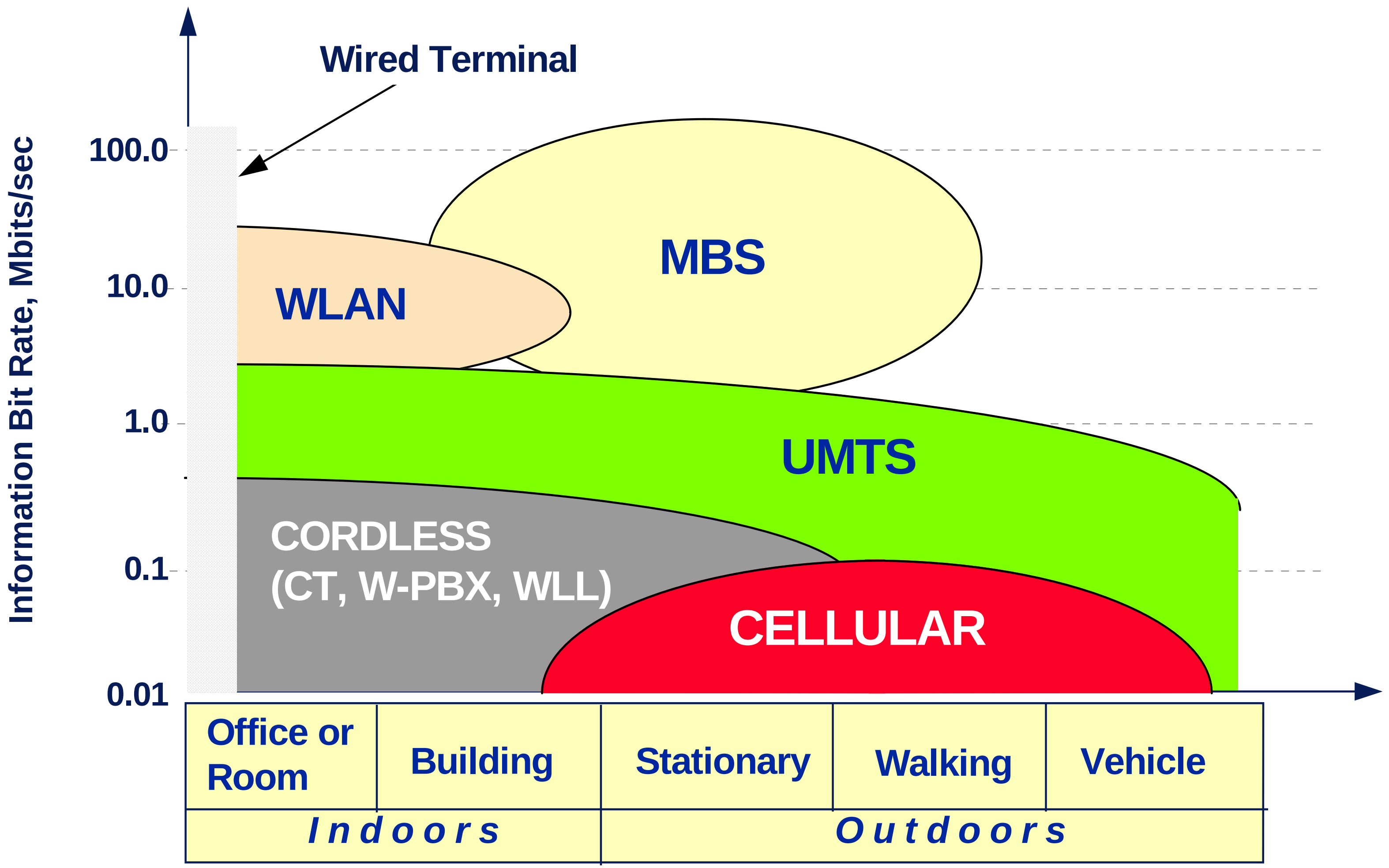
multimedia services

adaptive resource allocation depending on class of service and mobility

| | | | | |
|---|---|---|---|---|
| GSM | → | GPRS<br>General Packet<br>Radio Service | → | UMTS<br>Universal Mobile<br>Tlc System |

UMTS → radio access will be based on few different standards, software radio technology

# Mobility vs. Capacity



# Private Mobile Radio Systems

TETRA: ETSI 1989-

Ex.: surveillance, fight-fire, ...

Different requirements and techniques with respect to public systems:

even less populated areas must be served, the mean call duration is 30 sec. against some min. for public systems, different access time, lost calls not cleared policy (→ FIFO queuing with priority), trunking to resource sharing, etc.

Intelligent Transportation Systems

Integration of cellular systems (GSM, GPRS, UMTS), satellite systems, GPS, short range systems to support and control road traffic.

# Cellular Network Architecture ex.: GSM

Three levels hierarchy:

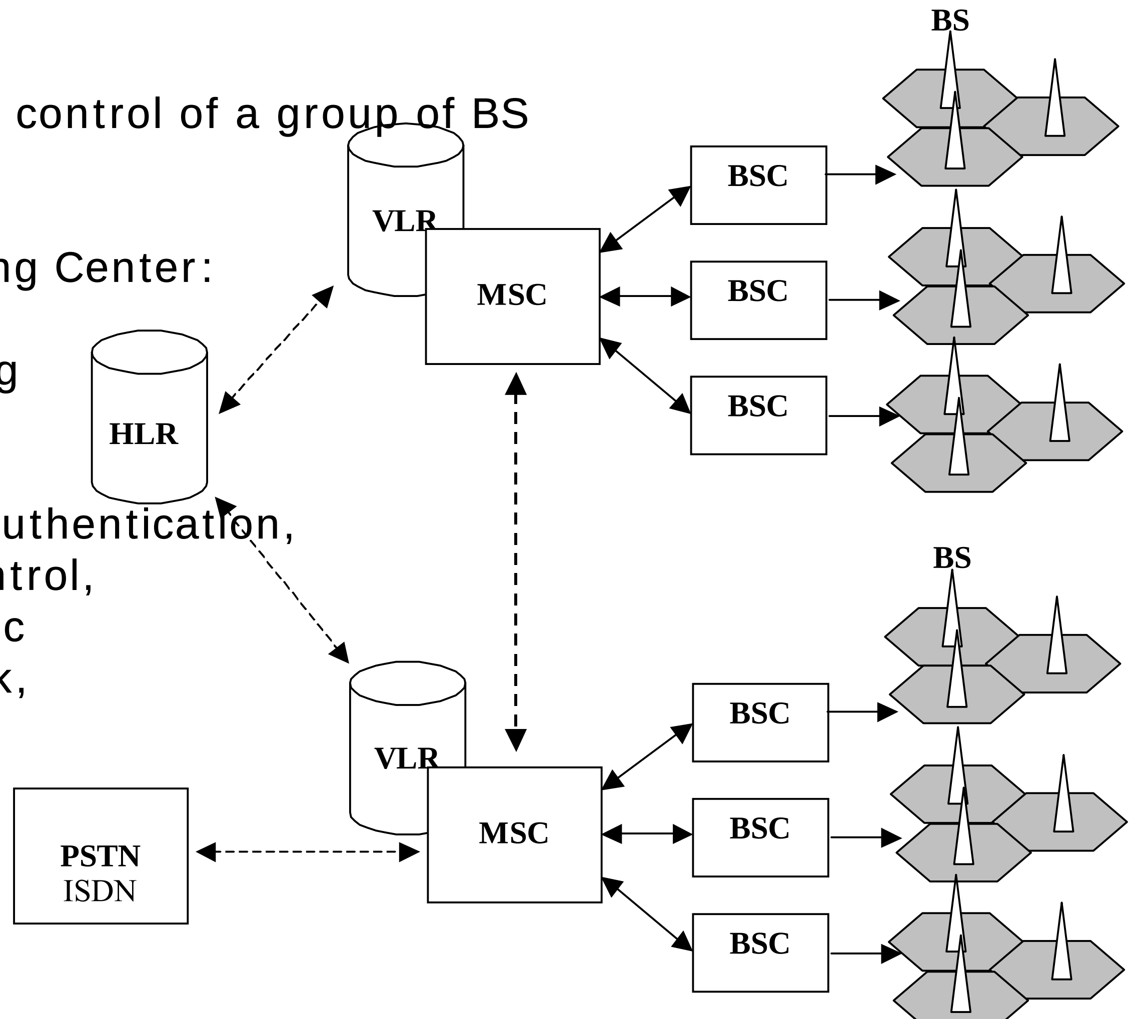
1. **BS** Base Station: cell coverage, communication with the mobile terminal

2. **BSC** Base Station Controller: control of a group of BS in adjacent cells

3. **MSC** Mobile services Switching Center:

   - networking and switching among a group of BSC

   - mobility management (authentication, location, paging, tax, call control, signaling, connection to Public Switched Telephone Network, Integrated Service Digital Network, etc.)



# Mobility Management in GSM

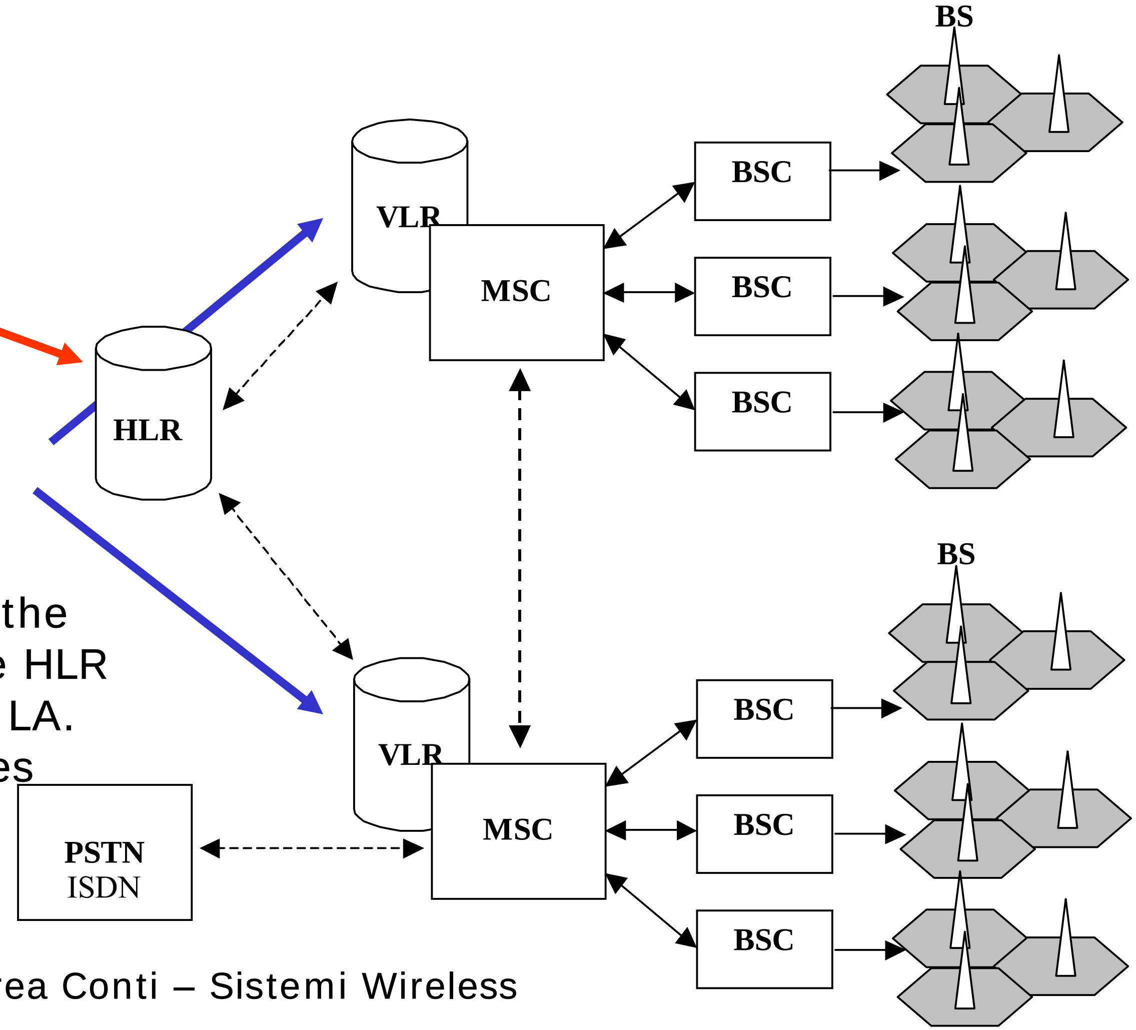
The territory is divided in Location Areas (LA) and a unique identifier of the LA is tx to the mobile stations (MS) over the BCCH (Broadcast Common Control Channel). When the MS detects a new LA id., it tx a request of Location Updating.

Two databases:

**HLR** (Home Location Register): info on user subscription

**VLR** (Visitor Location Register ): integrated in each MSC infos on users in that LA

When a user enters in a new LA, the VLR of that LA is updated and the HLR contains the identifier of the new LA. The dimension of the LA influences the complexity of mobility mng, paging, etc.



# Main Network Functionalities

Roaming: when the user migrates to a different operator, or to a public network

Location Updating: location area identifier is periodically updated, when the LA is changed, when the mobile is turned on, or when a call is generated or terminated. Each variation is tx to the HLR of the mobile.

Attach/Detach: mobile turned-on → attach status + paging if called;
mobile turned-off → detach status

Deregistration: mobile canceled from VLR if it does not originate or receive calls for an interval (ex. 1 day). This is communicated to the HLR.

Handover: procedure to guarantee the call continuity during the passage of the mobile from a BS to another one.

# Mobile radio systems characteristics

Existing systems differ for:

- Allocated spectrum
- Voice & data rate
- Multiple access
- Duplexing
- Modulation & coding
- Tx Power
- Power Control
- Voice activity detection
- Handover
- Channel Allocation

| SYSTEM | TACS | GSM | GSM 1800 | DECT | Unit |
|---|---|---|---|---|---|
| | | | | | |
| Up link | 935-950 | 935-960 | 1805-1880 | 1880-1900 | MHz |
| Down link | 890-905 | 890-915 | 1710-1785 | 1880-1900 | MHz |
| Multiple access | FDMA | TDMA | TDMA | TDMA | |
| Duplexing | FDD | FDD | FDD | TDD | |
| Carrier spacing | 25 | 200 | 200 | 1728 | KHz |
| Channel per carrier | 1 | 8 | 8 | 12 | |
| Bandwidth per ch. | 50 | 50 | 50 | 144 | KHz |
| Modulation | FM | GMSK | GMSK | GMSK | |
| Bit/Chip rate | n.a. | 271 | 271 | 1152 | Kbit/s |
| Voice rate | n.a. | 22.8 | 22.8 | 32 | kbit/s |
| Voice coding | n.a. | RPE-LTP | RPE-LTP | ADPCM | |
| Bit rate (uncod.Voice) | n.a. | 13 | 13 | 32 | Kbit/s |
| Peak power (mob.) | 0.6 - 10 | 2-20 | 0.25-2 | 250 mW | W |
| Mean power (mob.) | 0-6 - 10 | 0.25 – 2.5 | 0.03 – 0.25 | 10 mW | W |
| Power Control | Yes | Yes | Yes | No | |
| Voice activity detect. | Yes | Yes | Yes | No | |
| Handover | Yes | Yes | Yes | Yes | |
| Dynamic Allocation | No | No | No | Yes | |

# Mobile radio systems characteristics

| SYSTEM | IS-54 | Qualcomm CDMA (IS-95) | GPRS | TETRA | UMTS-FDD | UMTS-TDD | Unità |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Up link | 869-894 | 869-894 | 935-960 | 380-400 | 1920-1980 | 1900-1920 | MHz |
| Down link | 824-849 | 824-849 | 890-915 | 410-430 | 2110-2170 | 2010-2025 | MHz |
| Multiple access | TDMA | CDMA | TDMA | TDMA | W-CDMA | TD-CDMA | |
| Duplexing | FDD | FDD | FDD | FDD | FDD | TDD | |
| Carrier spacing | 30 | 1250 | 200 | 25 | 5000 | 5000 | KHz |
| Channel per carrier | 3 | 55-62 | 8 | 4 | - | - | |
| Bandwidth per ch. | 20 | 21 | 50 | 12.5 | - | - | KHz |
| Modulation | π/4-DQPSK | QPSK (downl) 64-ary (upl) | GMSK | π/4-DQPSK | QPSK | QPSK | |
| Bit/Chip rate | 48.6 | 1228 | 271 | 36 | 3840 | 3840 | Kbit/s |
| Voice rate | 11.2 | 8 | 22.8 | 7.2 | 4.75-12.2 | 4.75-12.2 | Kbit/s |
| Voice coding | VSELP | CELP | RPE-LTP | ACELP | AMR | AMR | |
| Bit rate (uncod.Voice) | 7.95 | 1.2-9.6 | 13 | 4.5 | - | - | Kbit/s |
| Peak power (mob.) | 0.6-3 | 0.6-3 | 2-20 | 0.032-31 | 0.125-2 | 0.125-0.25 | W |
| Mean power (mob.) | 0.6-3 | 0.2-1 | 0.2-2.5 | - | - | - | W |
| Power control | Yes | Yes | Yes | Yes | Yes | Yes | |
| Voice activity detect. | Opt. | Yes | Yes | Yes | Yes | Yes | |
| Handover | Yes | Yes | Yes | Opt. | Yes | Yes | |
| Dynamic Allocation | No | n.a. | Yes | Yes | Yes | Yes | |
| | | | | | | | |

# Multiple access

See part on interference, and deterministic MA protocols, duplexing, ...

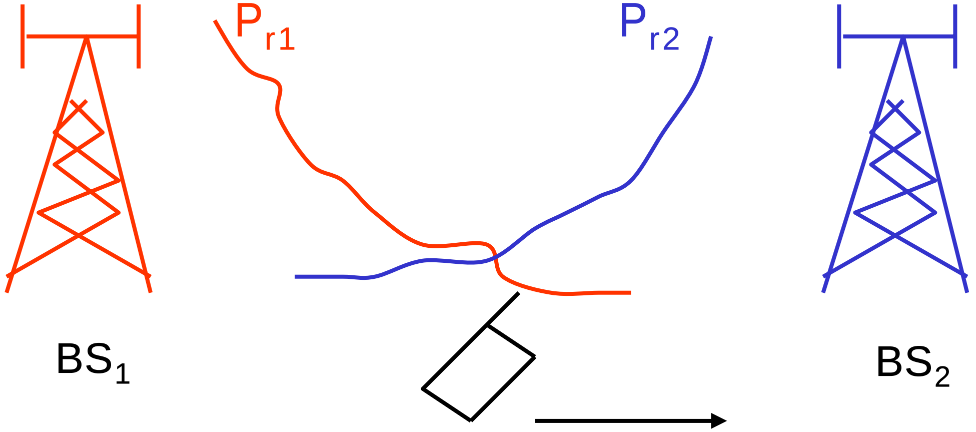
# Handover

... procedures to guarantee the call continuity during the passage of the mobile from a BS to another one (inter-cell) or from a channel to another (intra-cell).

Mobile outgoing its cell → perceived QoS decreases
BSC changes the BS depending on BS-MS channel measurements.

HO intra-BSC (@BSC) or HO inter-BSC (@MSC).

Cell dimension decreasing → capacity increasing but also the handover rate increases.



# Basics on the Handover and Resources Allocation

HO implies many functionalities for signaling and position updating.

Compromise between average number of HO, QoS and network complexity.

There are different policies for channel assignment into a cluster:

FCA: Fixed Channel Allocation Ex. TACS, GSM
Resources (t,f,c) are statically allocated to the BTS depending on off-line estimated requirements on the Carrier-to-Interference Ratio (CIR).
BTS more simple but the network reconfiguration is difficult and a resource planning is needed.

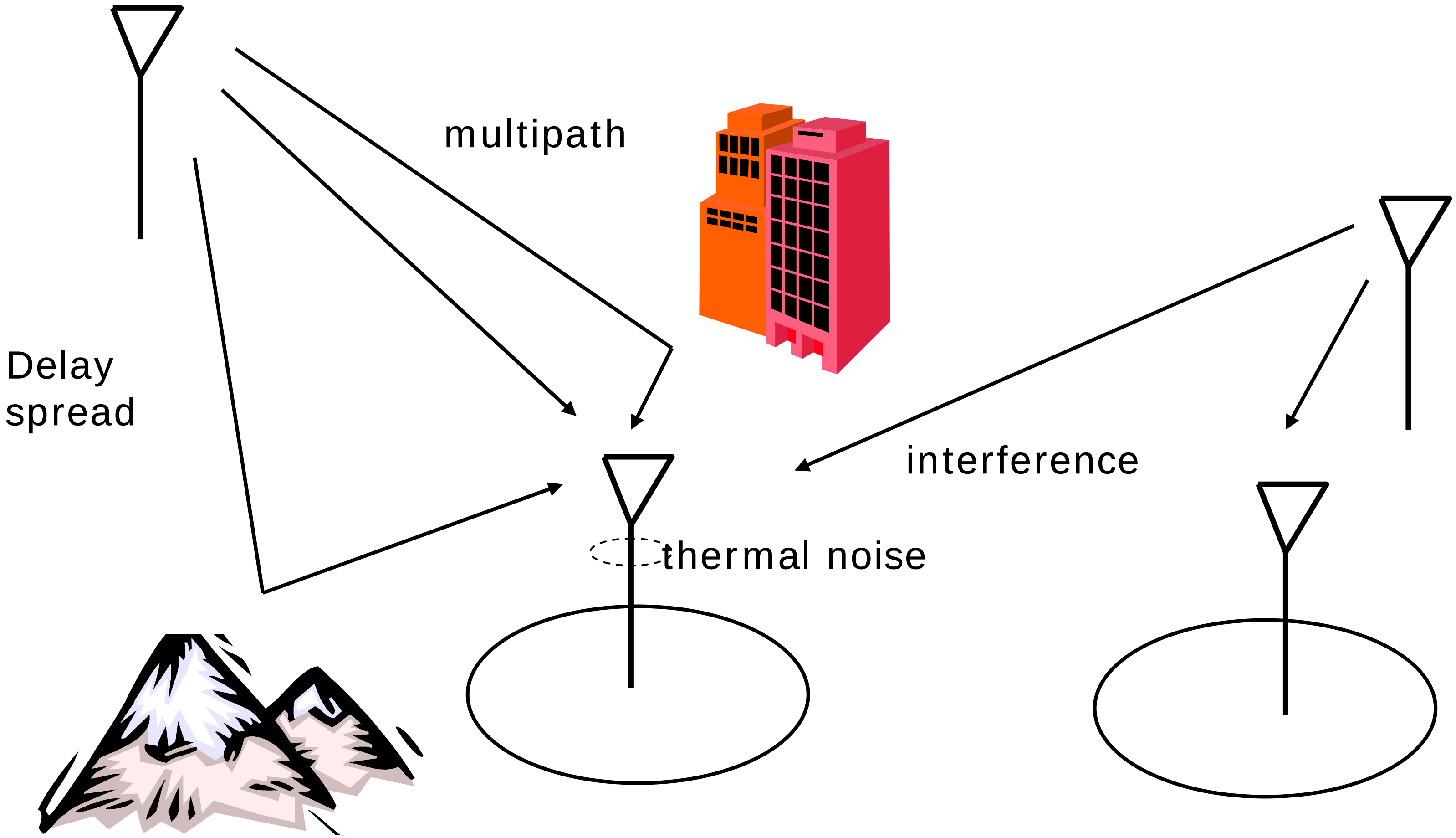
DCA: Dynamic Channel Allocation Ex. DECT, IMT2000
Every BTS can use all resources (t,f,c) and is reconfigured depending on traffic and CIR conditions in a centralized (better because there is knowledge of the entire network status) or distributed way (based on interference measurements).

# The impact of interference - digital tlc

QoS(SNR,SIR)

# Impairments

Propagation, Thermal noise, Interference



# Frequency reuse

Territory divided in areas (cell) covered by base stations → the BS guarantees a link for the mobile station with a QoS better than a threshold for a certain percentage of the time (*coverage*).

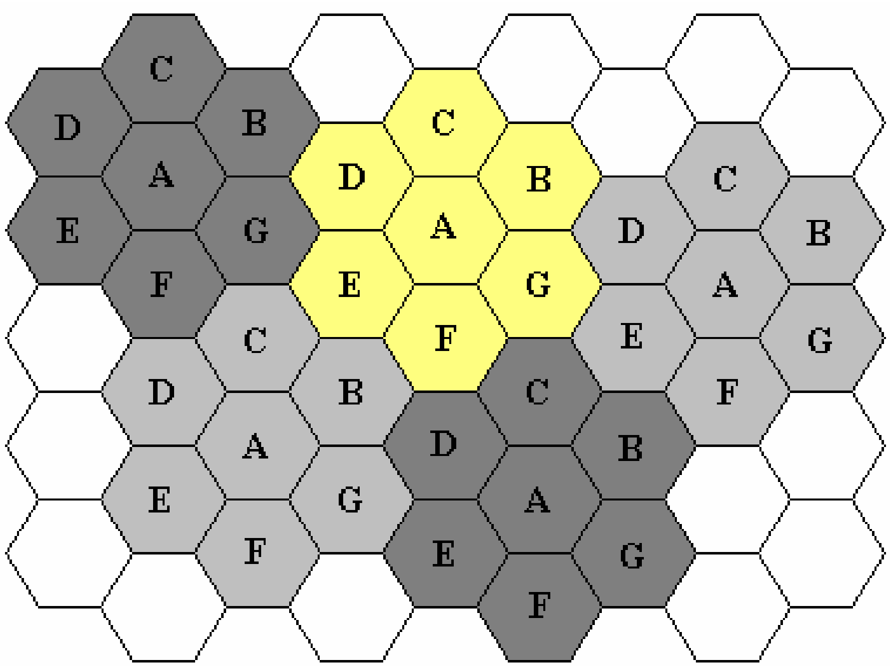
Form and dimension of the cell depends on tx power, antenna radiation pattern, environment → real cells are irregular

**Main impairments:** thermal noise and cochannel interference (CCI) from users reusing the same resources at the same time

→ resources are divided within a group of cell named **cluster** and reused in cells at a certain distance (**reuse distance**) that depends on the number of cells per cluster (**cluster size**)

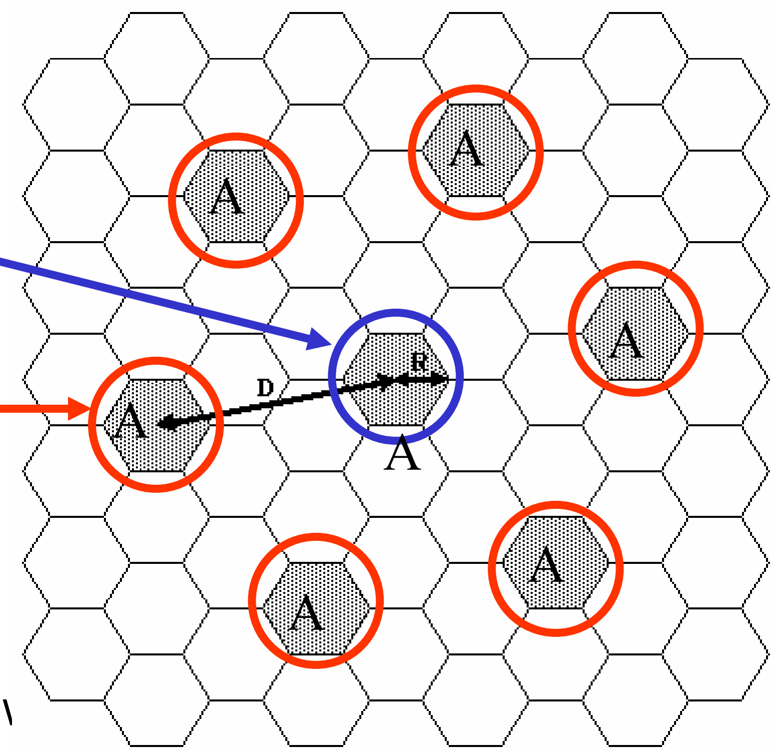
→ increasing of the Carrier-to-Interference Ratio (**CIR**)

# Ex. Cluster size N=7




Useful cell

Interfering cells for N=7 and
omnidirectional antennas.
First tier of interferers.



# CIR and cluster size

To understand how the cluster size, **N**, affects the CIR:

up-link (MS to BS)

*Assumption*: path-loss approx deterministic model $d^{\beta}$ and *h* depends on tx power, wavelength, antenna gain, and $\beta$ in [2,5] .

$$P_R = h \cdot d^{-\beta}$$

Desired user at the border of its cell (pessimistic assumption), interferers at the center $\Rightarrow$

$$C = h \cdot R^{-\beta} \qquad I_i = h \cdot D^{-\beta} \qquad I = 6 \cdot I_i$$

for six uncorrelated interferers at distance D.

$$\Rightarrow \quad \frac{C}{I} = \frac{1}{6}\left(\frac{D}{R}\right)^{\beta} \qquad \Rightarrow \quad \frac{C}{I} = \frac{1}{6}(3 \cdot N)^{\beta/2}$$

geometry

$$\frac{D}{R} = \sqrt{3 \cdot N}$$

**CIR increases with N**

Possible values of the cluster size: $N=i^2+ij+j^2$ with i and j natural both $\neq 0$ ($N=1,3,4,7,9,12,\ldots$)

The choice of N (minimum possible for complexity in the planning and channel allocation) is a trade-off between CIR requirements and spectral efficiency.

## Spectral Efficiency for mobile radio systems

Different definitions in literature. Ex.: no. of channels per unit of area and bandwidth

$B_t$ total bandwidth [MHz], A area of the cell [$Km^2$], $B_{ch}$ bandwidth per channel [MHz], $n_{ch}=B_t/(B_{ch}\ N)$ channel per cell

$$E = \frac{n_{ch}}{B_t \cdot A} = \frac{1}{N \cdot B_{ch} \cdot A} \qquad \left[\frac{\text{channel}}{\text{Km}^2 \cdot \text{MHz}}\right]$$

**E decreases with N**

Another definition of spectral efficiency is in terms of carried traffic per unit of area and bandwidth

$E_c$ Erlang per cell

$$E = \frac{E_c}{B_t \cdot A} \qquad \left[\frac{\text{Erlang}}{\text{Km}^2 \cdot \text{MHz}}\right]$$

**E decreases with N**

The compromise between CIR and the spectral efficiency depends on the users' density, so on the cell area

$$\Downarrow$$

Pico-cell for areas with large demand of service (urban) and macro-cell for low traffic (rural environment).

# Blocking Probability

For systems M/M/n/0 (lost calls cleared, arrival Poissonian, service time exp. distributed), the B-Erlang formula is useful to provide the **blocking probability**, $P_B$, that is the probability that a call can not be served.

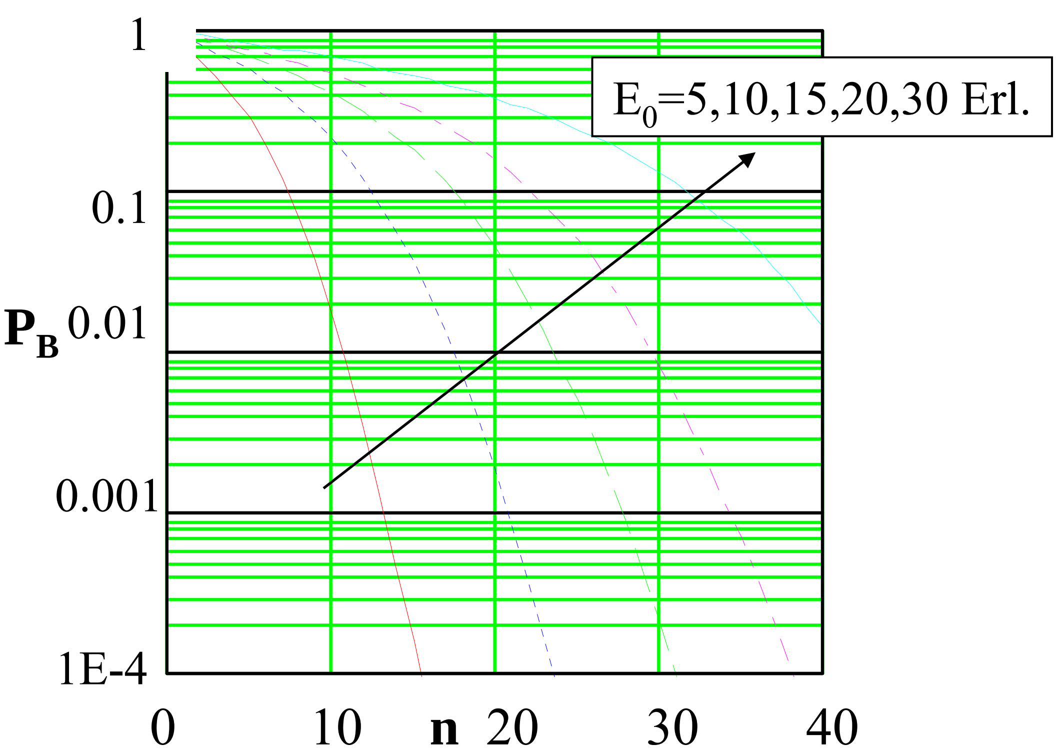
$$P_B = \mathrm{B}(n_{ch}, E_0) = \frac{E_0^{n_{ch}} / n_{ch}!}{\sum_{k=0}^{n_{ch}} E_0^k / k!}$$

Offered traffic per cell

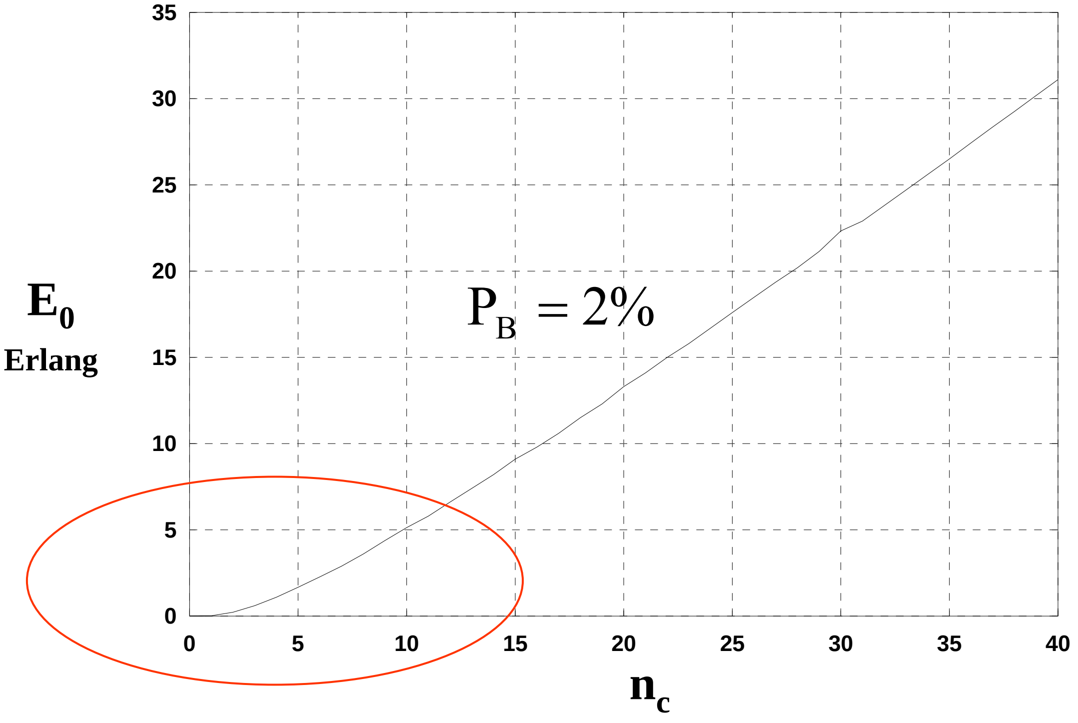
$$\mathrm{E_c} = \mathrm{E_o}\left(1 - \mathrm{P_B}\right)$$

$\Downarrow$

spectral efficiency



$\Downarrow$




Non-linear region

# Ex.: evaluation of the number of served users 1/2

$B_t$=6 MHz, $B_{ch}$=27.6 KHz
$n_{uh}$=average number of calls per hour per user
$n_{uk}$=average number of user per $Km^2$
$t_c$=mean call duration

exagonal cells

Offered traffic density $$e_0 = n_{uh} \cdot n_{uk} \cdot t_c = \frac{E_0}{A} = \frac{E_0}{R^2 3\sqrt{3}/2}$$ [Erlang/Km$^2$]

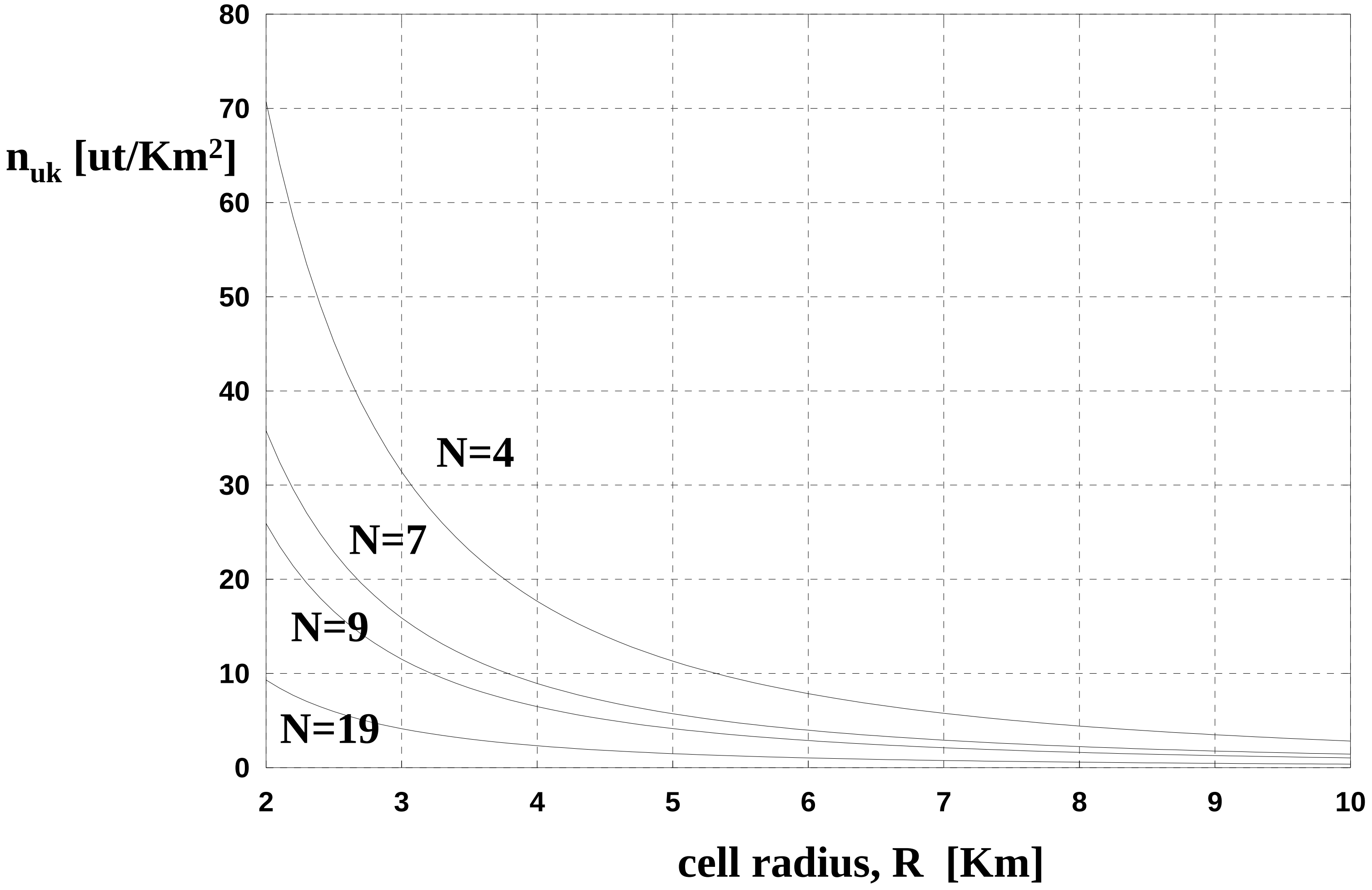
$$\Rightarrow \quad n_{uk} = \frac{E_0}{n_{uh} \cdot t_c \cdot R^2 3\sqrt{3}/2}$$ [Users/Km$^2$]

The maximum offered traffic available, $E_0$, is obtained by the blocking probability and the number of channels per cell.

*Ex.* $t_c$=1.5 min.
$n_{uh}$=2.4 calls/hour/user
$P_B$=2%

| Cluster size N | [Channel/Cell] | [Erlang/cell] |
|---|---|---|
| 4 | 54 | 44 |
| 7 | 31 | 22 |
| 9 | 24 | 17 |
| 19 | 11 | 5.8 |

# Ex.: evaluation of the number of served users 2 / 2



# Channel characterization and modeling

Radio-wave propagation through wireless channels affected by various impairments such as multipath and shadowing.

Precise math description of this phenomenon either unknown or too complex for tractable comm. systems analyses.

$$\Downarrow$$

**statistical modeling** depending on environment

See part on fast fading and shadowing,...

*Typical case for urban area (TUx): (12 tap setting)*

| Tap number | Relative time (μs) | | Average relative power (dB) | | doppler spectrum |
|---|---|---|---|---|---|
| | (1) | (2) | (1) | (2) | |
| 1 | 0,0 | 0,0 | -4,0 | -4,0 | CLASS |
| 2 | 0,1 | 0,2 | -3,0 | -3,0 | CLASS |
| 3 | 0,3 | 0,4 | 0,0 | 0,0 | CLASS |
| 4 | 0,5 | 0,6 | -2,6 | -2,0 | CLASS |
| 5 | 0,8 | 0,8 | -3,0 | -3,0 | CLASS |
| 6 | 1,1 | 1,2 | -5,0 | -5,0 | CLASS |
| 7 | 1,3 | 1,4 | -7,0 | -7,0 | CLASS |
| 8 | 1,7 | 1,8 | -5,0 | -5,0 | CLASS |
| 9 | 2,3 | 2,4 | -6,5 | -6,0 | CLASS |
| 10 | 3,1 | 3,0 | -8,6 | -9,0 | CLASS |
| 11 | 3,2 | 3,2 | -11,0 | -11,0 | CLASS |
| 12 | 5,0 | 5,0 | -10,0 | -10,0 | CLASS |

The reduced TUx setting (6 taps) is:

| Tap number | Relative time (μs) | | Average relative power (dB) | | doppler spectrum |
|---|---|---|---|---|---|
| | (1) | (2) | (1) | (2) | |
| 1 | 0,0 | 0,0 | -3,0 | -3,0 | CLASS |
| 2 | 0,2 | 0,2 | 0,0 | 0,0 | CLASS |
| 3 | 0,5 | 0,6 | -2,0 | -2,0 | CLASS |
| 4 | 1,6 | 1,6 | -6,0 | -6,0 | CLASS |
| 5 | 2,3 | 2,4 | -8,0 | -8,0 | CLASS |
| 6 | 5,0 | 5,0 | -10,0 | -10,0 | CLASS |

## **Paths profile for GSM**

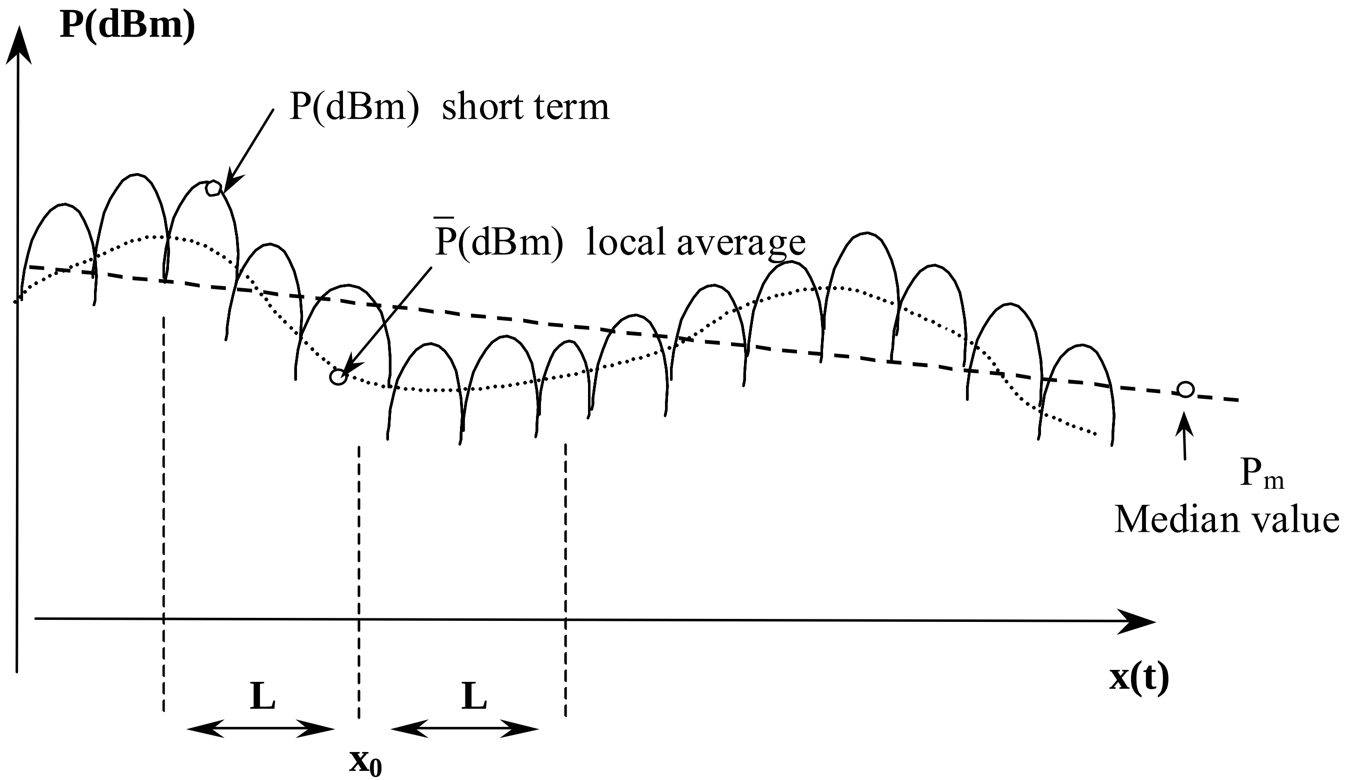
*ETSI reccom. 05.05*

# Channel model for mobile radio systems

Due to terminals mobility the channel change in time (for static environments the rx power change with the position $x(t)=x_0+v\,t$)

$$\Downarrow$$

It is necessary to introduce a statistical description of the channel



# Models for path-loss

There are different models suitable for different environments.

$$A_{I_m} = c \cdot d^{\beta}$$ *c* and *ß* obtained by fitting experimental data.

At 900*MHz* ß $\in$ [2,5]. Nominal case (free-space) is *b* = 2 and*c* = $(4\pi/\lambda)^2$.

**Hata model**

Valid in 150 - 1000 MHz, BS height 30m < $h_b$ < 200m, MS height 1m < $h_m$ < 10m and distance BS-MS 1 < $d(Km)$< 20

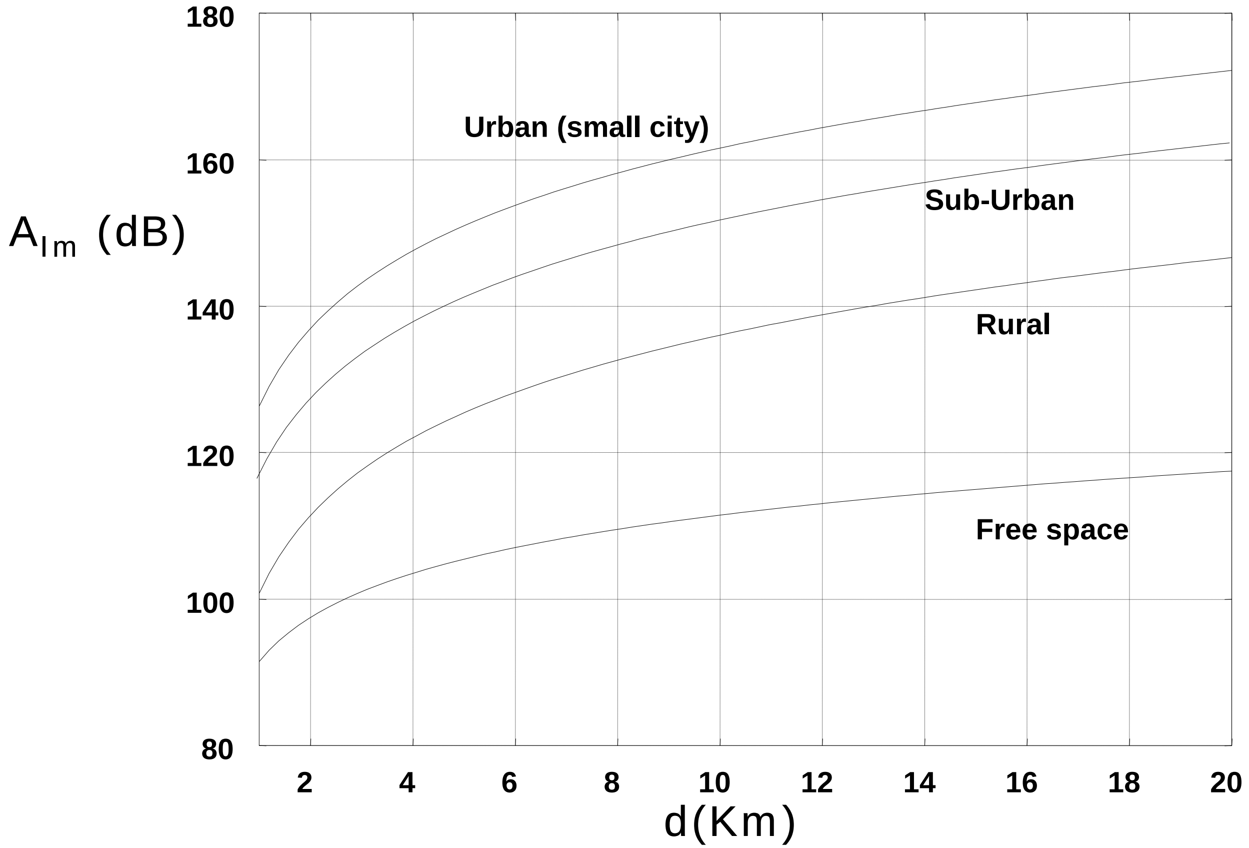
$$A_{I_m}(dB) = \begin{cases} A + B\log_{10}(d) & \text{in urban area} \\ A + B\log_{10}(d) - C & \text{in suburban area} \\ A + B\log_{10}(d) - D & \text{in rural area} \end{cases}$$

with $A = 69.55 + 26.16\log_{10}(f_0) - 13.82 \log_{10}(h_b) - a(h_m)$

$B = 44.9 - 6.55\log_{10}(h_b)$, $C = 5.4 + 2[\log_{10}(f_0/28)]^2$

$D = 40.94 + 4.78[\log_{10}(f_0)]^2 - 19.33\log_{10}(f_{10})$

$$a(h_m) = \begin{cases} (1.1\log_{10}(f_0) - 0.7)h_m - 1.56\log_{10}(f_0) - 0.8 & \text{small cities} \\ 8.28(\log_{10}(1.54h_m))^2 - 1.1 & \text{big cities and } f_0 > 400MHz \end{cases}$$




Path-loss (Hata model) @ 900 MHZ, hb=30m hm=1.5m.

# QoS-based outage

*QoS @ the user*: error rate that the user perceives in a time interval of few seconds (many symbols).

$\Rightarrow$ error rate averaged with respect to fast fading.

QoS-based outage: $$P_0 = P\left\{\overline{P}_e(\overline{\gamma}) > P_{ex}\right\}$$

**Outage Domain** $$OD = \left\{\overline{\gamma} : \overline{P}_e(\overline{\gamma}) > P_{ex}\right\}$$

$$\overline{\gamma}_x = \overline{P}_e^{-1}(P_{ex})$$

$$\Rightarrow P_0 = \int_{OD} f_\gamma(\xi)\, d\xi = \int_0^{\overline{\gamma}_x} f_\gamma(\xi)\, d\xi$$

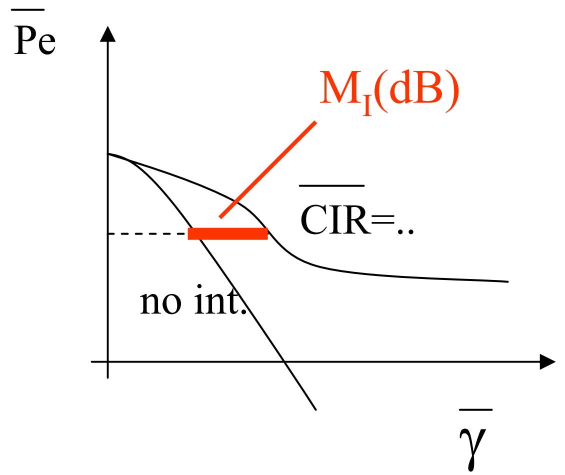
p.d.f. of SNR over SLOW fading

# Network dimensioning

- QoS: error rate that the user perceives in few seconds

  $\Rightarrow$ averaged with respect to fast fading

$$\overline{Pe}(\overline{SNR}, \overline{CIR})$$




Fixing a target QoS $\Rightarrow$ margin on the mean CIR, $M_I$

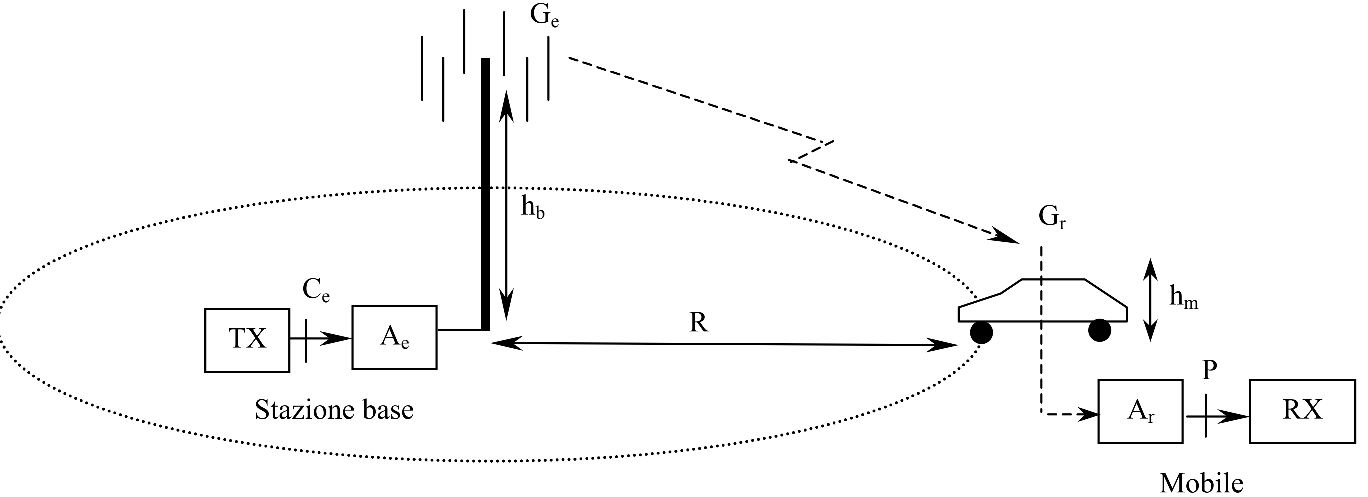
- Trade-off spectral efficiency - CIR

  $\Downarrow$

  cluster size, N

- Fixed the margin on the mean CIR $\rightarrow$ cell design (tx power, cell dimension,...) as in the interference-free case

# Propagation model




$$P_m = C_e G_e G_r \frac{1}{A_e A_r A_{I_m}}$$

$P(x) = P_m \cdot s^2(x) \cdot r^2(x)$

$C_e$ mean tx power, $G_e$ and $G_r$ tx and rx antenna gain, $A_e$ and $A_r$ attenuation due to antenna connections at the tx and the rx.

$A_{Im}$ = median value of the isotropic attenuation, it depends on distance tx-rx, frequency, and path-loss model

# Cell design (interference free)

Performance limited by thermal noise, cochannel interference (CCI) and channel variations.

Cell radius R

Path-loss $A_{lm}=c\ d^{\beta}$

Long-term rx power $$\overline{P}(d)=P_m(d)\cdot s^2=P_m(d)=k\cdot d^{-\beta}$$

with $$k=\frac{C_e G_e G_r}{A_e A_r c}$$

$\overline{P}_x$

k dimensioned to satisfy (in the absence of shadowing) the requirements on the threshold on the long-term rx power overall the cell (i.e., for d=R).

**Coverage, $P_c$:** percentage of cell area with QoS greater than a threshold

$$\mathrm{Pc}=\mathbf{P}\left\{\overline{\mathrm{P}}_{\mathrm{e}}\leq\overline{\mathrm{P}}_{\mathrm{ex}}\right\}\Rightarrow\mathbf{P}\left\{\overline{\gamma}\geq\overline{\gamma}_{\mathrm{x}}\right\}\Rightarrow\mathbf{P}\left\{\overline{\mathrm{P}}\geq\overline{\mathrm{P}}_{\mathrm{x}}\right\}$$

# .. effect of shadowing

$$\overline{P}(d) = s^2 \cdot P_m(d)$$

If no margin are used , the prob. that

$$\overline{P}(R) > \overline{P}_x \Rightarrow \text{Prob}\{s(dB) < 0\} = 50\%$$

⇒at d=R the coverage is 50% ⇒ a margin against shadowing is needed!

$$P_m(R) = M_{sh} \cdot \overline{P}_x$$

in the presence of CCI
it contains the margin on CIR

*coverage at distance d*:

$$P_c(d) = \text{Prob}\{\overline{P}(d) \geq \overline{P}_x\} = \text{Prob}\{10\log_{10}\overline{P}(d) \geq 10\log_{10}\overline{P}_x\}$$

$$\text{P}_\text{m}(\text{d}) = \text{k} \cdot \text{d}^{-\beta}$$

$$\overline{P}(d) = P_m(d) \cdot s^2$$

and considering that m is a log-normal r.v. with parameter $\sigma_{dB}$, i.e., m in dB is ~ $N(0, \sigma_{dB}^2)$:

$$P_c(d) = \text{Prob}\left\{20\log_{10} s > 10\beta \log_{10}\frac{d}{R} - M_{sh}(dB)\right\}$$

$$\Rightarrow \qquad P_c(d) = \frac{1}{2}\text{erfc}\left(\frac{-M_{sh}(dB) + 10\beta\log_{10}(d/R)}{\sqrt{2}\sigma_{dB}}\right)$$

coverage at the cell border (d=R): $P_c(R) = \frac{1}{2}\text{erfc}\left(\frac{-M_{sh}(dB)}{\sqrt{2}\sigma_{dB}}\right)$

# Coverage

Average of Pc(d) on the entire cell.

For circular cells of radius R:

$$Pc = \frac{1}{\pi R^2}\int_A P_c(d)dA = \frac{2}{R^2}\int_0^R d \cdot P_c(d)d\mathrm{d}$$

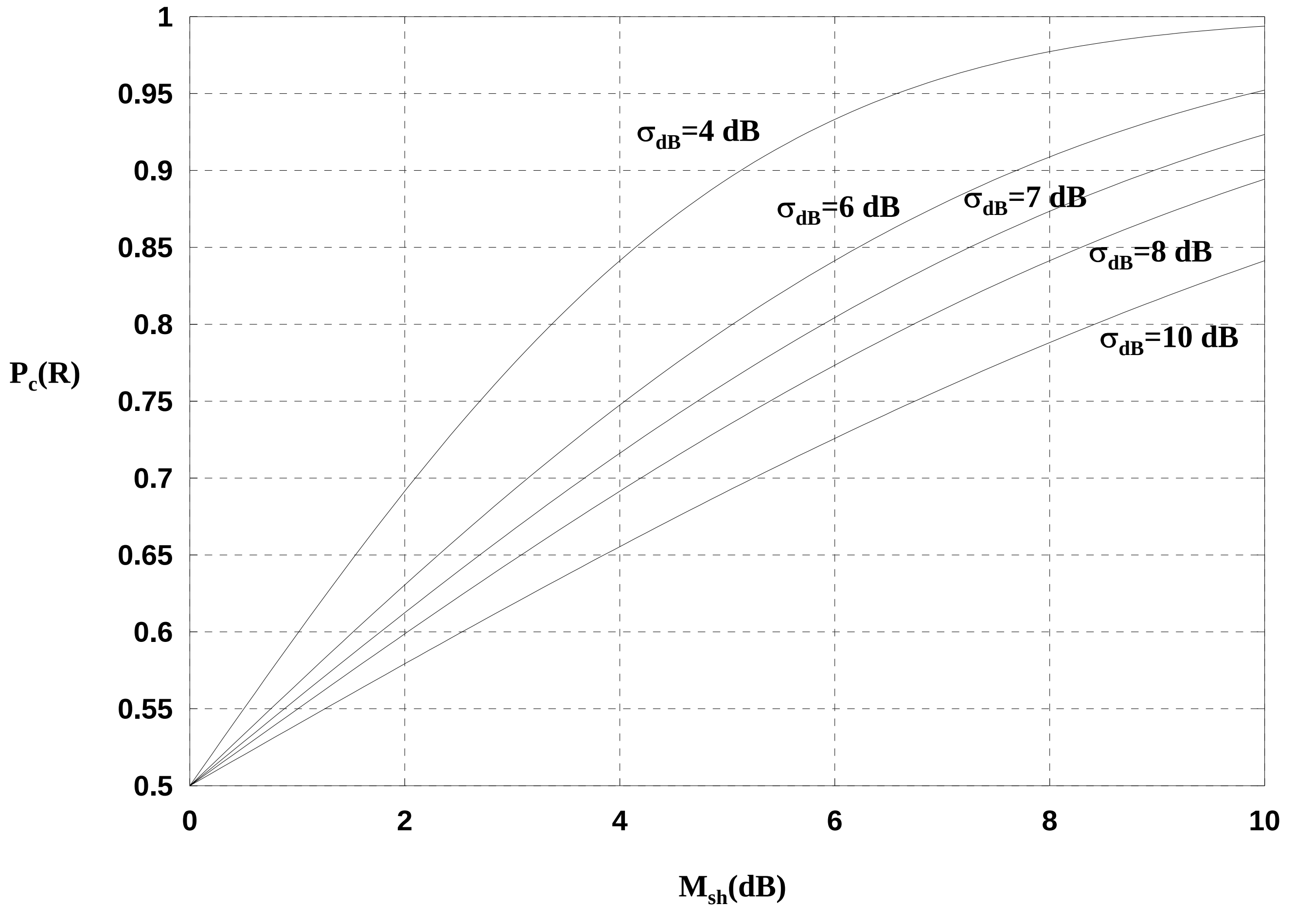
$$\mathrm{a} = \frac{-\mathrm{M}_{\mathrm{sh}}(\mathrm{dB})}{\sqrt{2}\sigma_{\mathrm{dB}}}$$

$$\mathrm{b} = 10\beta\log_{10}\left(\frac{\mathrm{e}}{\sqrt{2}\sigma_{\mathrm{dB}}}\right)$$

$$\mathrm{Pc} = \frac{1}{2}\left\{1+\mathrm{erf}(\mathrm{a}) + \exp\left(\frac{2\mathrm{ab}+1}{\mathrm{b}^2}\right)\left[1-\mathrm{erf}\left(\frac{\mathrm{ab}+1}{\mathrm{b}}\right)\right]\right\}.$$

*Typical requirement*: $P_c(R) = 75\%$

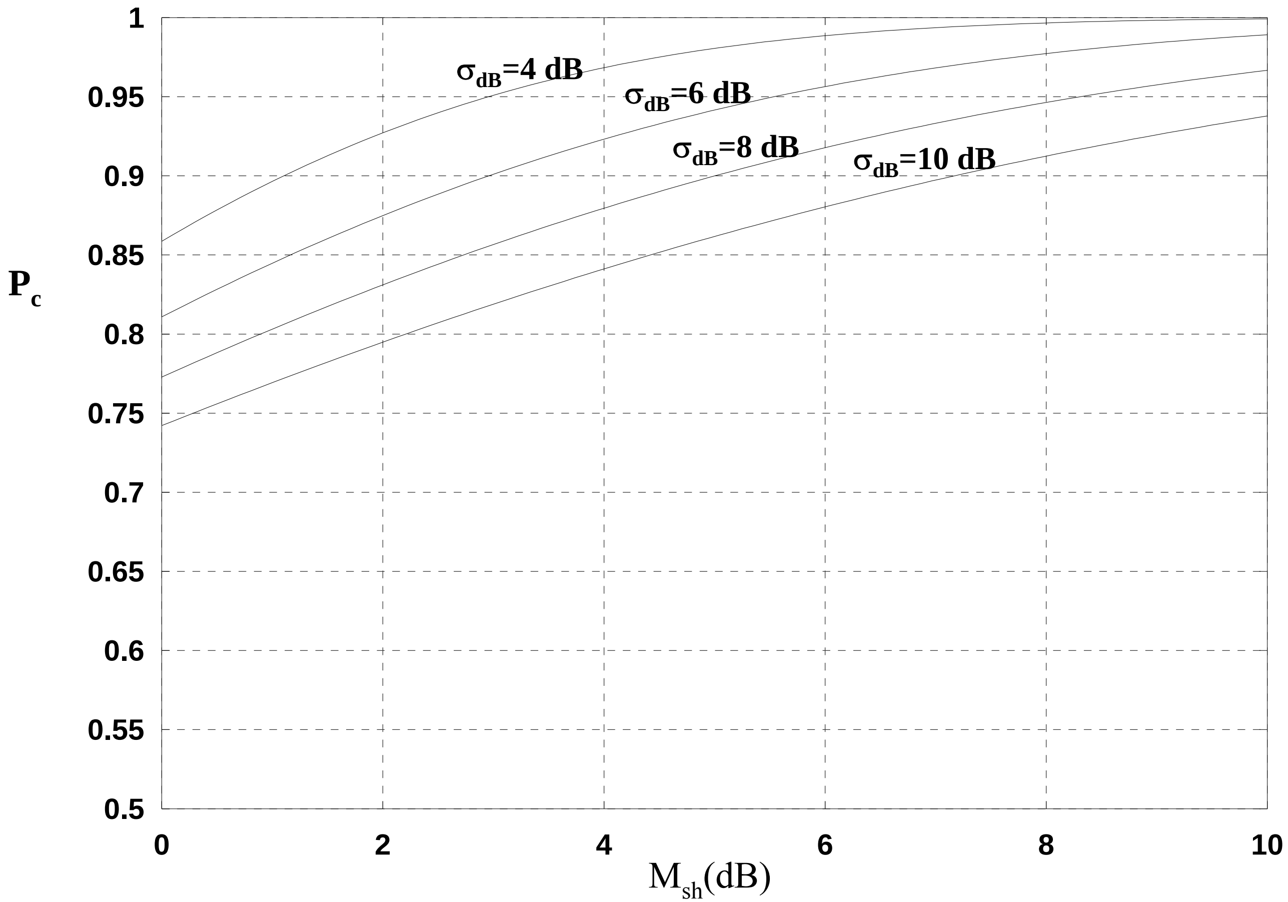
Ex.: $\beta=4$, $\sigma_{dB}=8$ dB, $Pc(R)=75\% \Rightarrow M_{sh}=5dB$




$\beta=4$

# Coverage results

$M_{sh} = 5dB \Rightarrow Pc = 90\%$




$\beta=4$