Cellular systems & GSM

Wireless Systems, a.a. 2014/2015

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

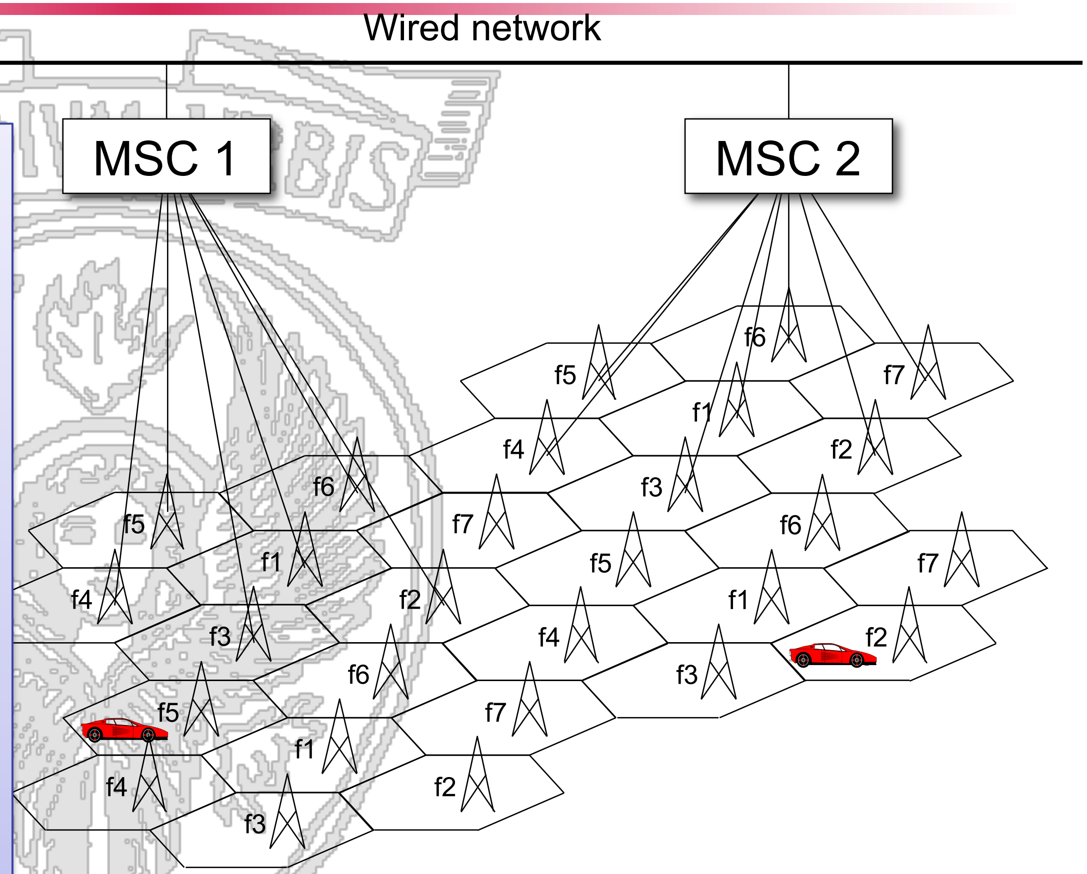
[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

Frequency reuse: cellular systems

SAPIENZA
UNIVERSITÀ DI ROMA

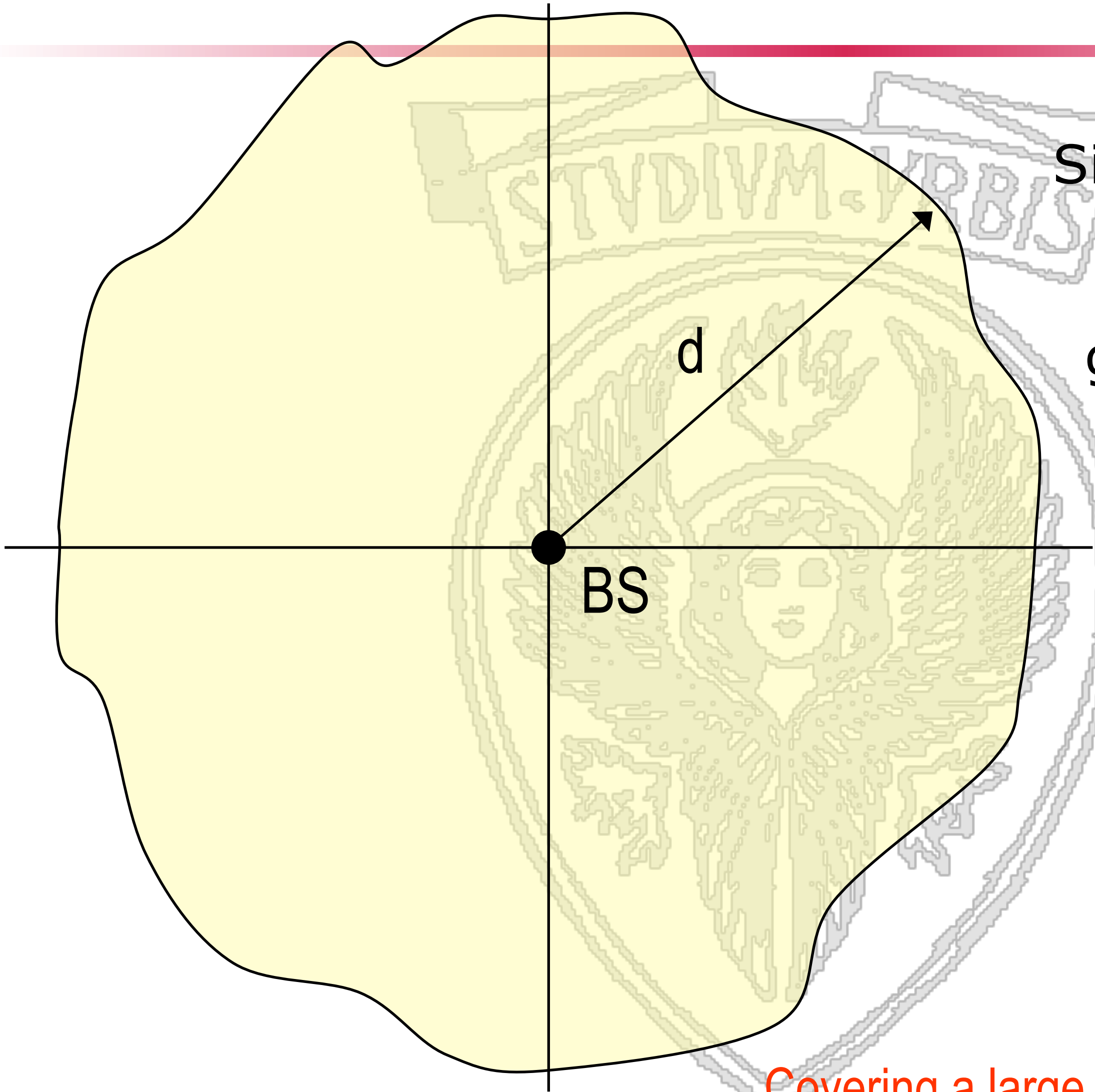
Cellular systems architecture

- ➔ 1 BS per cell
  - ⇨ Cell: Portion of territory covered by one radio station
  - ⇨ One or more carriers (frequencies; channels) per cell
- ➔ Mobile users full-duplex connected with BS
- ➔ 1 MSC controls many BSs
- ➔ MSC connected to PSTN



BS = Base Station
MSC = Mobile Switching Centre
PSTN = Public Switching Telephone Network

Coverage for a terrestrial zone



Signal OK if P_{rx} > -X dBm

$P_{rx} = c\, P_{tx}\, d^{-4}$

greater P_{tx} → greater d

1 Base Station

N=12 channels

- (e.g. 1 channel = 1 carrier)

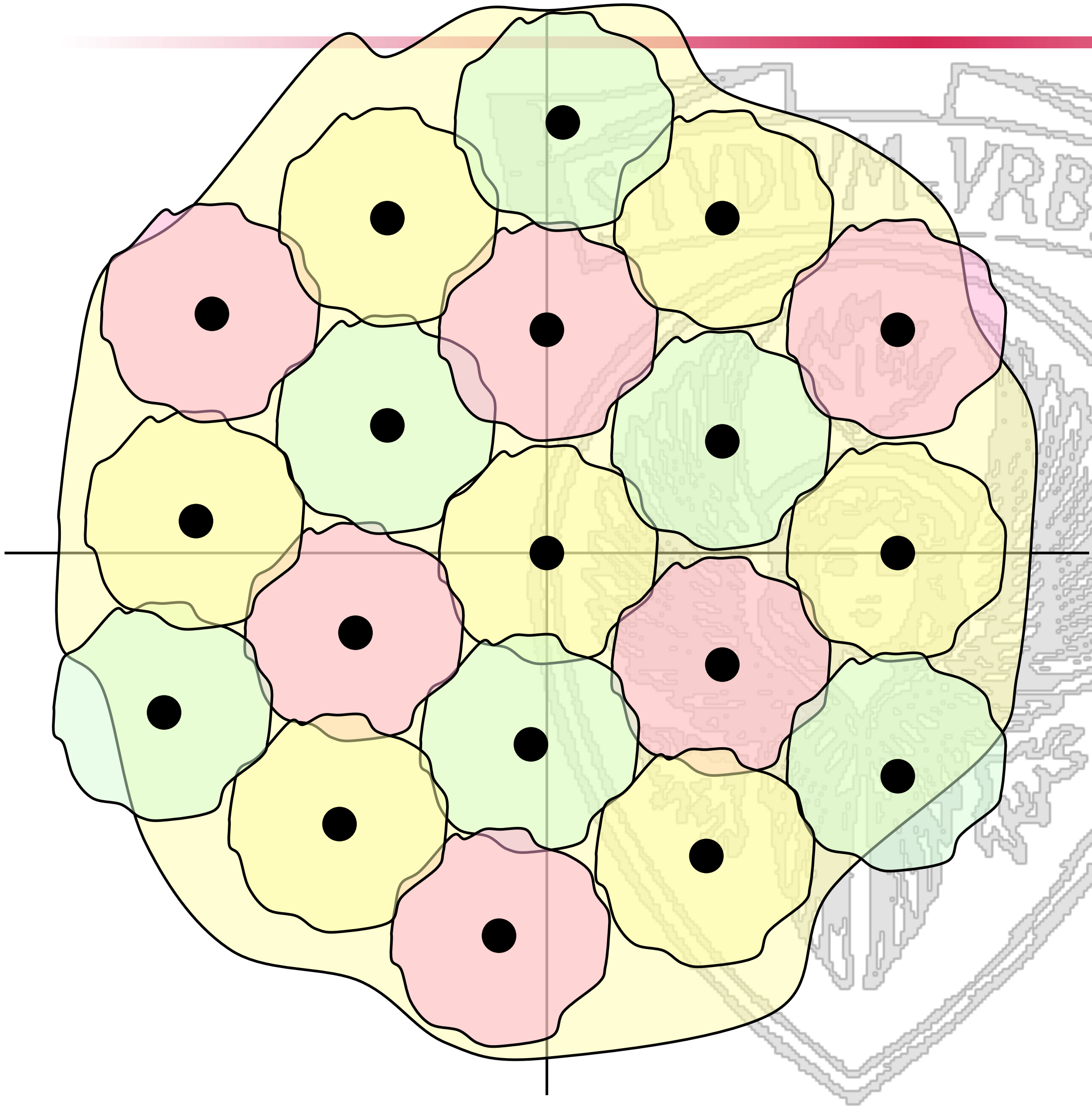
⬇

N=12 simultaneous calls

Covering a large geographical area is NOT possible

Cellular coverage

target: cover the same area with a l arger number of BSs



19 Base Station

12 carriers

4 carriers/cell

Worst case:

4 calls (all users in same cell)

Best case:

76 calls (4 users per cell, 19 cells)

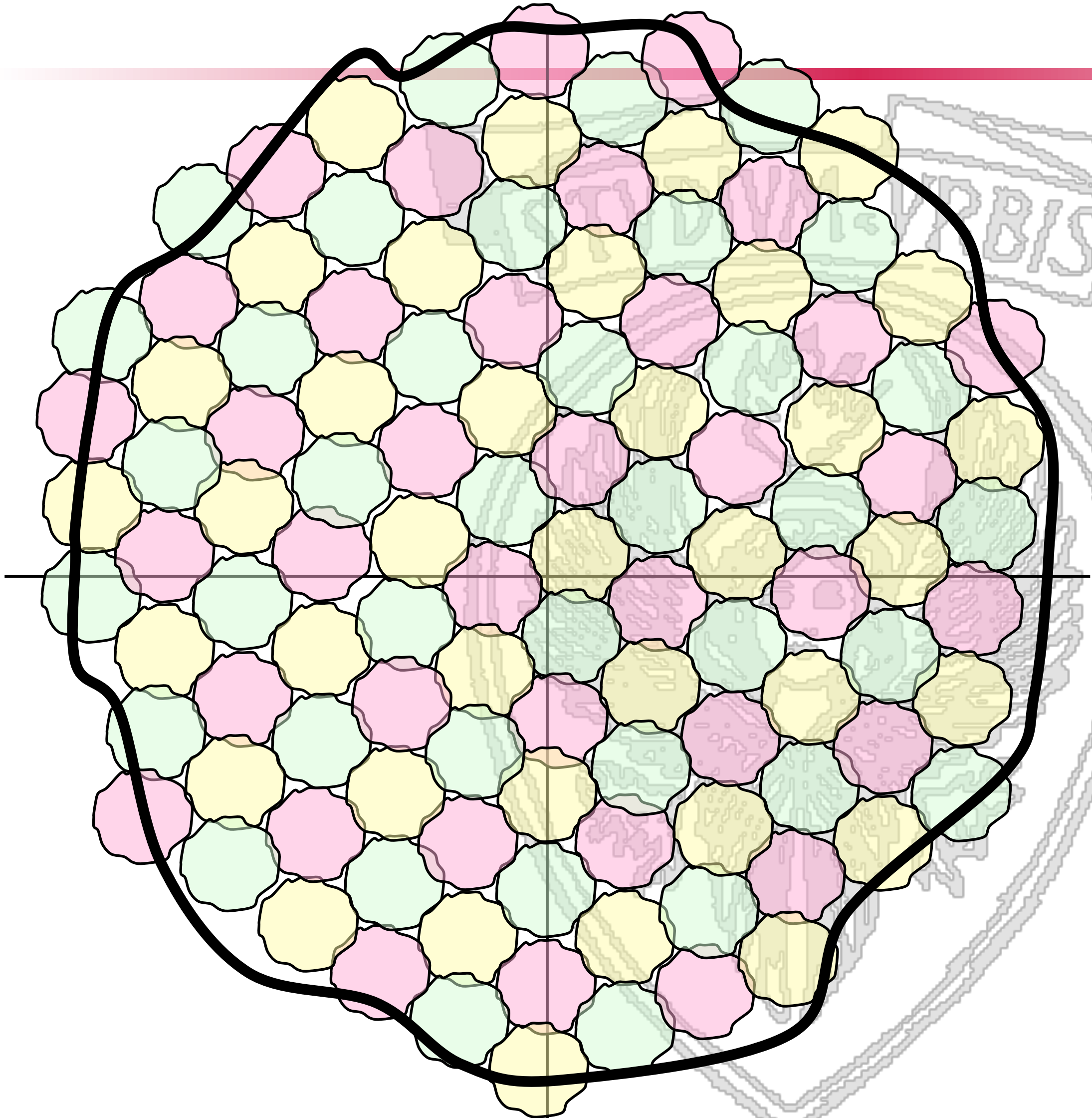
Average case >> 12

Low transmit power

Key advantages:

- Increased capacity (freq. reuse)
- Decreased tx power

Cellular coverage (microcells)



many BS

Very low power!!

Unlimited capacity!!

Usage of same spectrum

(12 carriers)

(4 carriers/cell)

Disadvantage:

mobility management

additional infrastructure costs

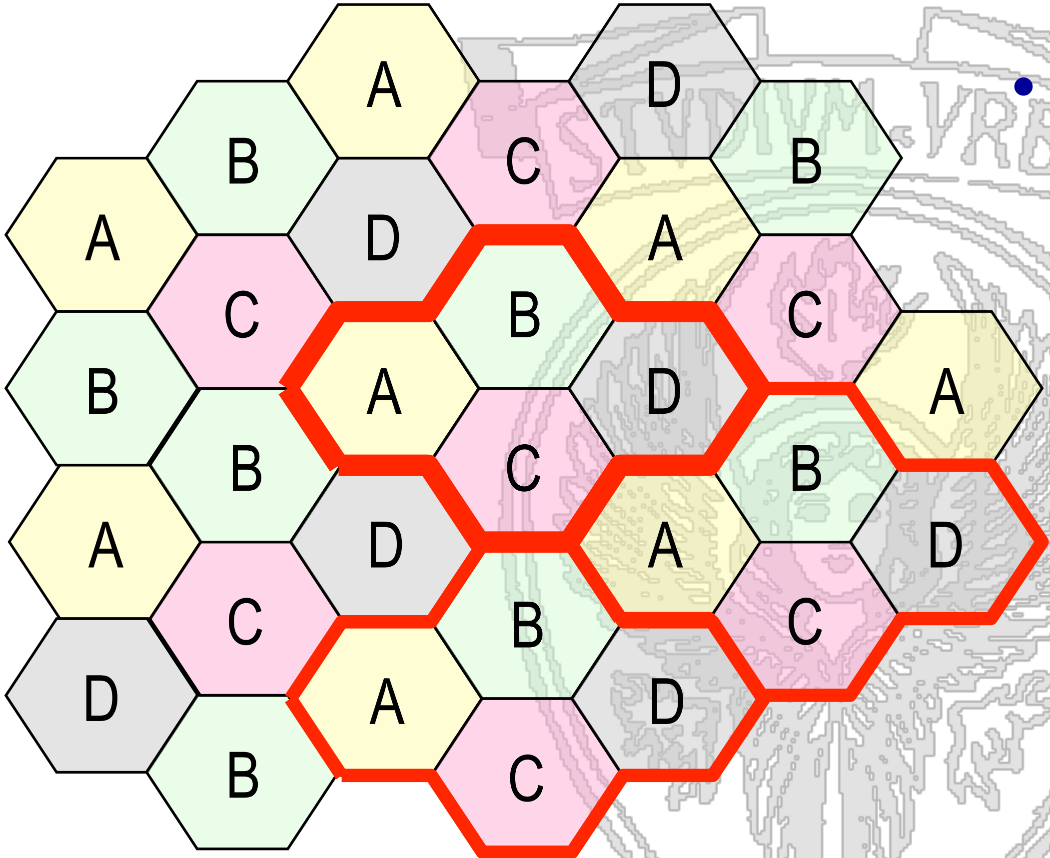
Cellular capacity

- Increased via frequency reuse
  - Frequency reuse depends on interference
  - need to sufficiently separate cells
    - ✓ reuse pattern = cluster size (7 → 4 → 3): discussed later

- Cellular system capacity: depends on
  - overall number of carriers
    - ✓ Larger spectrum occupation
  - frequency reuse pattern
  - Cell size
    - ✓ Smaller cell (cell → microcell → picocell) = greater capacity
    - ✓ Smaller cell = lower transmission power
    - ✓ Smaller cell = increased handover management burden

SAPIENZA
UNIVERSITÀ DI ROMA

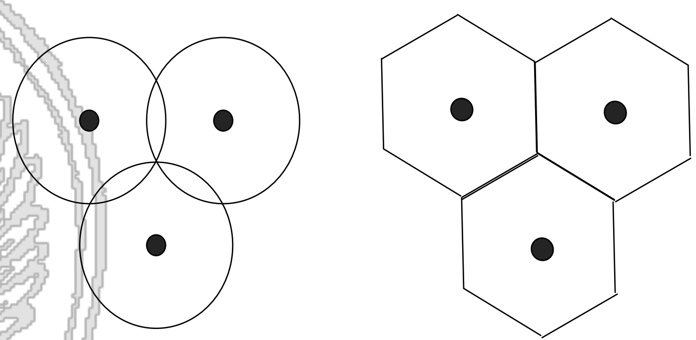
Hexagonal cells



➔Example case:

⇨Reuse pattern = 4

- Hexagon:
  - Good approximation for circle



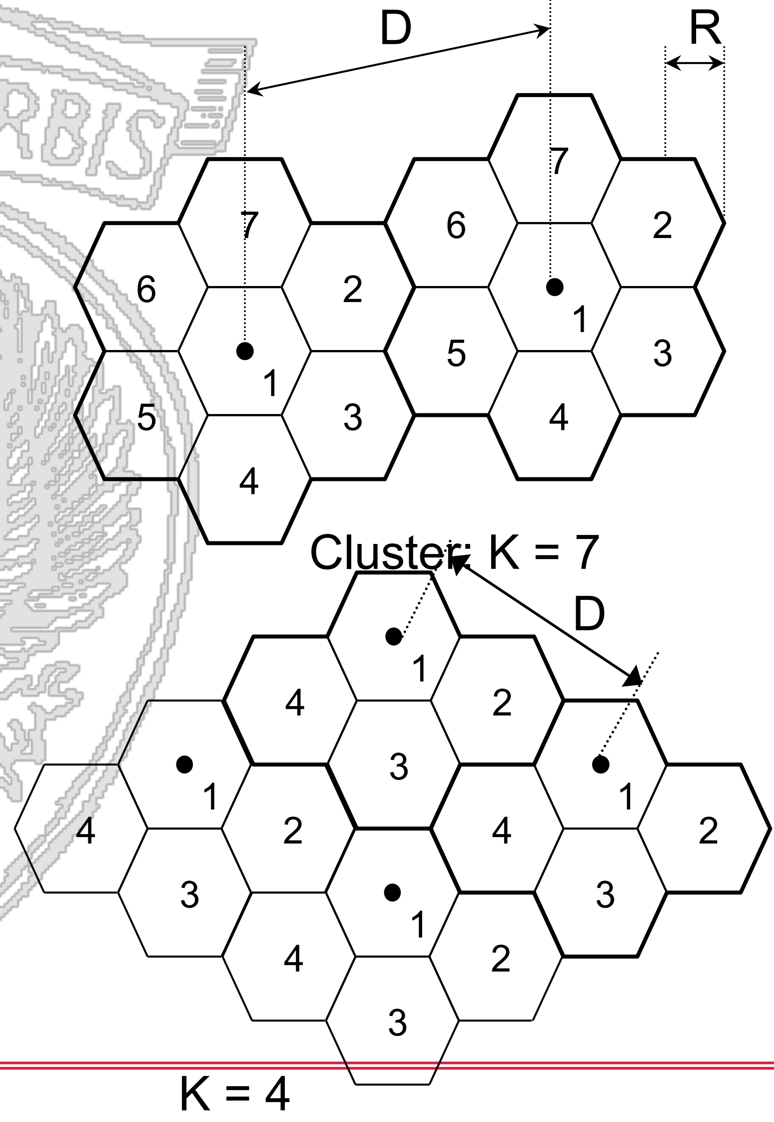
  - Ideal coverage pattern
    - ✓ no “holes”
    - ✓ no cell superposition

PART 2
Cellular Coverage Concepts

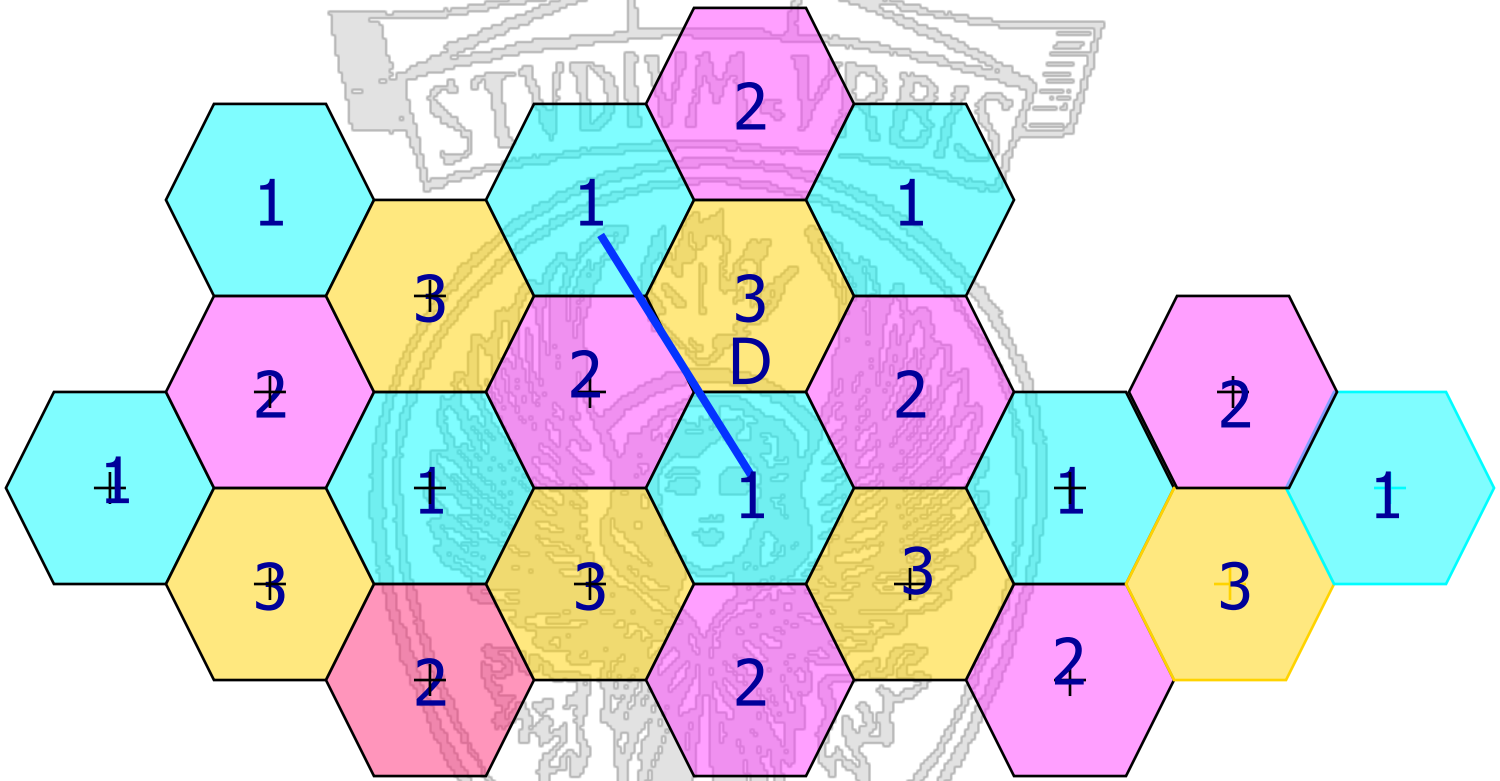
Lecture 2.2
Clusters and CCI

Reuse patterns

- Reuse distance:
  - Key concept
  - In the real world depends on
    - ✓Territorial patterns (hills, etc)
    - ✓Transmitted power
      - and other propagation issues such as antenna directivity, height of transmission antenna, etc
- Simplified hexagonal cells model:
  - reuse distance depends on reuse pattern (cluster size)
  - Possible clusters:
    - ✓3,4,7,9,12,13,16,19,…

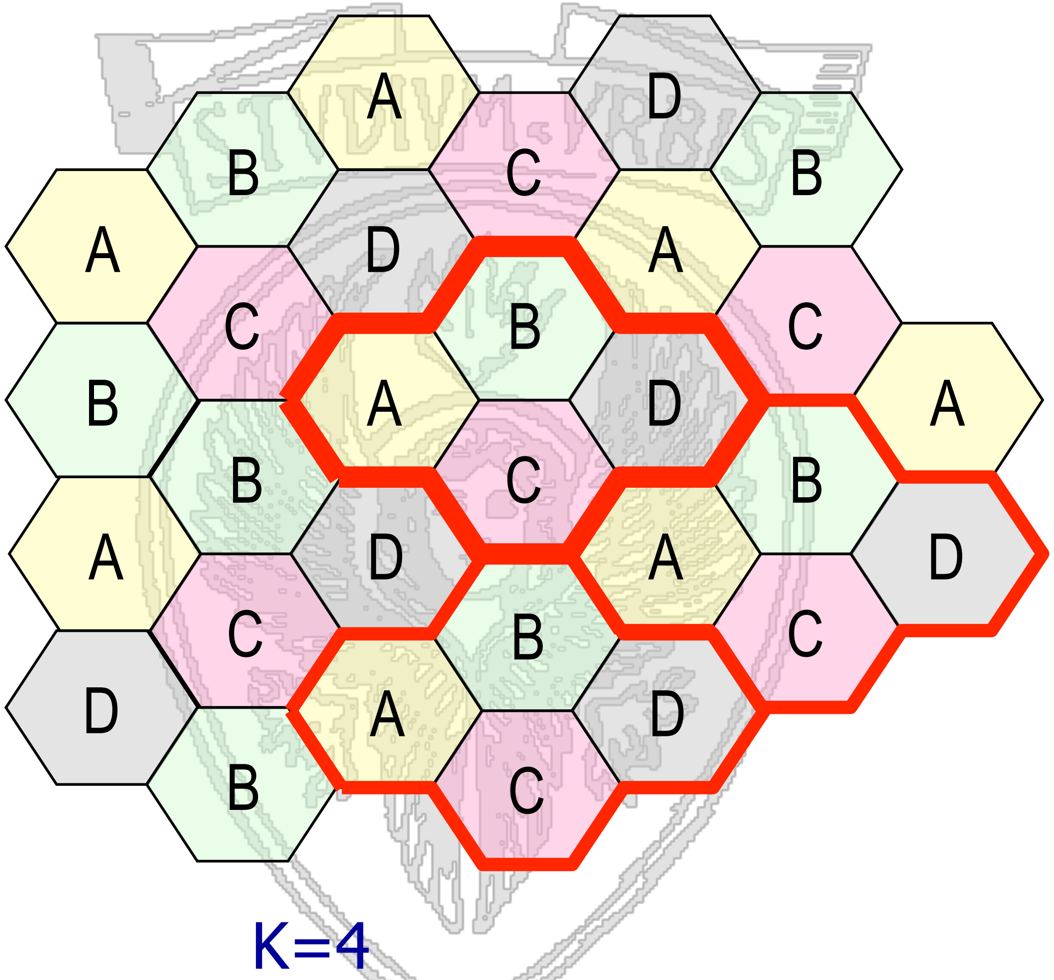


Cluster size

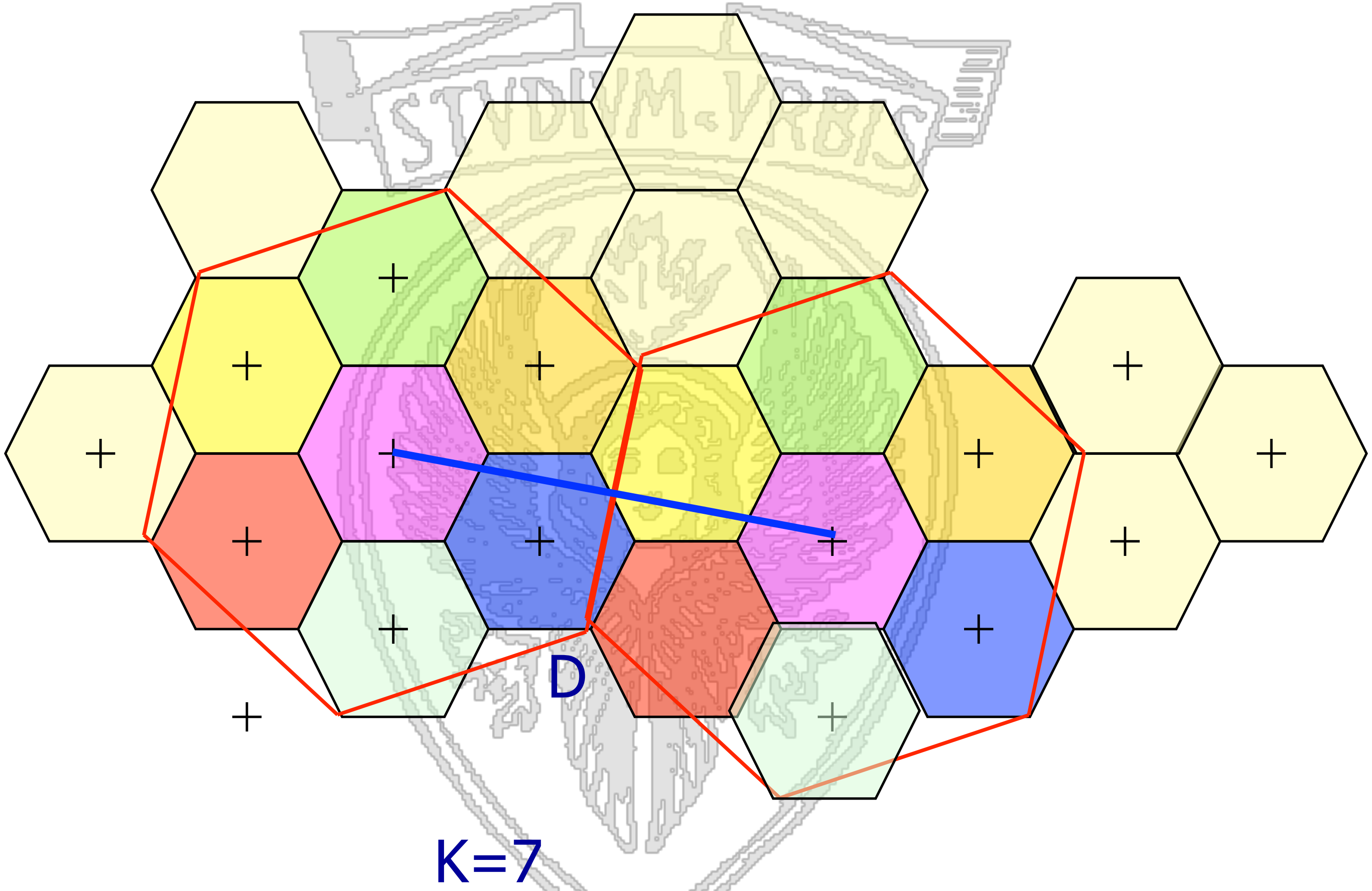


K=3

Cluster size



Cluster size

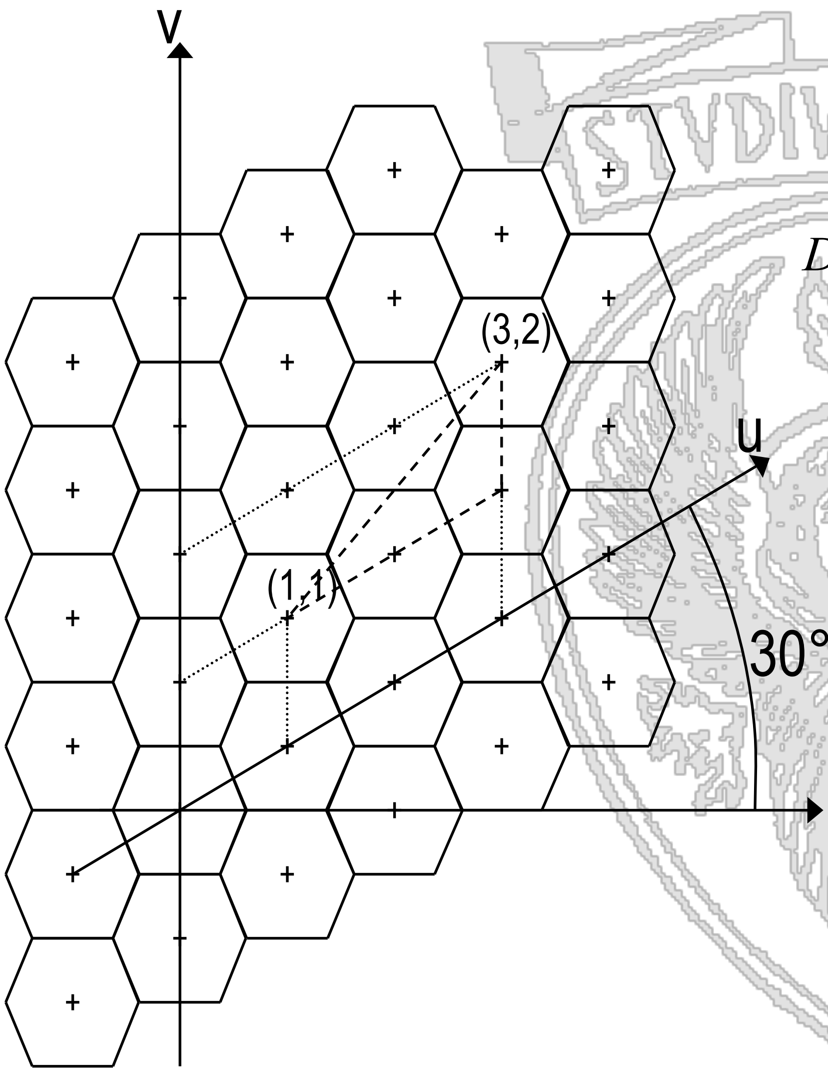


Reuse distance

- General formula $D = R\sqrt{3K}$
- Valid for hexagonal geometry
- D = reuse distance
- R = cell radius
- K=cluster size
- q = D/R =frequency reuse factor

K	q=D/R
3	3,00
4	3,46
7	4,58
9	5,20
12	6,00
13	6,24

Proof



- Distance between two cell centers:
  - $(u_1,v_1) \leftarrow\rightarrow (u_2,v_2)$

$$D = \sqrt{\left[(u_2-u_1)\cos 30^o\right]^2 + \left[(v_2-v_1)+(u_2-u_1)\sin 30^o\right]^2}$$

  - Simplifies to:

$$D = \sqrt{(u_2-u_1)^2 + (v_2-v_1)^2 + (u_2-u_1)(v_2-v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D = \sqrt{i^2 + j^2 + ij}\sqrt{3}R$$

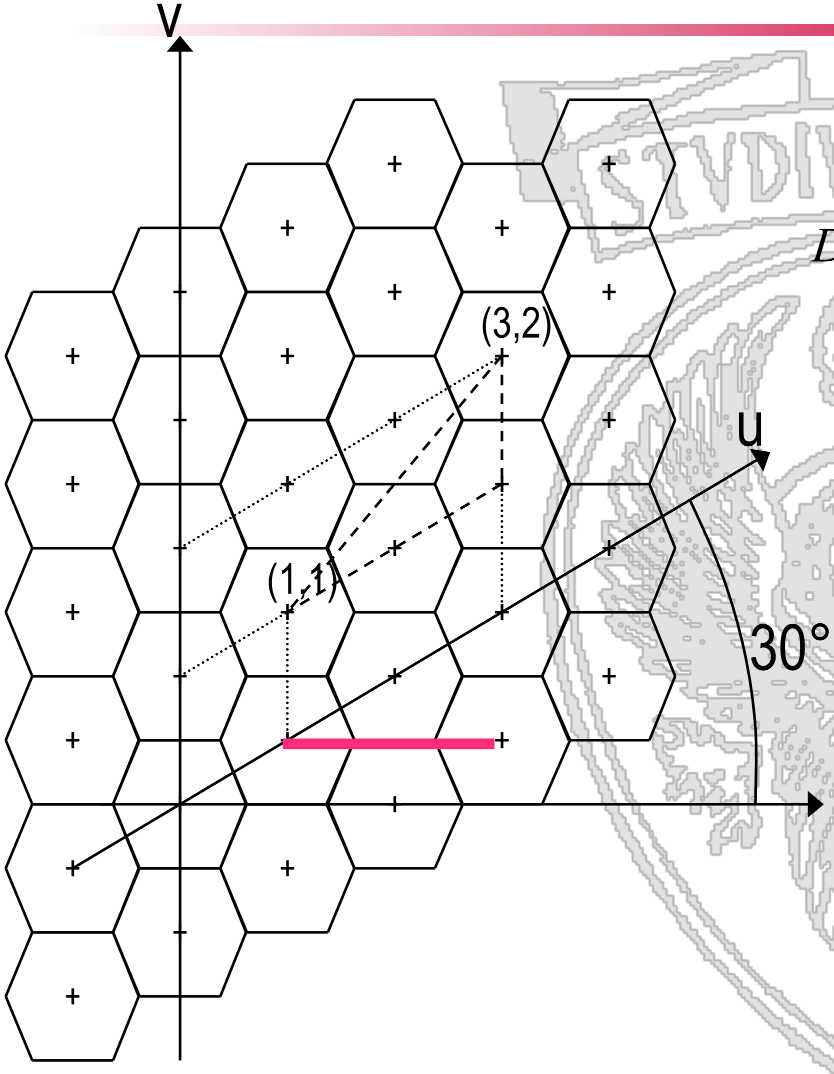
$$D_R = \sqrt{i^2 + j^2 + ij}$$

  - Cluster: easy to see that

$$K = D_R^2 = i^2 + j^2 + ij$$

  - hence: $D = R\sqrt{3K}$

Proof



- Distance between two cell centers:
  - $(u_1,v_1) \leftrightarrow (u_2,v_2)$

$$D=\sqrt{\left[(u_2-u_1)\cos 30^o\right]^2+\left[(v_2-v_1)+(u_2-u_1)\sin 30^o\right]^2}$$

  - Simplifies to:

$$D=\sqrt{(u_2-u_1)^2+(v_2-v_1)^2+(u_2-u_1)(v_2-v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D=\sqrt{i^2+j^2+ij}\sqrt{3}R$$

$$D_R=\sqrt{i^2+j^2+ij}$$

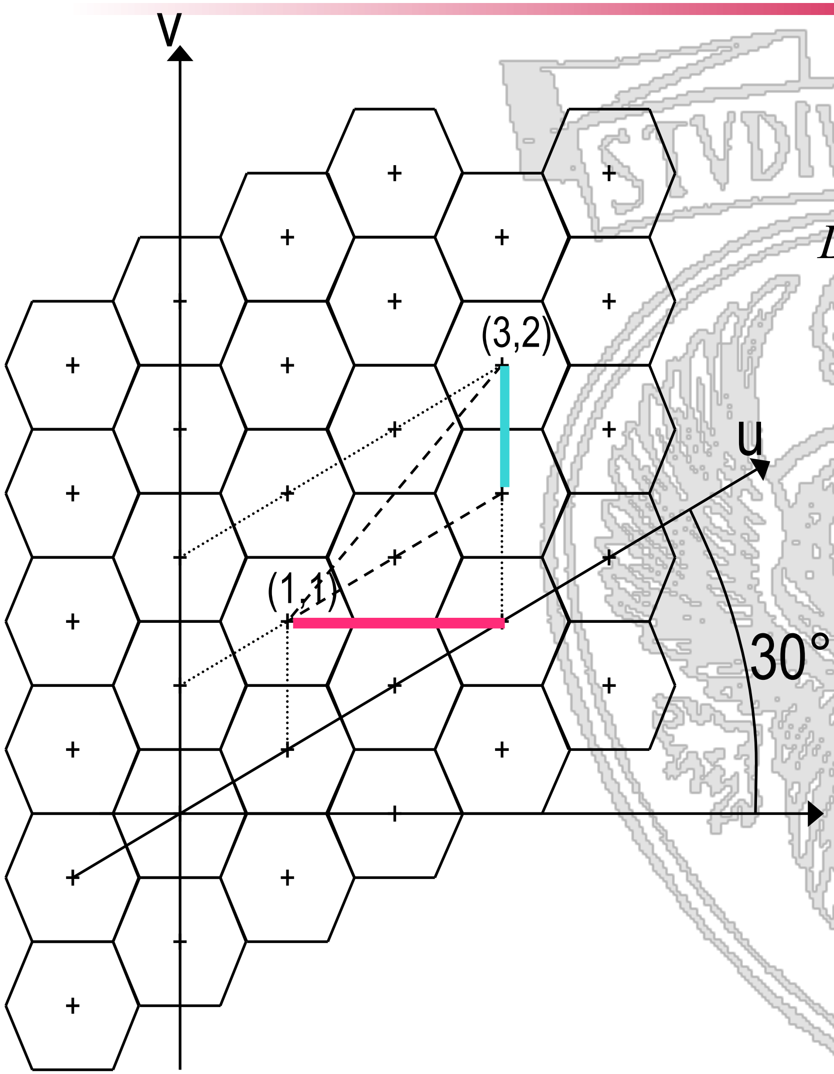
  - Cluster: easy to see that

$$K=D_R^2=i^2+j^2+ij$$

  - hence:

$$D=R\sqrt{3K}$$

Proof



- Distance between two cell centers:
  - $(u_1,v_1) \leftarrow\rightarrow (u_2,v_2)$

$$D = \sqrt{\left[(u_2 - u_1)\cos 30^o\right]^2 + \left[(v_2 - v_1) + (u_2 - u_1)\sin 30^o\right]^2}$$

  - Simplifies to:

$$D = \sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2 + (u_2 - u_1)(v_2 - v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D = \sqrt{i^2 + j^2 + ij}\sqrt{3}R$$

$$D_R = \sqrt{i^2 + j^2 + ij}$$

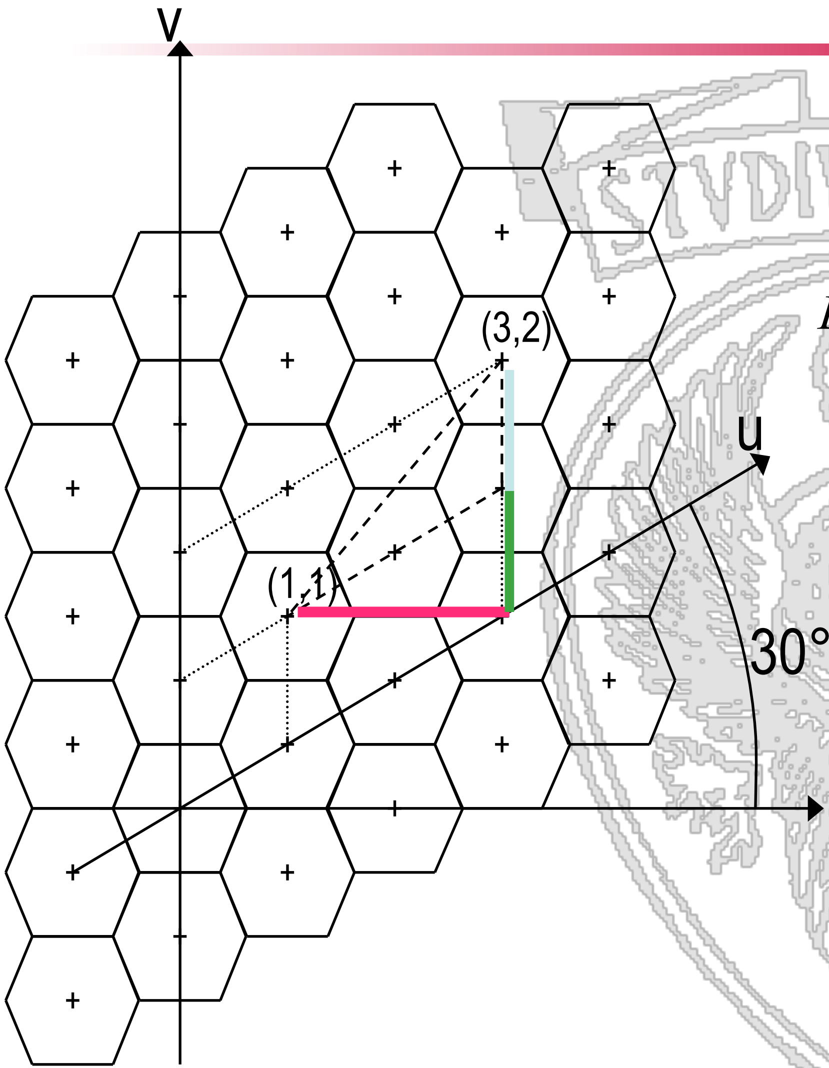
  - Cluster: easy to see that

$$K = D_R^2 = i^2 + j^2 + ij$$

  - hence:

$$D = R\sqrt{3K}$$

Proof



- Distance between two cell centers:
  - $(u_1,v_1) \leftrightarrow (u_2,v_2)$

$$D = \sqrt{\left[(u_2-u_1)\cos 30^o\right]^2 + \left[(v_2-v_1) + (u_2-u_1)\sin 30^o\right]^2}$$

  - Simplifies to:

$$D = \sqrt{(u_2-u_1)^2 + (v_2-v_1)^2 + (u_2-u_1)(v_2-v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D = \sqrt{i^2 + j^2 + ij}\sqrt{3}R$$

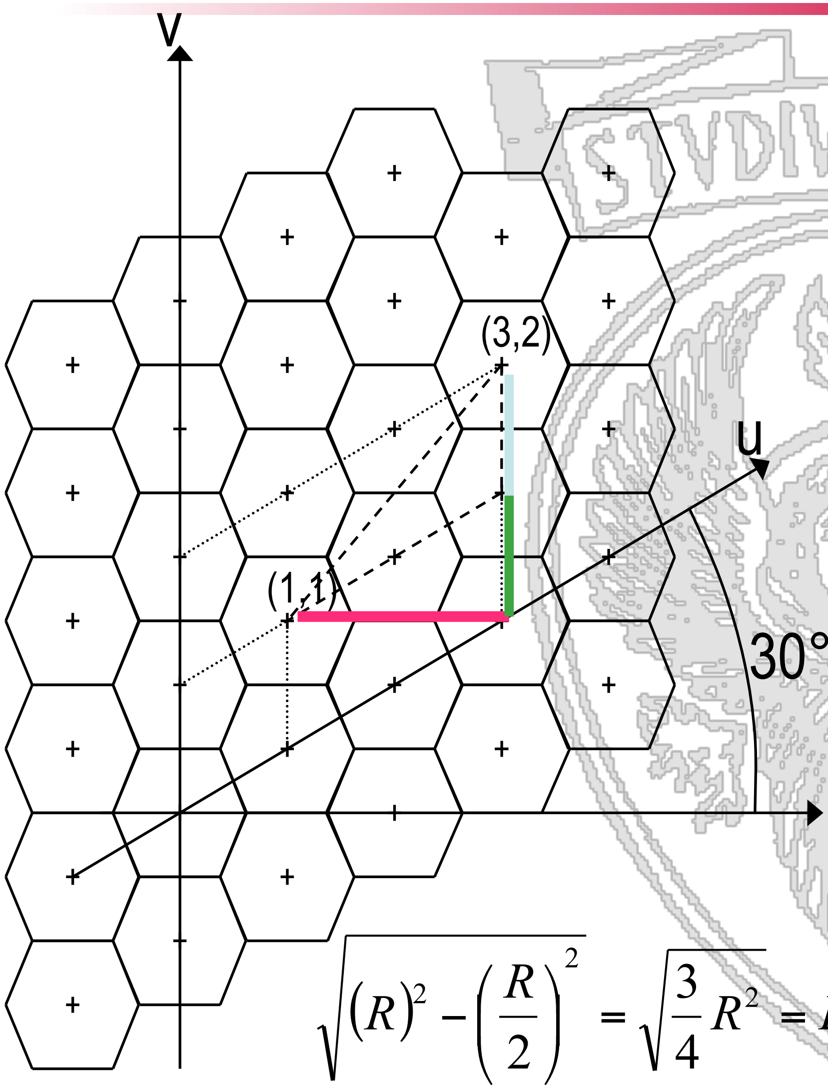
$$D_R = \sqrt{i^2 + j^2 + ij}$$

  - Cluster: easy to see that

$$K = D_R^2 = i^2 + j^2 + ij$$

  - hence: $D = R\sqrt{3K}$

Proof



$$\sqrt{(R)^2 - \left(\frac{R}{2}\right)^2} = \sqrt{\frac{3}{4}R^2} = R\frac{\sqrt{3}}{2}$$

- Distance between two cell centers:
  - $(u_1,v_1) \leftarrow\rightarrow (u_2,v_2)$

$$D = \sqrt{\left[(u_2-u_1)\cos 30^o\right]^2 + \left[(v_2-v_1)+(u_2-u_1)\sin 30^o\right]}$$

  - Simplifies to:

$$D = \sqrt{(u_2-u_1)^2 + (v_2-v_1)^2 + (u_2-u_1)(v_2-v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D = \sqrt{i^2 + j^2 + ij}\sqrt{3}R$$

Distance Between centers Of adjacent clusters

$$D_R = \sqrt{i^2 + j^2 + ij}$$

  - Cluster: easy to see that

$$K = D_R^2 = i^2 + j^2 + ij$$

$$D = R\sqrt{3K}$$

- Distance between two cell centers:
  - $(u_1,v_1) \leftrightarrow (u_2,v_2)$

$$D=\sqrt{\left[(u_2-u_1)\cos 30^o\right]^2+\left[(v_2-v_1)+(u_2-u_1)\sin 30^o\right]^2}$$

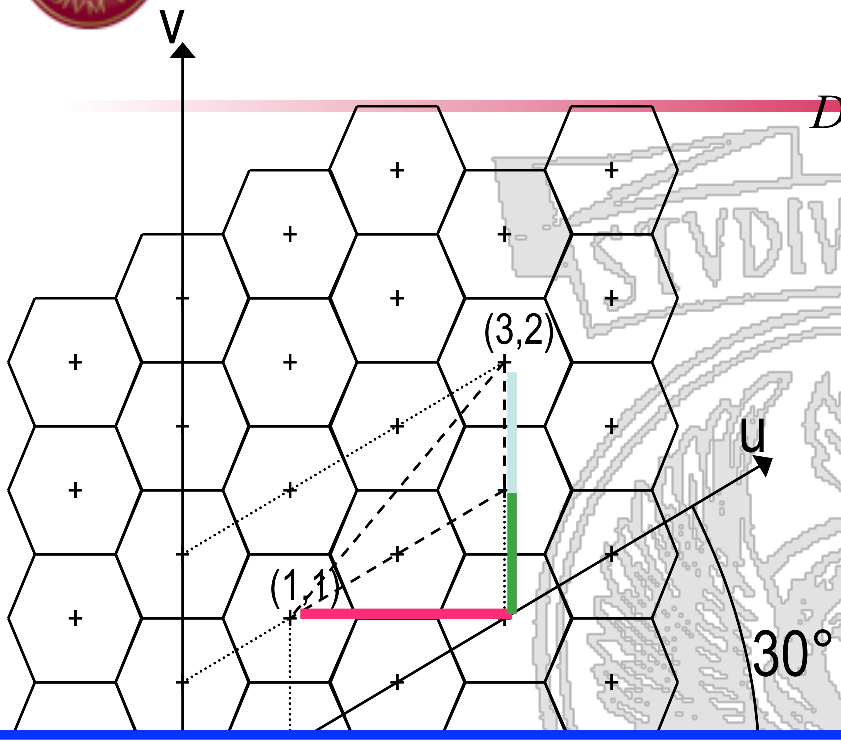
  - Simplifies to:

$$D=\sqrt{(u_2-u_1)^2+(v_2-v_1)^2+(u_2-u_1)(v_2-v_1)}$$

  - Distance of cell (i,j) from (0,0):

$$D=\sqrt{i^2+j^2+ij}\sqrt{3}R$$

Distance Between centers Of adjacent clusters



If R is the radius of a hexagon, half the distance between two adjacent hexagonal cells is

$$\sqrt{(R)^2-\left(\frac{R}{2}\right)^2}=\sqrt{\frac{3}{4}R^2}=R\frac{\sqrt{3}}{2}$$

So the distance between two adjacent cells is 2 times this amount!

SAPIENZA
UNIVERSITÀ DI ROMA

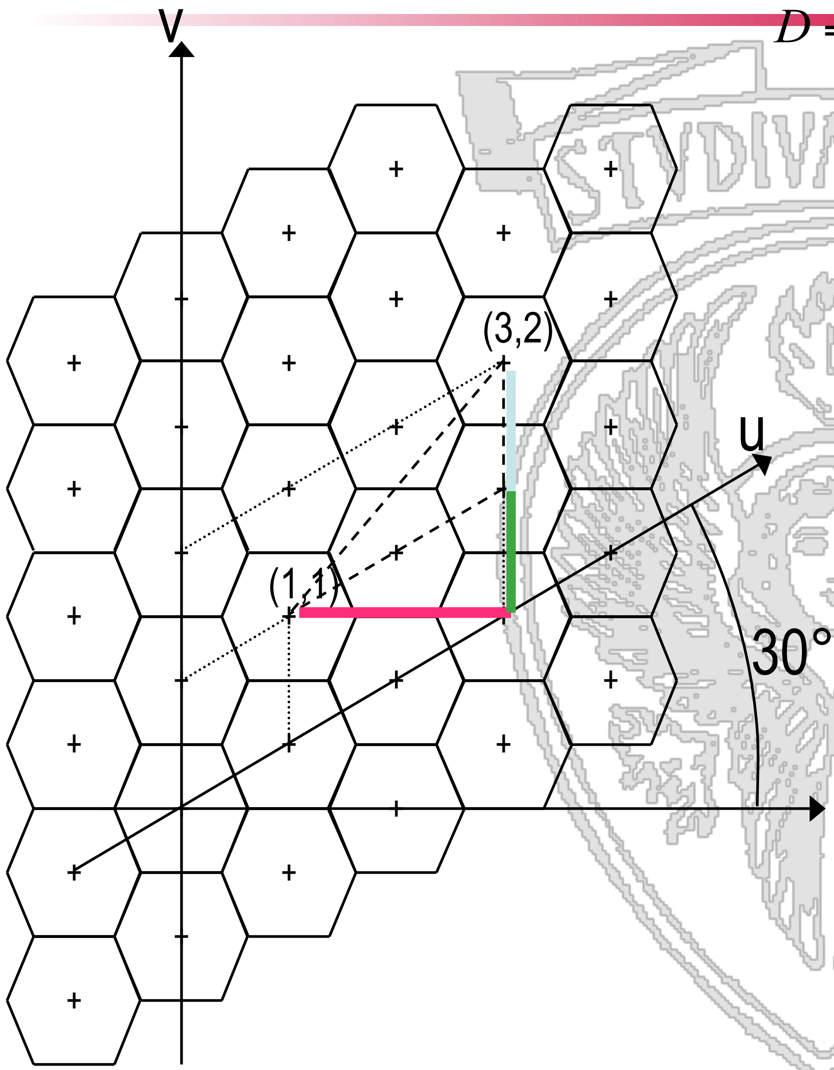
Proof

- Distance between two cell centers:
  - $(u_1,v_1) \leftrightarrow (u_2,v_2)$

$$D = \sqrt{\left[(u_2-u_1)\cos 30^o\right]^2 + \left[(v_2-v_1)+(u_2-u_1)\sin 30^o\right]^2}$$

  - Simplifies to:

$$D = \sqrt{(u_2-u_1)^2 + (v_2-v_1)^2 + (u_2-u_1)(v_2-v_1)}$$



  - Distance of cell (i,j) from (0,0):

$$D = \sqrt{i^2 + j^2 + ij}\sqrt{3}R$$

$$D_R = \sqrt{i^2 + j^2 + ij}$$ (we are defining D_R)

  - Cluster: possible to see that

$$K = D_R^2 = i^2 + j^2 + ij$$

$$K = D^2 / 3R^2$$

  - hence:

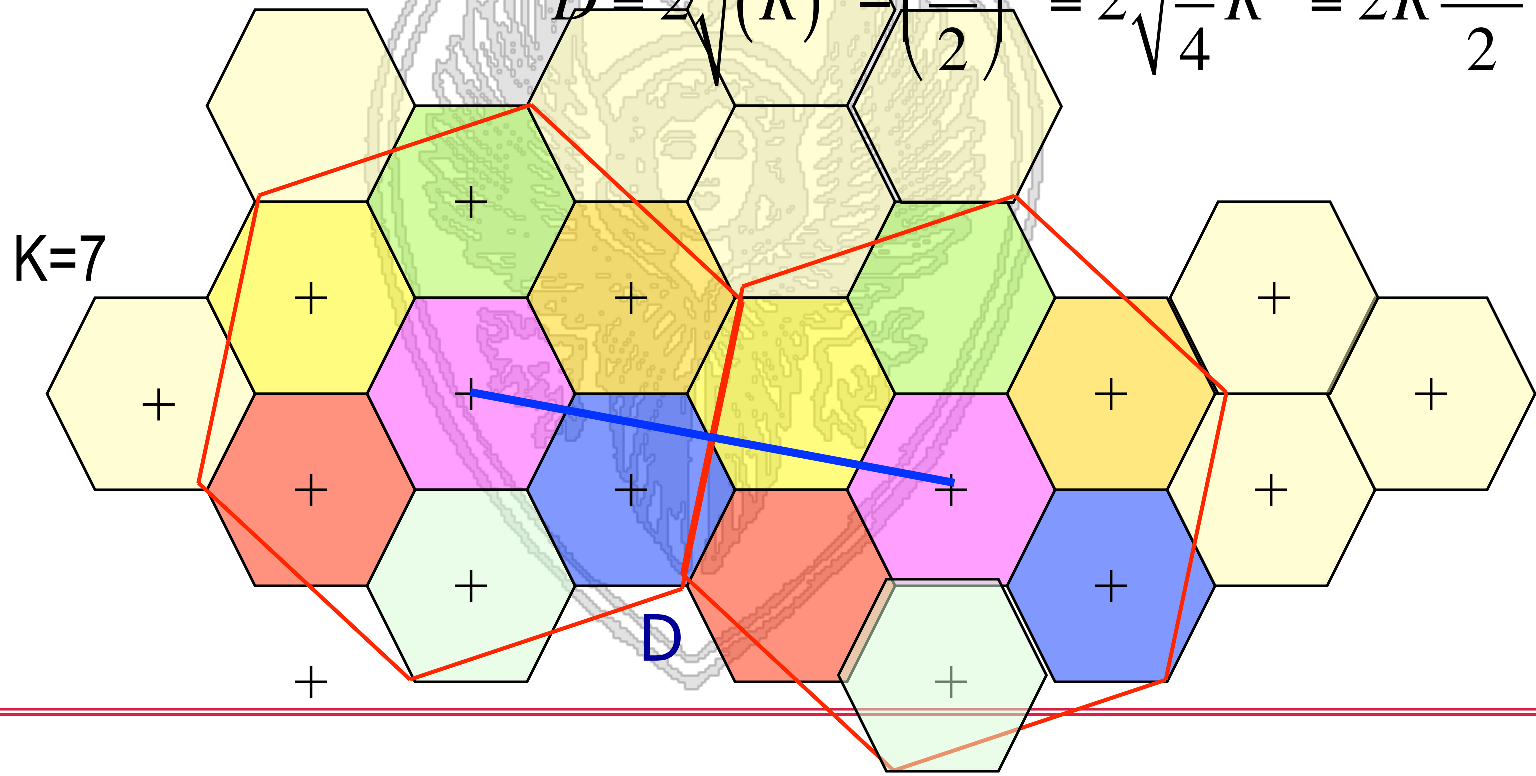
$$D = R\sqrt{3K}$$

Proof

$$K = D_R^2 = i^2 + j^2 + ij$$

- Let us focus on a cell using a set of carriers A
- We cover the area with "clusters of cells" providing the pattern for frequency reuse
- Let D be the fixed distance between the centers of interfering cells in adjacent clusters
- We can approximate the area of each cluster with the area of a hexagon whose radius is given by $D/\sqrt{3}$

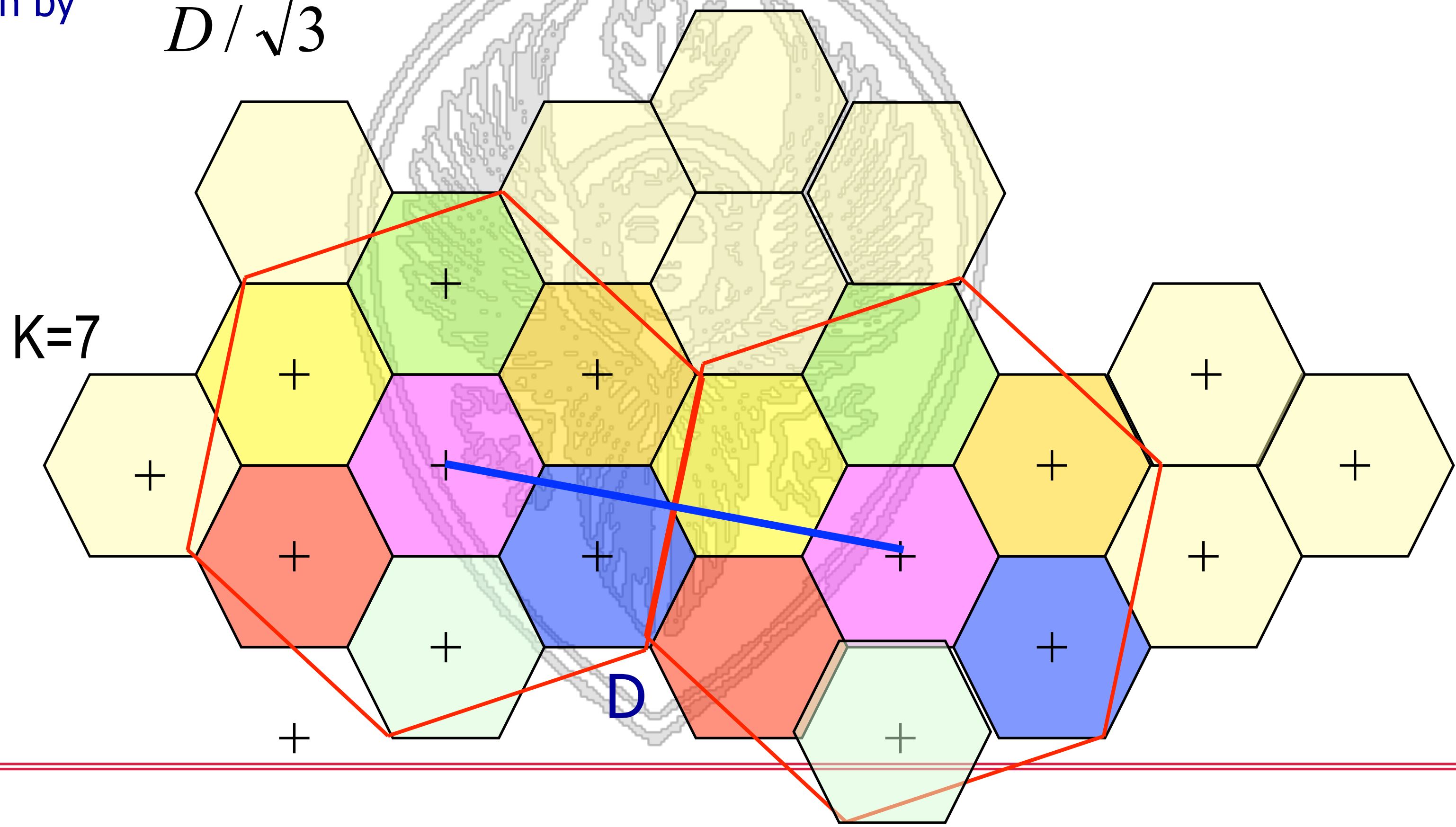
$$D = 2\sqrt{(R)^2 - \left(\frac{R}{2}\right)^2} = 2\sqrt{\frac{3}{4}R^2} = 2R\frac{\sqrt{3}}{2} = R\sqrt{3}$$



Proof

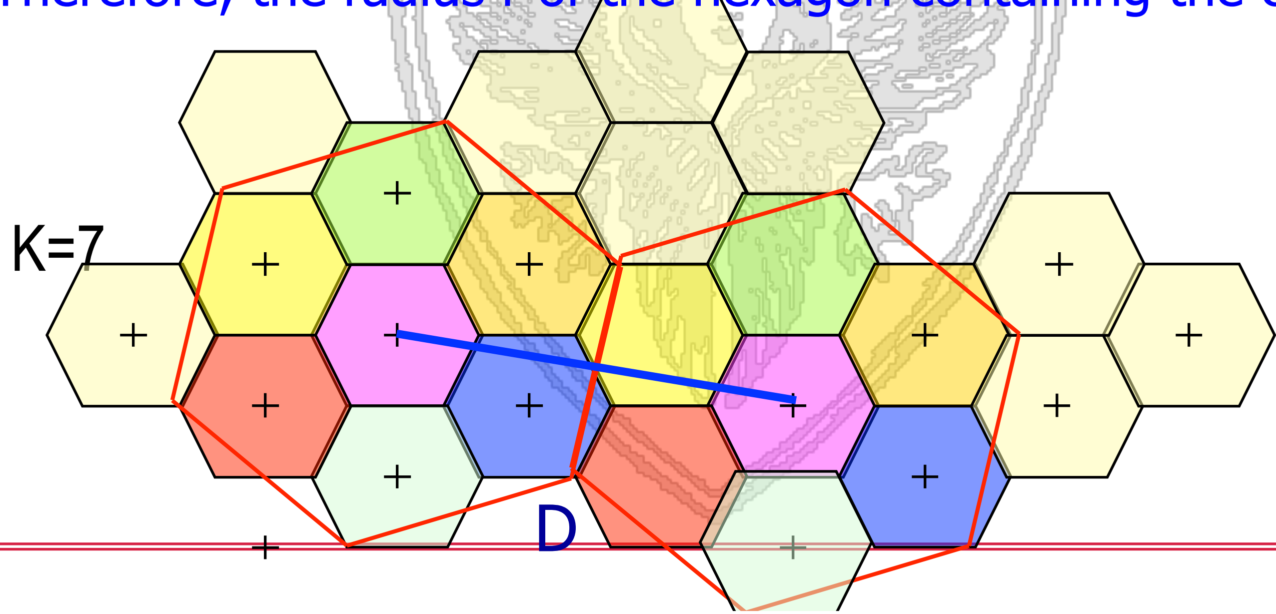
$$K = D_R^2 = i^2 + j^2 + ij$$

- Let us focus on a cell using a set of carriers A
- We cover the area with "clusters of cells" providing the pattern for frequency reuse
- Let D be the fixed distance between the centers of interfering cells in adjacent clusters
- We can approximate the area of each cluster with the area of a hexagon whose radius is given by $D / \sqrt{3}$



Proof

- We can approximate the area of each cluster with the area of a hexagon whose radius is given by $D/\sqrt{3}$
- if the radius of a hexagonal cell is r, the distance between the centers of two adjacent hexagons is $d = \sqrt{3}r$
- The distance between the centers of adjacent clusters is defined as D
- Therefore, the radius r of the hexagon containing the cluster is $D/\sqrt{3}$



Proof

- The area occupied by a cluster A is then given by:

$$\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}$$

- How many hexagons of area $\frac{3}{2}(R)^2\sqrt{3}$

may be in an area equal to $\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}$?

- Answer:

$$K = \frac{A_{cluster}}{A_{cella}} = \frac{\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}}{\frac{3}{2}(R)^2\sqrt{3}} = \left(\frac{D}{R\sqrt{3}}\right)^2 = (D_R)^2$$

$$K = \left(\frac{D}{R\sqrt{3}}\right)^2 = \frac{D^2}{3R^2} \Rightarrow D = \sqrt{3KR^2} = \boxed{R\sqrt{3K}}$$

Proof

- The area occupied by a cluster A is then given by:

$$\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}$$

- How many hexagons of area $\frac{3}{2}(R)^2\sqrt{3}$

may be in an area equal to $\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}$?

Since:

$$D=\sqrt{i^2+j^2+ij}\sqrt{3}R$$

$$D_R=\sqrt{i^2+j^2+ij}$$

- Answer:

$$K=\frac{A_{cluster}}{A_{cella}}=\frac{\frac{3}{2}\left(\frac{D}{\sqrt{3}}\right)^2\sqrt{3}}{\frac{3}{2}(R)^2\sqrt{3}}=\left(\frac{D}{R\sqrt{3}}\right)^2=(D_R)^2$$

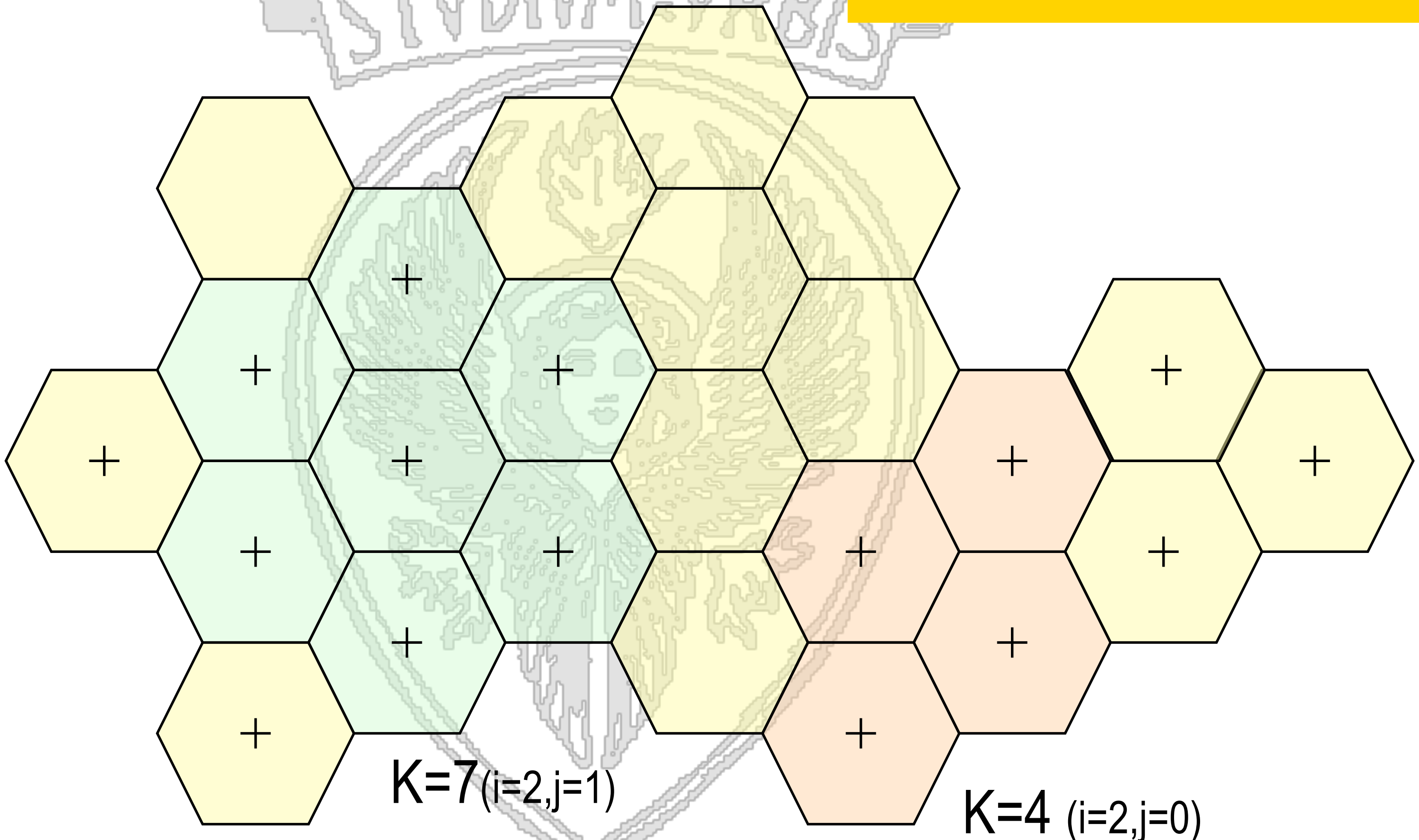
$$K=\left(\frac{D}{R\sqrt{3}}\right)^2=\frac{D^2}{3R^2}$$

$$\Rightarrow\quad D=\sqrt{3KR^2}=R\sqrt{3K}$$

SAPIENZA
UNIVERSITÀ DI ROMA

Clusters

$$K = D_R^2 = i^2 + j^2 + ij$$



SAPIENZA
UNIVERSITÀ DI ROMA

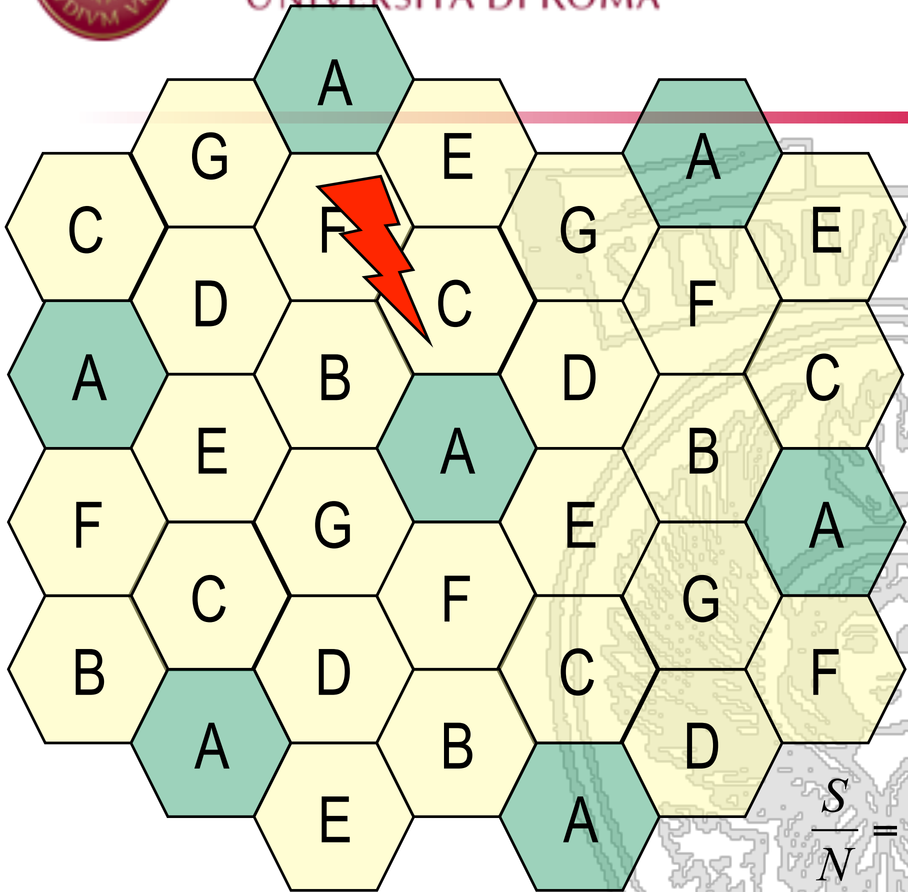
Possible clusters

all integer i,j values

i	j	K=ii+jj+ij	q=D/R
1	0	1	1,73
1	1	3	3,00
2	0	4	3,46
2	1	7	4,58
2	2	12	6,00
3	0	9	5,20
3	1	13	6,24
3	2	19	7,55
3	3	27	9,00
4	0	16	6,93
4	1	21	7,94
4	2	28	9,17
4	3	37	10,54
4	4	48	12,00
5	0	25	8,66
5	1	31	9,64

Feasible cluster sizes: 1,3,4,7,9,12,13,16,…

Co-Channel Interference



- Frequency reuse implies that remote cells interfere with tagged one
- Co-Channel Interference (CCI)
  - sum of interference from remote cells

$$\frac{S}{N} = \frac{\text{signal power (S)}}{\text{noise power } (\mathrm{N_S}) + \text{interfering signal power (I)}}$$

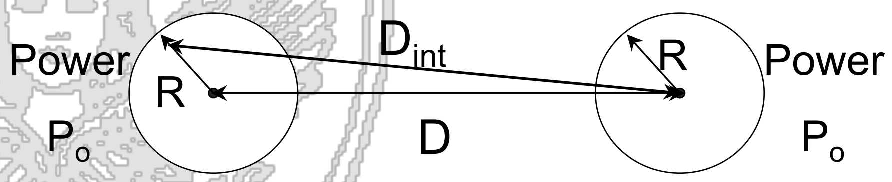
$$\frac{S}{I} = \frac{\text{signal power (S)}}{\text{interfering signal power (I)}}$$

$$\frac{S}{N} \approx \frac{S}{I} \quad \text{as } \mathrm{N_S} \text{ small}$$

CCI Computation – assumptions

- Assumptions
  - N_I=6 interfering cells
    - ✓ N_I=6: first ring interferers only
    - ✓ we neglect second-ring interferers
  - Negligible Noise N_S
    - ✓ S/N ~ S/I
  - $d^{-\eta}$ propagation law
    - ✓ η=4 (in general)
  - Same parameters for all BSs
    - ✓ Same P_{tx}, antenna gains, etc

- Key simplification
  - Signal for MS at distance R
  - Signal from BS interferers at distance D



$D_{int} \sim D$

CCI computation

$$\frac{S}{N} \approx \frac{S}{I} = \frac{\text{cost}\cdot R^{-\eta}}{\sum_{k=1}^{N_I} \text{cost}\cdot D^{-\eta}} =$$

By using the assumptions of same cost and same D:

$$= \frac{1}{N_I}\left(\frac{R}{D}\right)^{-\eta} = \frac{1}{N_I}\left(\frac{D}{R}\right)^{\eta} = \frac{1}{N_I} q^{\eta}$$

Results depend

on ratio q=D/R

(q=frequency reuse factor)

Alternative expression: recalling that $D = R\sqrt{3K}$

$$\frac{S}{N} \approx \frac{S}{I} = \frac{1}{N_I}\left(\frac{R}{R\sqrt{3K}}\right)^{-\eta} = \frac{1}{N_I}(3K)^{\eta/2} = \frac{(3K)^{\eta/2}}{6}$$

$N_I=6, \eta=4 \rightarrow \frac{S}{I} = \frac{(3K)^2}{6} = \frac{3}{2}K^2$

USAGE: Given an S/I target, cluster size K is obtained

Examples

$$\frac{S}{N} \approx \frac{S}{I} = \frac{(3K)^{\eta/2}}{6}$$

- target conditions:
  - S/I=9 dB
  - η=4
- Solution:

$$\frac{S}{I} = 10^{0.9} = 7.94 \approx 8$$

$$\left.\frac{S}{I} = \frac{(3K)^{\eta/2}}{6}\right|_{\eta=4} \Rightarrow K = \sqrt{\frac{2}{3} \cdot \frac{S}{I}}$$

$$K \geq 2.3 \quad \Rightarrow \quad K = 3$$

- target conditions:
  - S/I= 18dB
  - η=4.2
- Solution:

$$\frac{S}{I}[dB] = 5\eta \log(3K) - 10\log 6$$

$$\log(3K) = \frac{18 + 7.78}{21} = 1.23$$

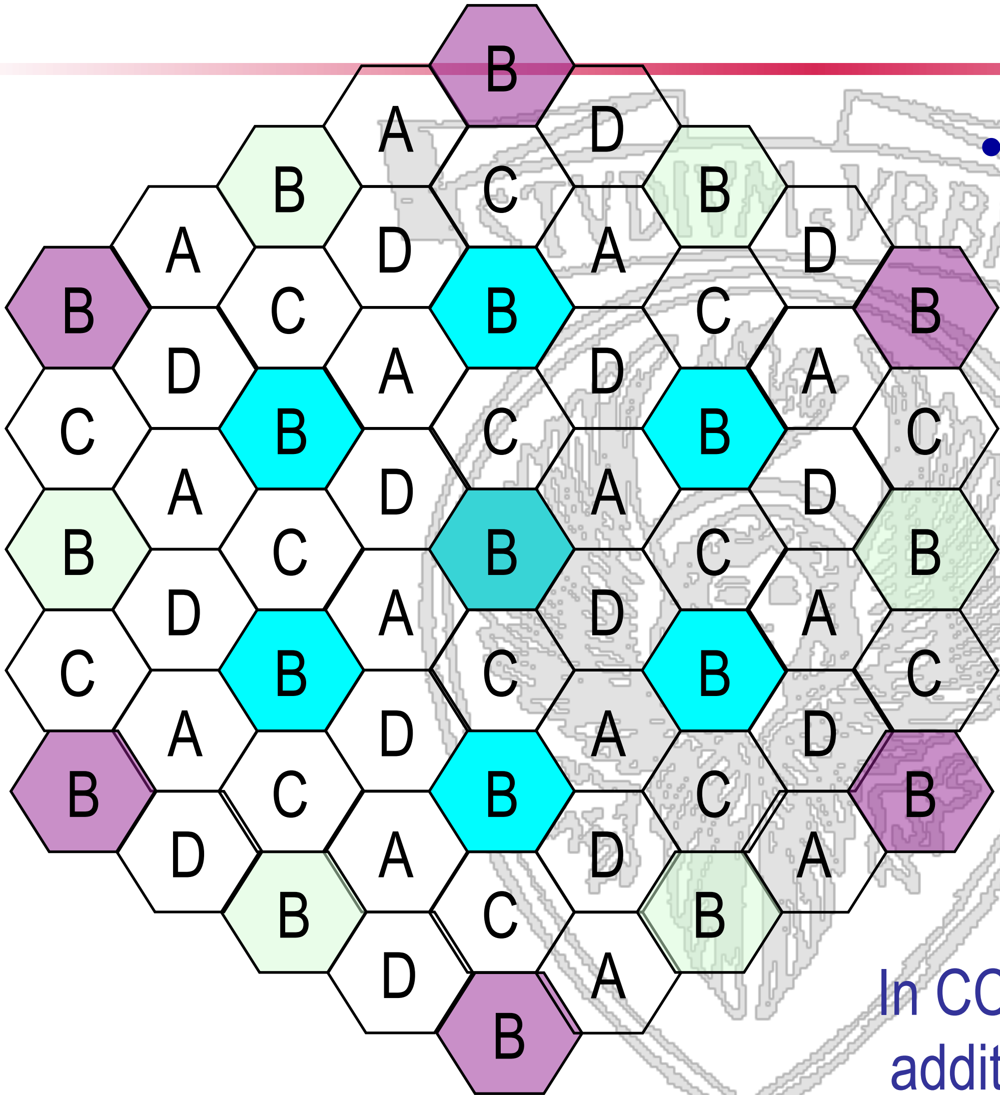
$$K \geq \frac{10^{1.23}}{3} = 5.63 \quad \Rightarrow \quad K = 7$$

S/I computation

assuming 6 interferers only (first ring)

K	q=D/R	S/I	S/I dB
3	3,00	13,5	11,3
4	3,46	24,0	13,8
7	4,58	73,5	18,7
9	5,20	121,5	20,8
12	6,00	216,0	23,3
13	6,24	253,5	24,0
16	6,93	384,0	25,8
19	7,55	541,5	27,3
21	7,94	661,5	28,2
25	8,66	937,5	29,7

Additional interferers



- case K=4
  - note that for each cluster there are always N_I=6 first-ring interferers

In CCI computation, contribute of additional interferers is marginal

Multiple Tiers of Interferers

- First tier of interferers are at distance D; secondtier at distance 2D; third tier at distance 3D etc.

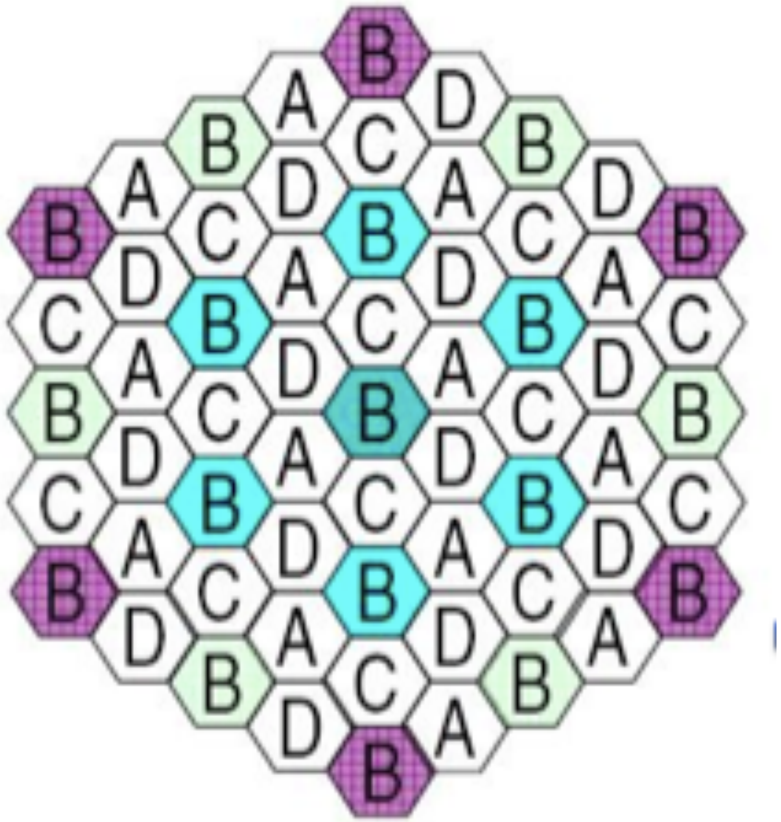
approximation

- Often interferers have a significant impact only if they belong to the first tier

- General formula:

$$SIR = \frac{R^{-\eta}}{N_{I1}(D)^{-\eta} + N_{I2}(2D)^{-\eta} + N_{I3}(3D)^{-\eta}}$$

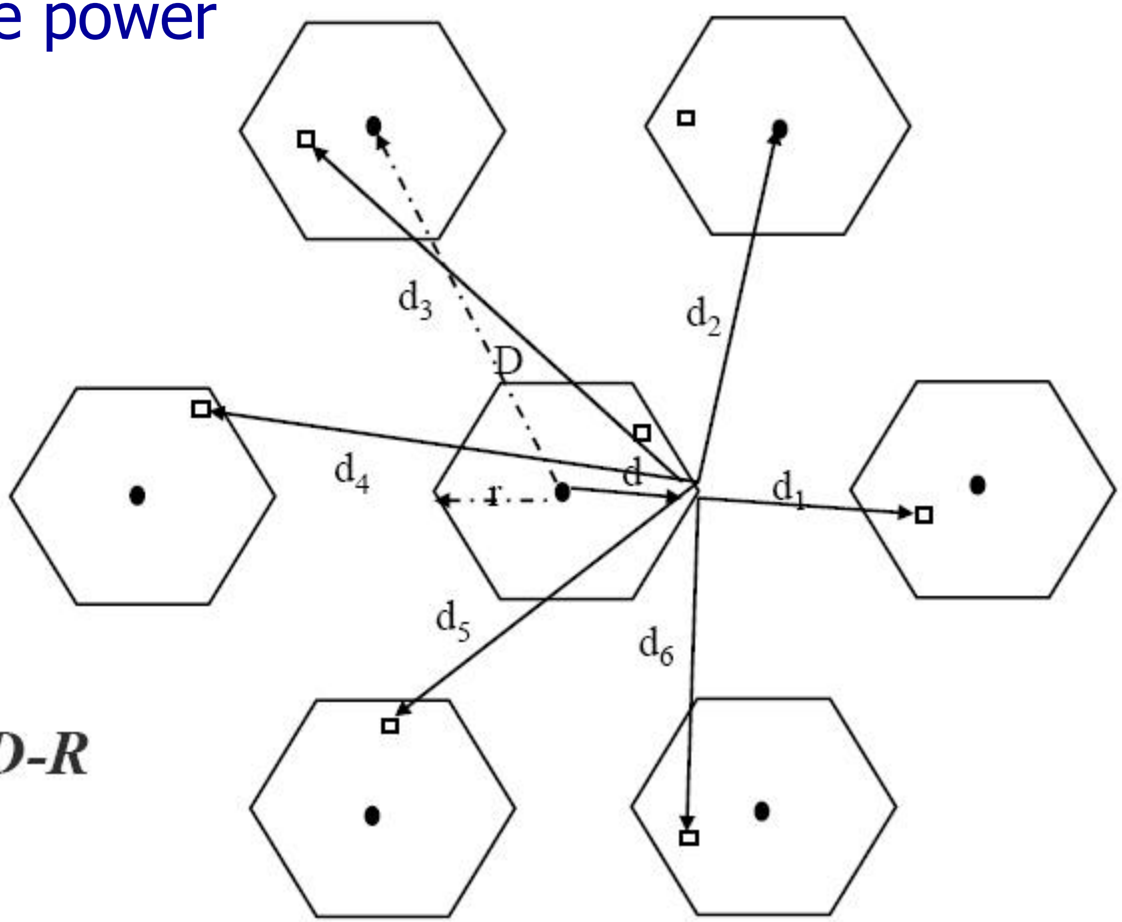
- NIi=number of interefers belonging to the i-th tier



Special case of co-channel interference

Same antennas and same power

$$SIR = \frac{P_t \cdot G \cdot d^{-\eta}}{\sum_{i=1}^{6} P_t \cdot G \cdot d_i^{-\eta}} = \frac{d^{-\eta}}{\sum_{i=1}^{6} d_i^{-\eta}}$$

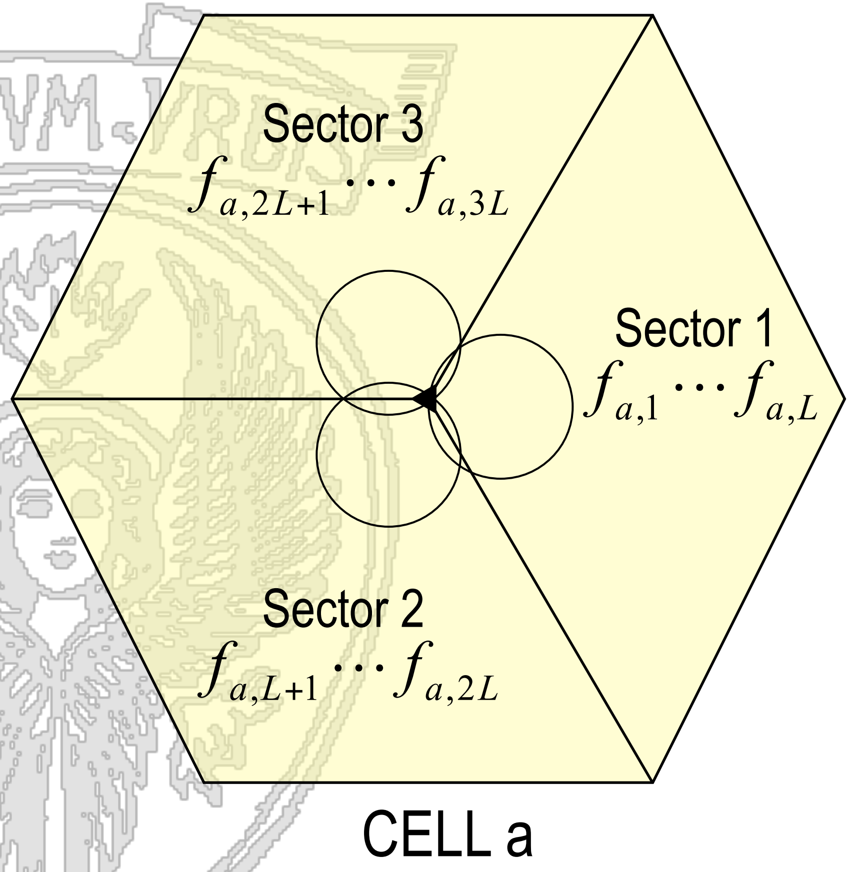


- Worst case: d=r
- Approximation: $d_i = D\text{-}R$

$$SIR = \frac{R^{-\eta}}{6(D\text{-}R)^{-\eta}}$$

Sectorization

- Directional antennas
- Cell divided into sectors
- Each sector uses different frequencies
  - To avoid interference at sector borders
- PROS:
  - CCI reduction
- CONS:
  - Increased handover rate
  - Less effective "trunking" leads to performnce impairments

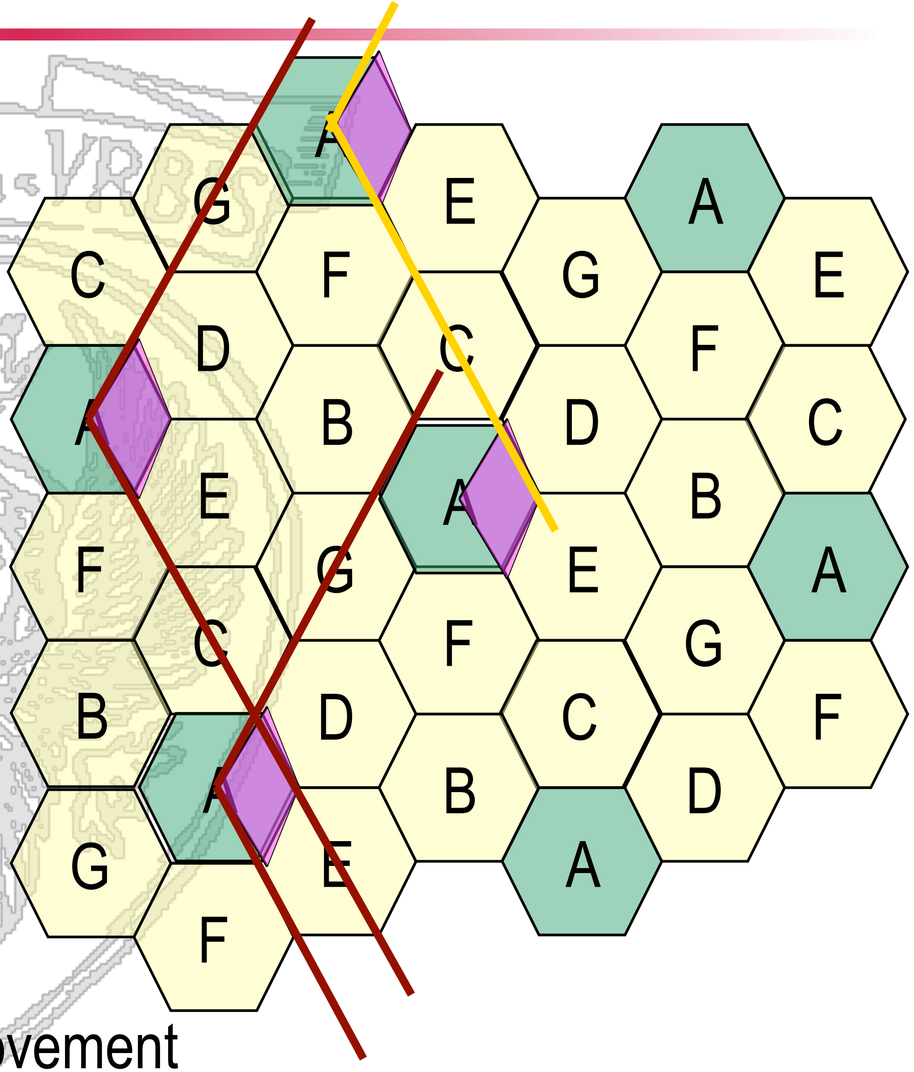


SAPIENZA
UNIVERSITÀ DI ROMA

CCI reduction via sectorization

three sectors case

- Inferference from 2 cells, only
  - Instead of 6 cells



With usual approxs

(specifically, $D_{int} \sim D$)

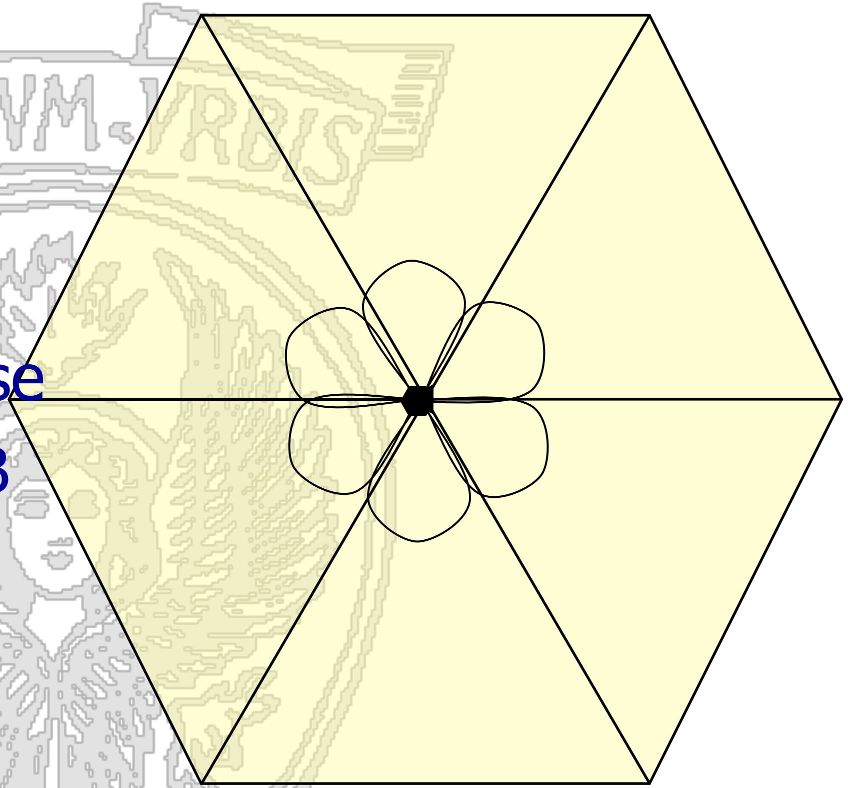
$$\left[\frac{S}{I}\right]_{120^o} = \frac{R^{-\eta}}{2D^{-\eta}} = 3\cdot\left[\frac{S}{I}\right]_{omni}$$

$$\left[\frac{S}{I}\right]_{120^o} dB = \left[\frac{S}{I}\right]_{omni} dB + 4.77$$

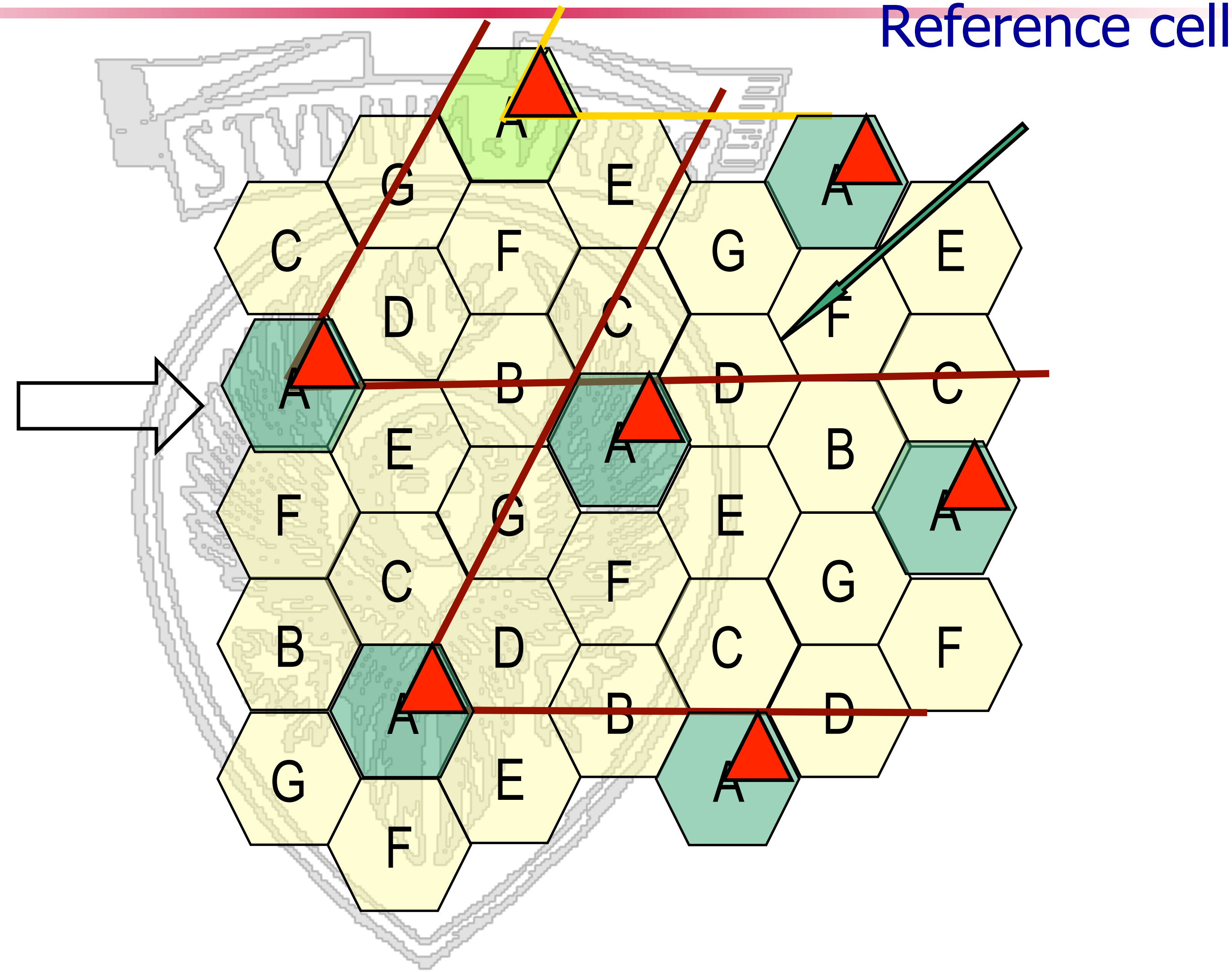
Conclusion: 3 sectors = 4.77 dB improvement

6 sectors

- 60° Directional antennas
- CCI reduction:
  - 1 interfereer only
  - 6 x S/I in the omni case
  - Improvement: 7.78 dB



6 sectors



Only BS which disturbs receptions / transmissions to / from MU in the reference cell

Cellular systems: Planning

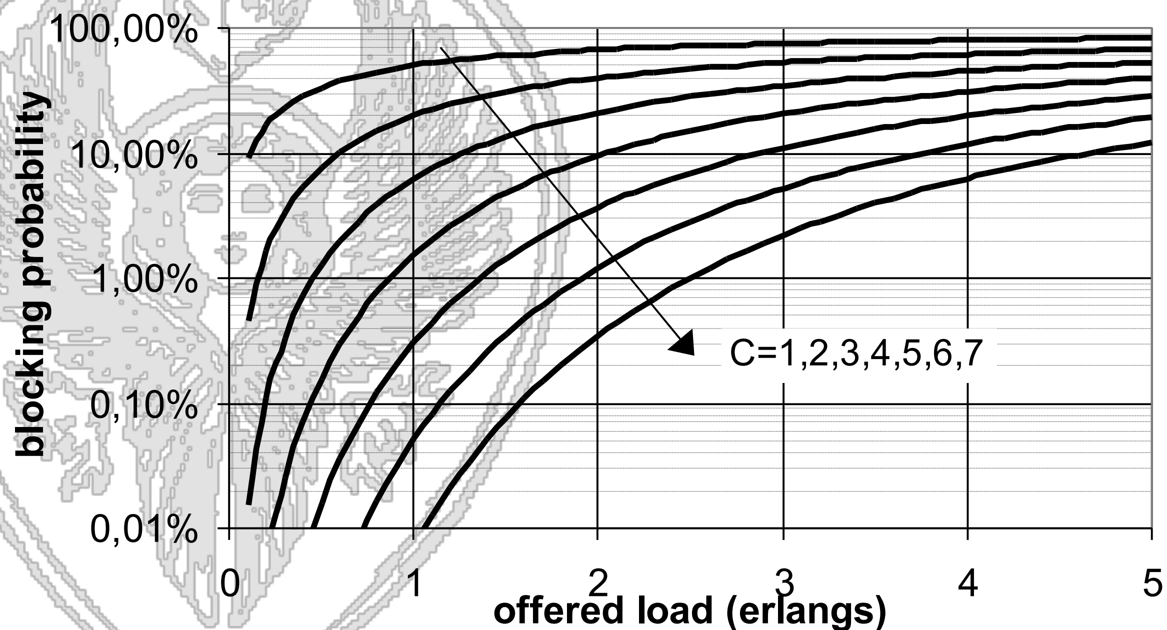
Blocking probability: Erlang-B

- Fundamental formula for telephone networks planning
  - A_o=offered traffic in Erlangs

$$\Pi_{block} = \frac{\frac{A_o^C}{C!}}{\sum_{j=0}^{C} \frac{A_o^j}{j!}} = E_{1,C}(A_o)$$

➔ Efficient recursive computation available

$$E_{1,C}(A_o) = \frac{A_o E_{1,C-1}(A_o)}{C + A_o E_{1,C-1}(A_o)}$$

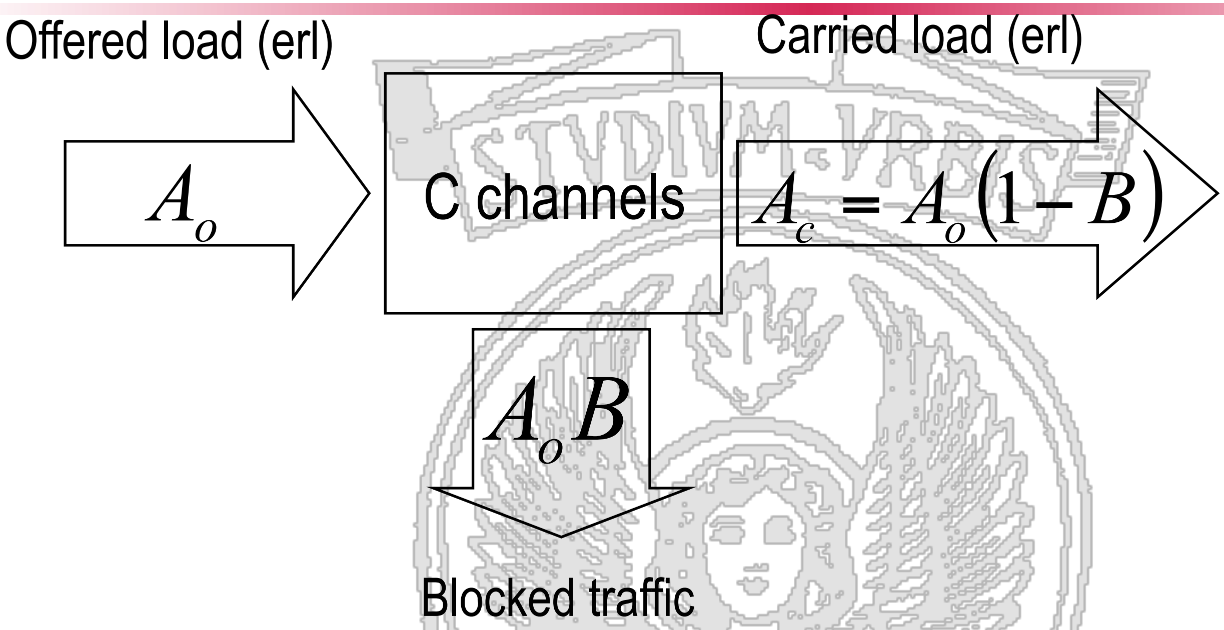


Capacity planning

- Target: support users with a given Grade Of Service (GOS)
  - GOS expressed in terms of upper-bound for the blocking probability
    - ✓ GOS example: subscribers should find a line available in the 99% of the cases, i.e. they should be blocked in no more than 1% of the attempts
- Given:
    - ✓ Offered load A_o
    - ✓ Target GOS B_{target}
  - C (number of channels) is obtained from numerical inversion of

$$B_{\text{target}} = E_{1,C}(A_o)$$

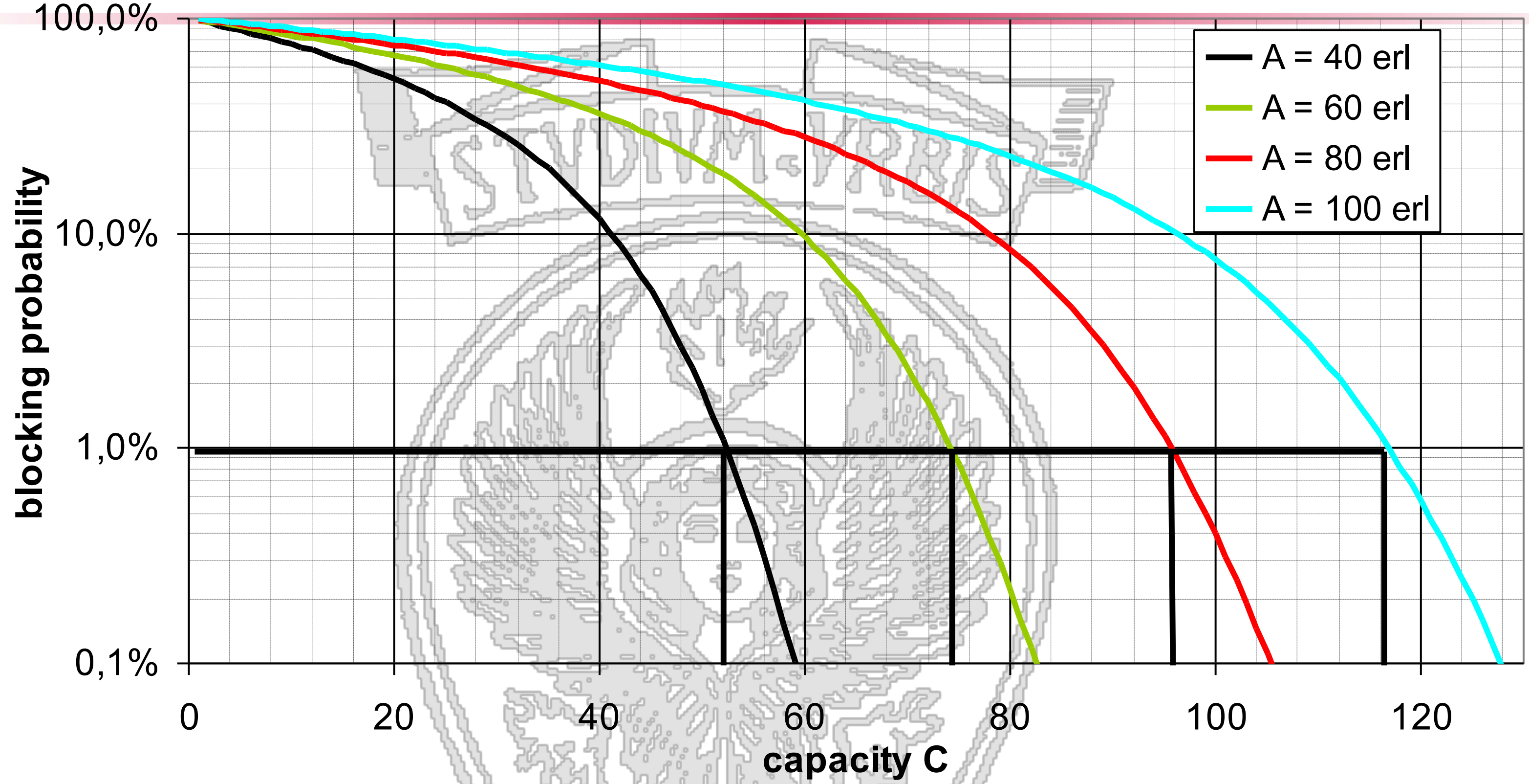
Channel usage efficiency



$$\text{efficiency:} \quad \rho = \frac{A_c}{C} = \frac{A_o\left(1-E_{1,C}(A_o)\right)}{C} \approx \frac{A_o}{C} \text{ if small blocking}$$

Fundamental property: for same GOS, efficiency increases as C grows!!

example



GOS = 1% maximum blocking.

Resulting system dimensioning and efficiency:

40 erl	C >= 53	ρ = 74.9%
60 erl	C >= 75	ρ = 79.3%
80 erl	C >= 96	ρ = 82.6%
100 erl	C >= 117	ρ = 84.6%

Trunking Efficiency

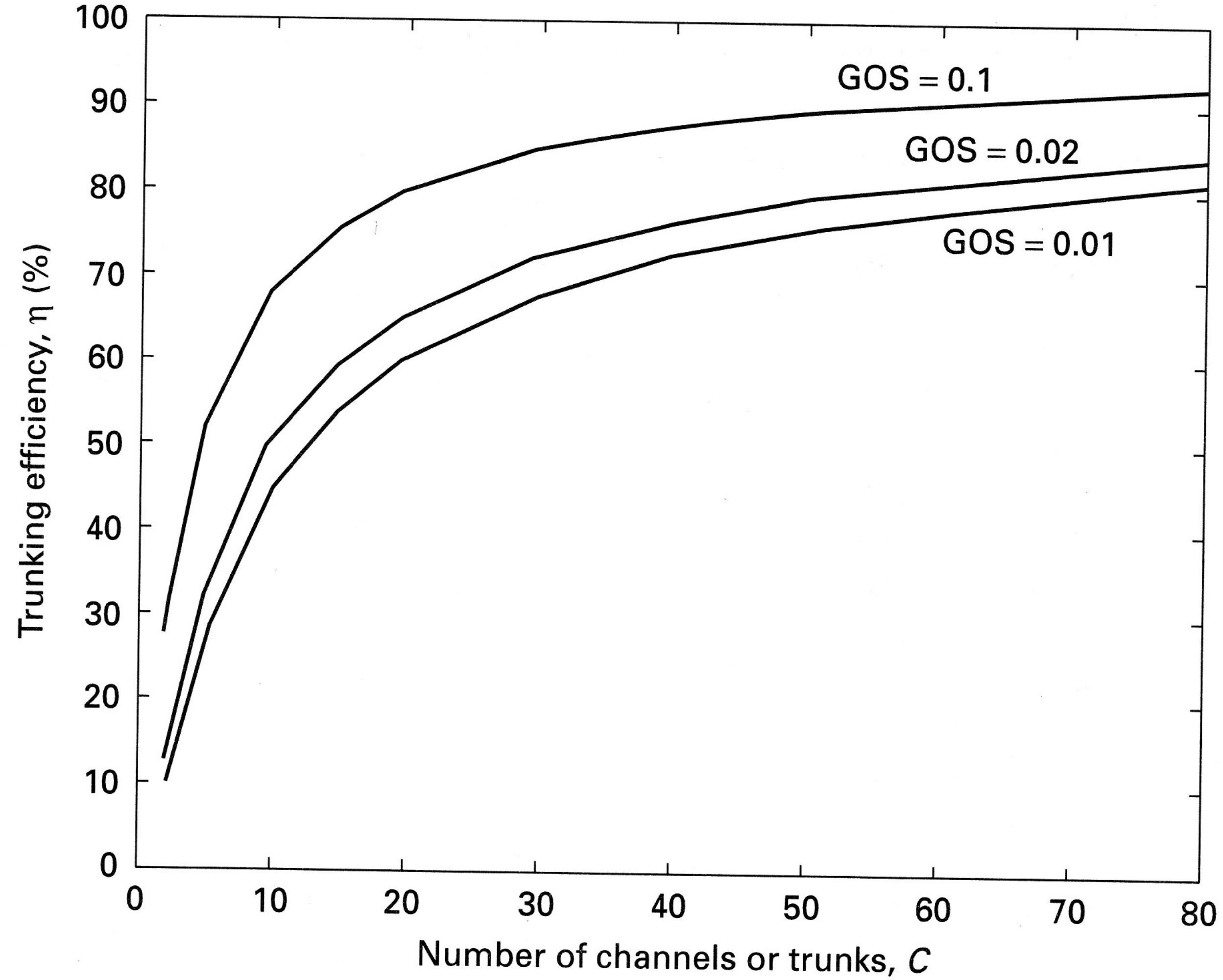


FIGURE 4.21 Trunking efficiency plots.

Erlang B calculation - tables

Example: How many channels are required to support 100 users with a GOS of 2% if the average traffic per user is 30 mE?

100x30mE = 3 Erlangs
3 Erlangs @ 2% GOS =

8 channels

Trunks	0.01	0.015	0.02	0.03
P(B)=				
1	0.010	0.015	0.020	0.031
2	0.153	0.190	0.223	0.282
3	0.455	0.536	0.603	0.715
4	0.870	0.992	1.092	1.259
5	1.361	1.524	1.657	1.877
6	1.913	2.114	2.277	2.544
7	2.503	2.743	2.936	3.250
8	3.129	3.405	3.627	3.987
9	3.783	4.095	4.345	4.748
10	4.462	4.808	5.084	5.529

ErlangB Online calculator:

http://mmc.et.tudelft.nl/~frits/Erlang.htm

Application to cellular networks

Cell size (radius R) may be determined on the basis of traffic considerations

Given a provider with 50 channels available, how many users can be supported
If each user makes an average of 4 calls/hour, each call lasting on average 2 minutes?

- First step:
  - Given num channels and GOS
    - C=50 available channels in a cell
    - Blocking probability<=2%
  - Evaluate maximum cell (offered) load
    - From Erlang-B inversion(tables) A=40.25 erl
- Second step
  - Given traffic generated by each user
    - Each user: 4 calls/busy-hour
    - Each call: 2 min on average
    - A_i=4x2/60=0.1333 erl/user
  - Evaluate max num of users in cell
    - M=40.25/0.1333 ~ 302

Second question: if the user density
Is 500 users/km2 how should we

Set the cell radius?

$$\delta = \frac{M}{\pi R^2} \Rightarrow R = \sqrt{\frac{M}{\pi\delta}}$$

➔ **Third step:**

- ⇨ Given density of users
  - →δ=500 users/km²
- ⇨ Evaluate cell radius
- ⇨ R~438m

It is preferrable
To approximate
With hexagons

- Three service providers are planning to provide cellular service for an urban area. The target GOS is 2% blocking. Users make 3 calls/busy-hour, each lasting 3 minutes in average (A_i=3/20=0.15)
  - Question: how many users can support each provider?
- Provider A configuration: 20 cells, each with 40 channels
- Provider B configuration: 30 cells, each with 30 channels
- Provider C configuration: 40 cells, each with 20 channels

➔ Provider A:

- ⇨ 40 channels/cell
- ⇨ at 2%: A_o=30.99 erl/cell
- ⇨ 619.8 erl-total (20 cells)
- ⇨ M=**4132** overall users

➔ Provider B:

- ⇨ 30 channels/cell
- ⇨ at 2%: A_o=21.93 erl/cell
- ⇨ 657.9 erl-total (30 cells)
- ⇨ M=**4386** overall users

➔ Provider C:

- ⇨ 20 channels/cell
- ⇨ at 2%: A_o=13.18 erl/cell
- ⇨ 527.2 erl-total (40 cells)
- ⇨ M=**3515** overall users

Compare case A with C! The reason is the lower efficiency of 20 channels versus 40

- Three service providers are planning to provide cellular service for an urban area. The target GOS is 2% blocking. Users make 3 calls/busy-hour, each lasting 3 minutes in average (A_i=3/20=0.15)
  - Question: how many users can support each provid
- Provider A configuration: 20 cells, each with 40 channels
- Provider B configuration: 30 cells, each with 30 channels
- Provider C configuration: 40 cells, each with 20 channels

→ Provider A:
- ⇨ 40 channels/cell
- ⇨ at 2%: A_0=30.99 erl/cell
- ⇨ 619.8 erl-total (20 cells)
- ⇨ M=**4132** overall users

→ Provider B:
- ⇨ 30 channels/cell
- ⇨ at 2%: A_0=21.93 erl/cell
- ⇨ 657.9 erl-total (30 cells)
- ⇨ M=**4386** overall users

→ Pr
- ⇨
- ⇨
- ⇨
- ⇨

the fact to have more cells with a few channels (for example, because we have selected a different K) does not port an advantage in terms of system capacity

Compare case A with C! The reason is the lower efficiency of 20

Sectorization and traffic

- Assume cluster K=7
- Omnidirectional antennas: S/I=18.7 dB
- 120^o sectors: S/I=23.4 dB
- 60^o sectors: S/I=26.4 dB

- Sectorization yields to better S/I
- BUT: the price to pay is a much lower trunking efficiency!

- With 60 channels/cell, GOS=1%,
  - Omni: 60 channels A_o=1x46.95= 46.95 erl
    ρ=77.46%
  - 120^o: 60/3=20 channels A_o=3x12.03= 36.09erl
    ρ=59.54%
  - 60^o: 60/6=10 channels A_o=6x4.46= 26.76erl
    ρ=44.15%

Erlang supported per sector

Sectorization and traffic

- Assume cluster K=7
- Omnidirectional antennas: S/I=18.7 dB
- 120° sectors: S/I=23.4 dB
- 60° sectors: S/I=26.4 dB

On the other hand

Lower CCI can allow

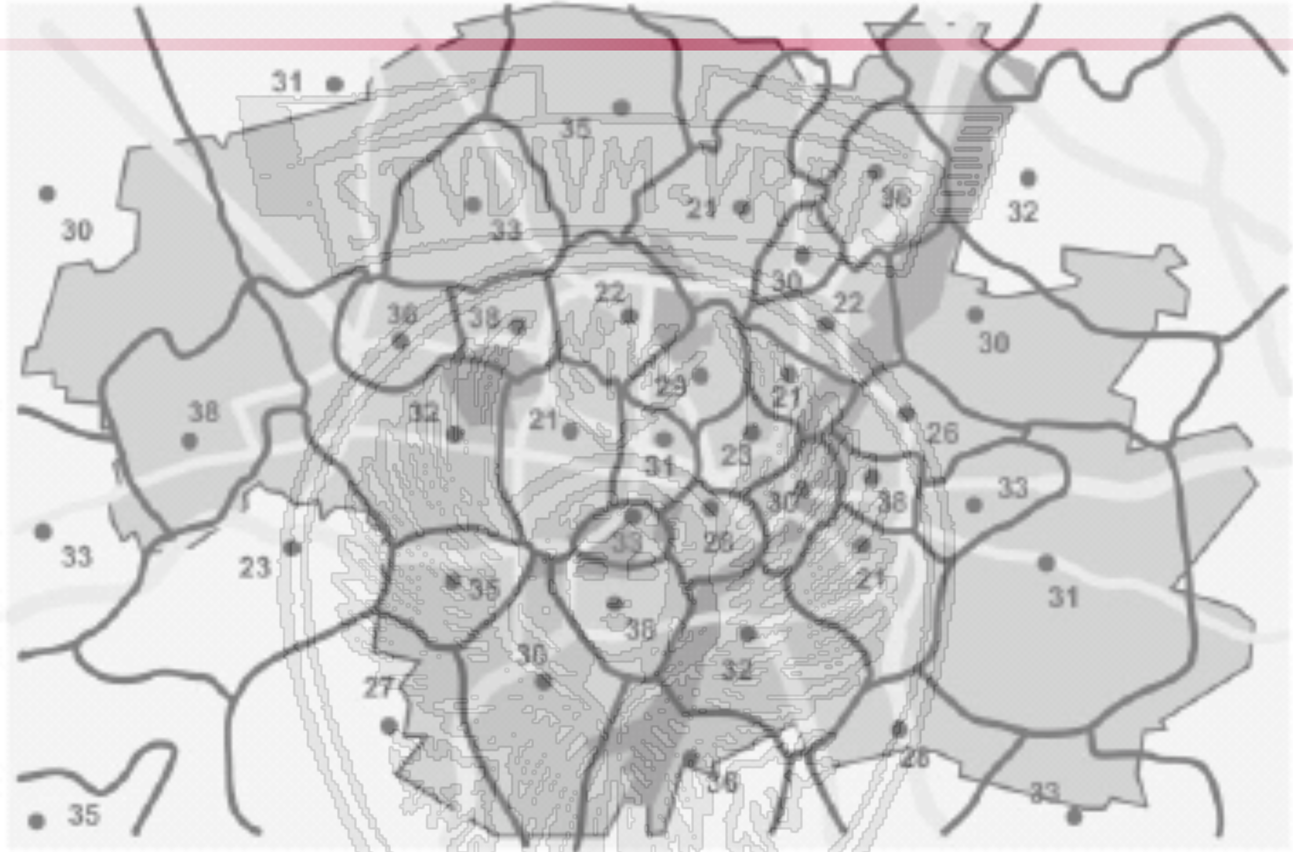
To select a smaller K

- Sectorization yields to better S/I
- BUT: the price to pay is a much lower trunking efficiency!

- With 60 channels/cell, GOS=1%,
  - Omni: 60 channels A_o=1x46.95= 46.95 erl
    ρ=77.46%
  - 120°: 60/3=20 channels A_o=3x12.03= 36.09erl
    ρ=59.54%
  - 60°: 60/6=10 channels A_o=6x4.46= 26.76erl
    ρ=44.15%

Erlang supported per sector

Cells in real world



Shaped by terrain, shadowing, etc

Cell border: local threshold, beyond which neighboring BS signal is received stronger than current one

History of cellular systems

Wireless Systems, a.a. 2014/2015

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

SAPIENZA
UNIVERSITÀ DI ROMA

GSM History (1)

- 1982: CEPT (Conférence Européenne des Administrations des Postes et des Télécommunications) sets up a special group to define a uniform set of rules for the future paneuropean cellular network
  - it was the Groupe Spécial Mobile from which GSM
  - later the acronym has been redefined as Global System for Mobile communications.
- Several analogic cellular systems had been previously developed in different european regions.
  - Lack of interoperability
  - Standardization required

GSM History (2)

- 1985: the group identifies the list of GSM recommendations that will be produced (in the end they will be 130: 1500 pages, 12 volumes! ... Plus all the recommendations dealing with the evolutions of GSM)
- 1986: a permanent group is set up to coordinate GSM standardization;
  - industry driven.

GSM History (3)

- 1987: Telecom operators sign a Memorandum of Understanding (MoU) on behalf of 12 european countries. MoU objectives are to:
  - Coordinate and align in time the development of european GSM networks
  - Verify cellular networks standardization
  - Plan/schedule service introduction
  - Agree on billing and routing policies

GSM History (4)

- 1988: ETSI (European Telecommunication Standards Institute) is established: work on GSM is moved to this forum and continued under the name of SMG-Special Mobile group
- 1990: it is decided that GSM specifications be also applied to DCS1800 (Digital Cellular System on 1800 MHz), a type of PCN (Personal Communication Networks) initially developed in UK
- 1991 (July) the commercial launch of GSM, scheduled for this date is postponed to 1992 due to the lack of compliant mobile terminals

GSM History (5)

- 1992: The final GSM standard is released. GSM becomes an acronym for Global System for Mobile Communications
- 1992: official introduction of GSM business
- 1993, the MoU now gathers 62 members from 39 countries; in addition other 32 organizations representing 19 countries participate as observers waiting to sign the MoU.

GSM History (6)

1994-95: introduction of SMS

1995-97: introduction of services at 1800 MHz and 1900 MHz (USA)

1996 standardization of enhanced coders, both full and half-rate

1997 dual-band terminals with enhanced encoder

1998: 320 GSM networks in 118 countries with 135 million users worldwide

1999: standard GPRS enables packet transmission, first WAP (Wireless Access Protocol) terminals over circuit-switched

2000/01: introduction of GPRS services

2001-2002: EDGE – Enhanced Datarates for GSM Evolution (2,5G)
Standardised in 2001-2002 Introduced in September 2004 – Theoretical data rates up to 373 kbit/s

GSM History (7)

- 1993-2001: GSM cellular network becomes the most widespread in the world, with nearly 80M users in Europe and 200M worldwide (almost 40M only in China), a non-marginal penetration in USA with nearly 10 operators, which have a share of market second only to AMPS (Advanced Mobile Phone Syestem) /D-AMPS. It has de facto become a global standard, affecting significantly the evolution towards 3rd generation networks and helping to determine the commercial failure of the satellite networks
- Mid '00ies: smartphone are introduced, 3G cellular systems are deployed→ multimedia applications start raising
- 2006: 2.18 billion connections in 212 countries. 82% market share globally. An incredible industrial success.

GSM History (8)

- Today: 4G LTE systems deployed in some systems, wireless access globally dominant, LTE-A standardization in progress
- Experts groups and standardization of 5G systems is starting

GSM cellular systems

Wireless Systems, a.a. 2014/2015

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

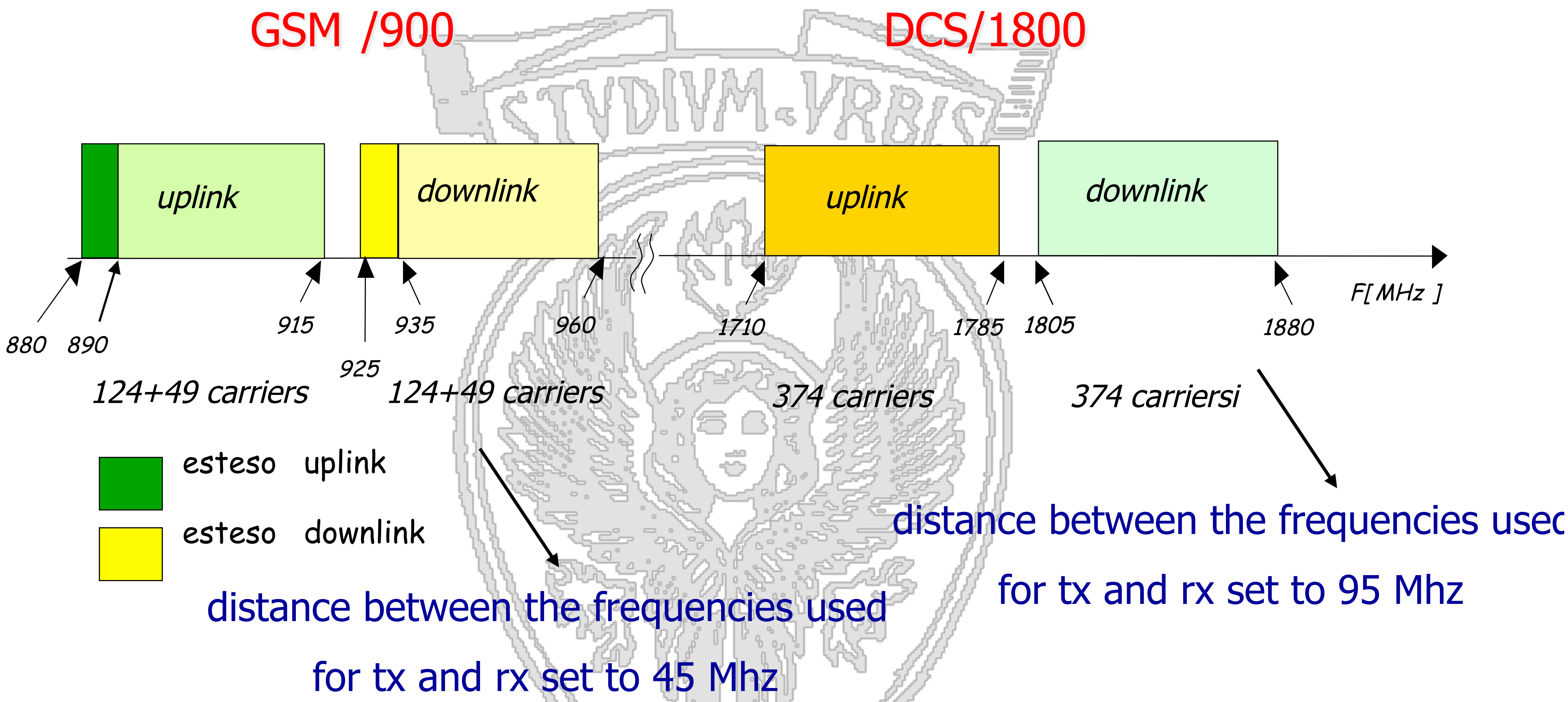
[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

General features

- *2ª* Generation (2G) cellular system
- Carrier bandwidth=200KHz
- Multicarrier TDMA multiple access (8 slots per carrier, thus 8 channels per carrier)→ TDMA/FDMA
- Full Duplex: Frequency Division Duplex (FDD)
- Modulation: GMSK; Spectrum efficiency: 1,35bps/Hz; Gross bit rate per carrier: 270,822 kbit/s
- 13Kbps full rate coder, 6.5Kbps half rate coder
- 992 full rate channels at 900Mhz, 2992 full rate channels for DCS 1800Mhz
- Frequency reuse
- Power control, discontineous transmission
- Adaptive equalization
- Services
  - telephony with many additional services
  - circuit swirching data network (single-channel or multi-channel)
  - packet switching data network (GPRS - General Packet Radio Service)

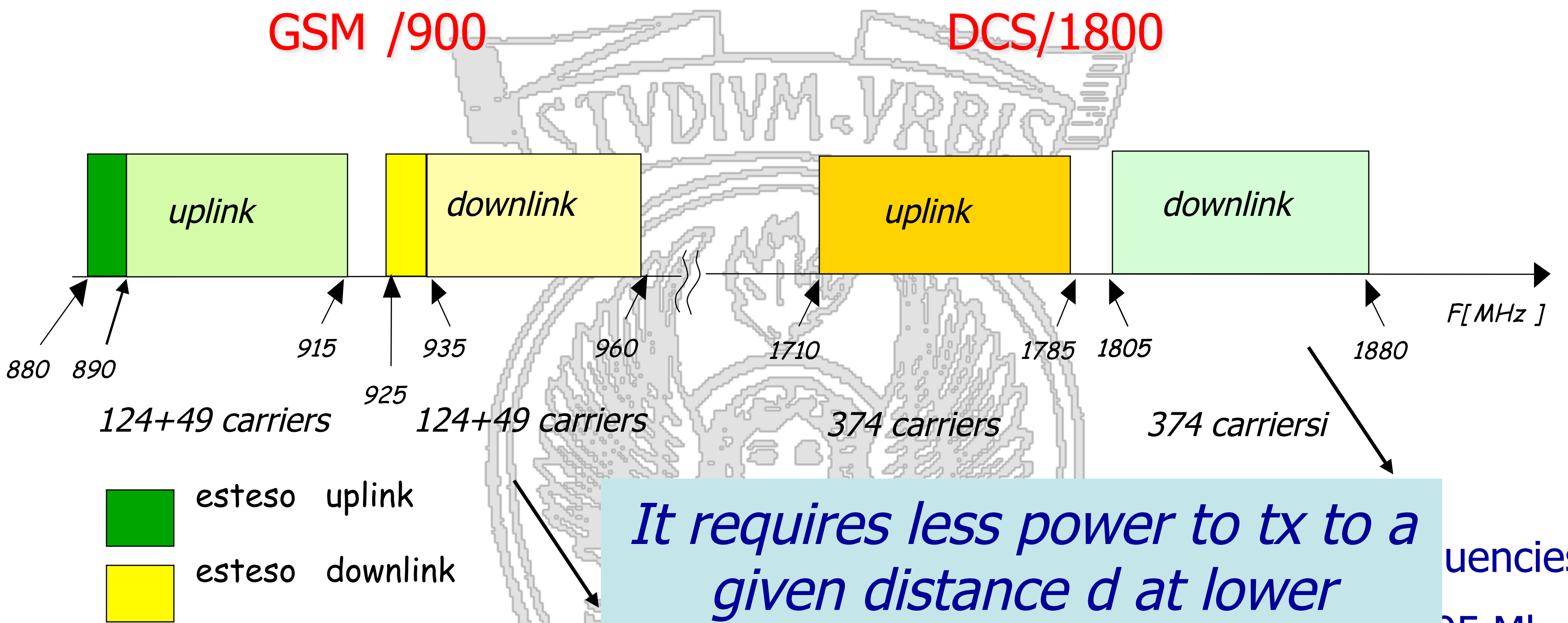
SAPIENZA
UNIVERSITÀ DI ROMA

Allocated frequencies



- In UK and USA it uses bands around 1900 MHz instead of around 1800 MHz (1850÷1910 uplink, 1930÷1990 downlink).

Allocated frequencies



distance between th ... uencies usec

for tx and rx s ... 95 Mhz

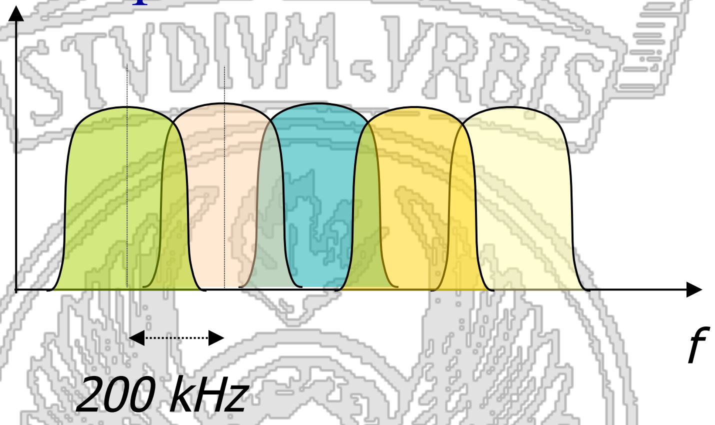
- In UK and USA it ... of around 1800 MHz ... downlink).

It requires less power to tx to a given distance d at lower frequencies.

The lower portion of the spectrum is allocated to uplink channels, saving MS consumed power

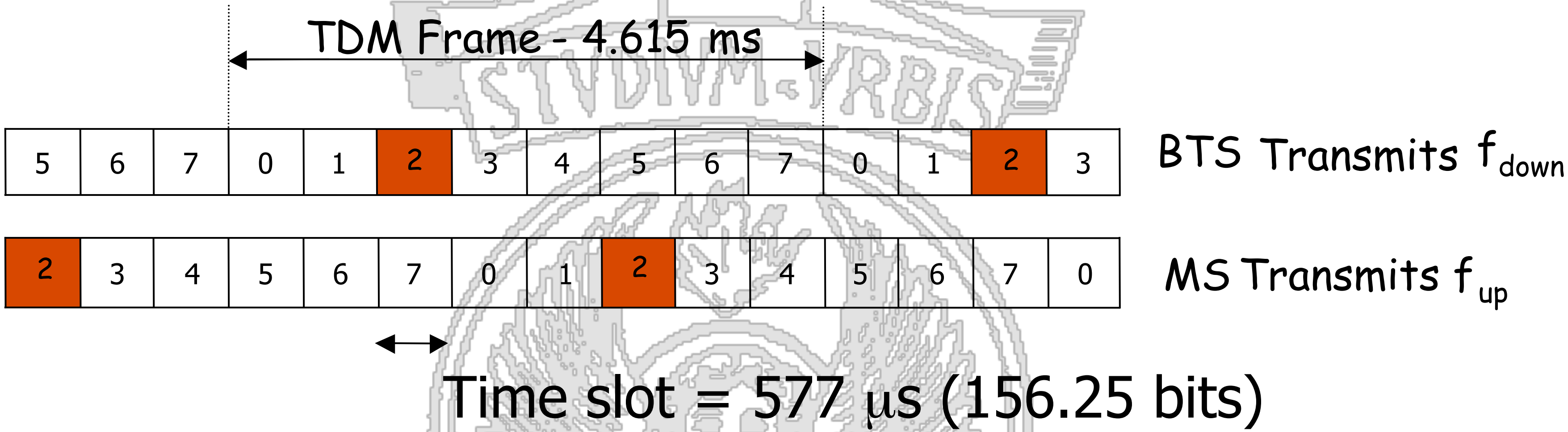
Carriers and channels

- Center frequencies are spaced 200 kHz



- Gross bit rate per channel: 270.833 Kb/s
- Carriers are identified by a ARFCN (Absolute Radio Frequency Channel Number)
- GMSK (Gaussian Minimum Shift Keying) modulation
- The two carriers used for transmission/reception to/from a device are always 45 MHz apart in GSM 900- They are spaced of a different fixed bandwidth (95 MHz) in DCS 1800

TDMA Frame



- On each radio carrier the TDMA structure allows us to create up to 8 channels for the transmission of voice encoded at 13 Kb / s

Other key features

- Power Control
  - *the power emitted from the stations, mobile and base, is adjusted according to the conditions of propagation*
- Discontinous Trasmission
  - *during pauses in speech, coded voice transmission is interrupted to reduce interference and energy consumption*

SAPIENZA
UNIVERSITÀ DI ROMA

3.2 – GSM Architecture

Si veda: - O. Bertazioli, L. Favalli, *GSM-GPRS*, Hoepli Informatica 2002.

High level network architecture (1/2)

Services / Applications

SIM

ME:

Mobile equipment

UE: User equipment

Access Network

(AN)

Core Network

(CN)

Ext.

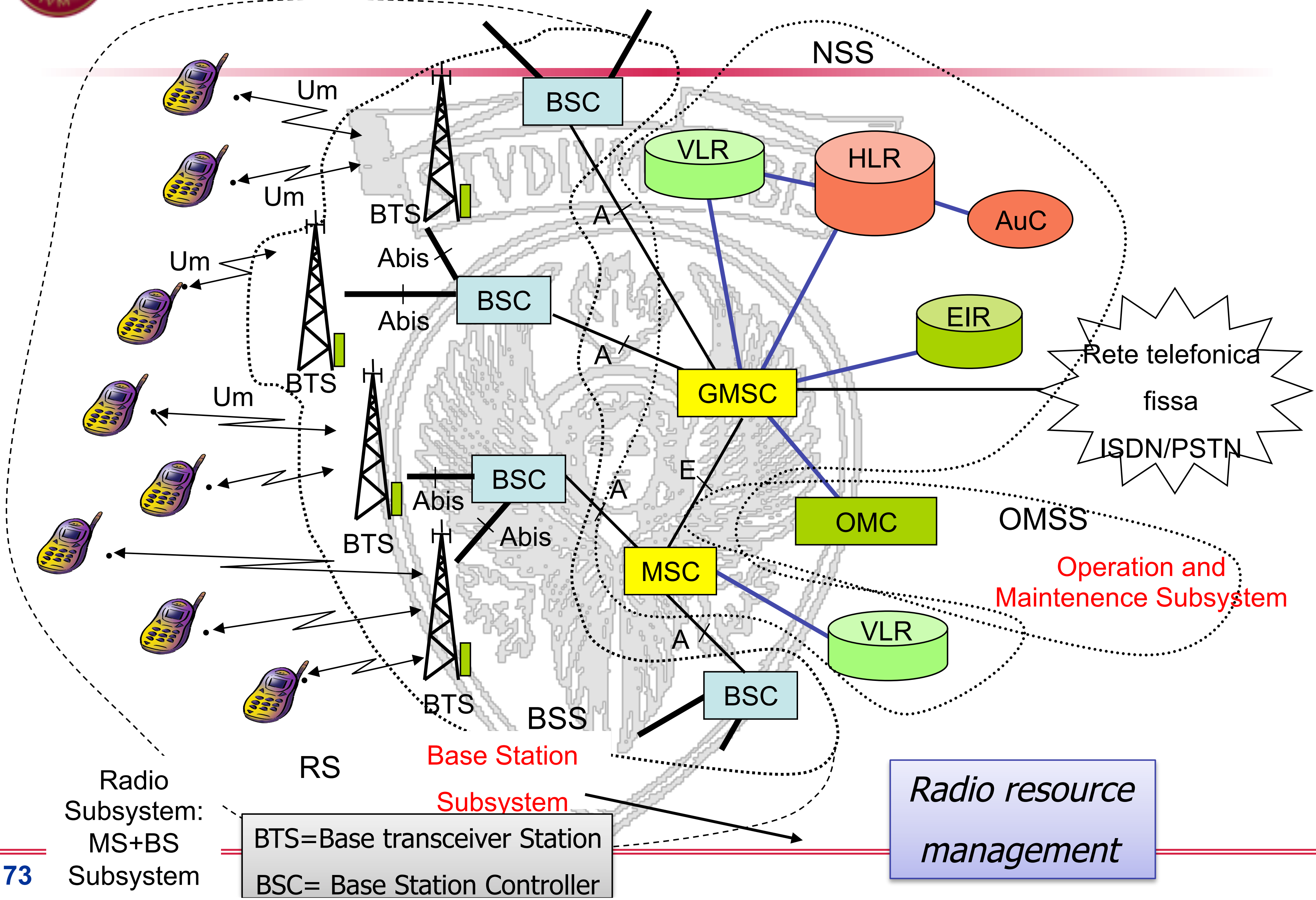
network

SAPIENZA
UNIVERSITÀ DI ROMA

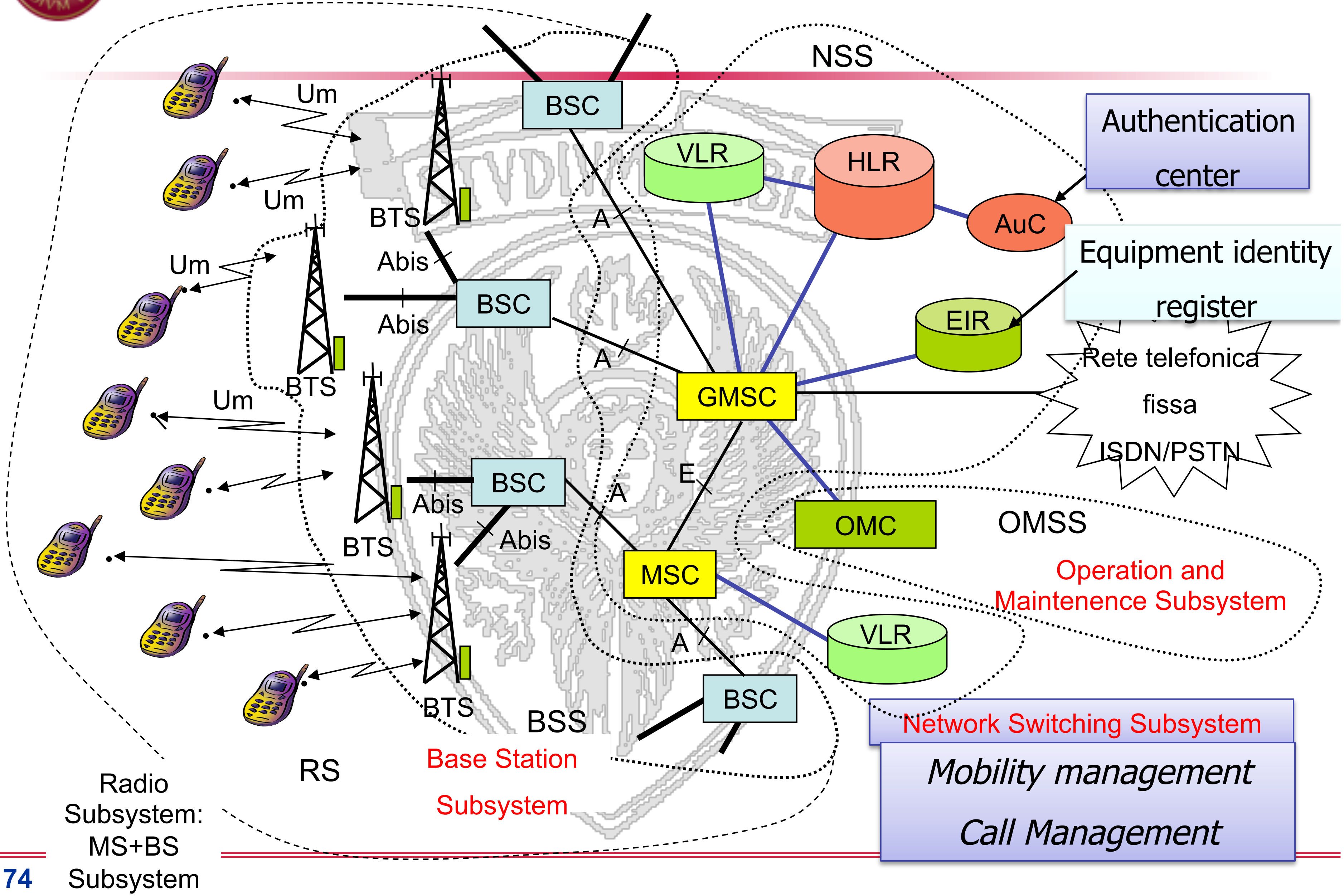
High level network architecture (2/2)

- The network contains functionally of: User Equipment (UE), Access Network (AN), and Core Network (CN)
  - User equipment: Interfaces the user, handles radio functionality
  - Access network: Communication to and from the user equipment, handles all radio related functionality in the network
  - Core network: Communication between access network and external networks, handles all switching and routing
- Services and applications lie above the network

Network architecture



Architettura della rete



SAPIENZA UNIVERSITÀ DI ROMA

GSM Areas

- *PLMN (Public Land Mobile Network) Area:*
  - Service area of a cellular network
- *MSC/VLR Area:*
  - Area managed by an MSC. Data regarding users in the area are temporarily stored in a database called VLR associated to the MSC
- *Location Area:*
  - a MSC/VLR area is logically divided into one or more Location Area (LA). If a user changes LA he(she has to perform a location update. LA are identified by the *LAI (Location Area Identifier),* which is transmitted by the BTS of the LA over the broadcast control channel.
- *Cell:*
  - Area covered by a BTS. It is identified by a *BSIC (Base Station Identity Code),* which is transmitted by the BTS over the broadcast control channel.

(Mobile Station - MS)

- It is the terminal owned by the user
- Three categories depending on the nominal power:
  - Vehicular: antenna can emit up to 20 W
  - laptops: the antenna can emit up to 8 W to the antenna, are transportable, but they need a considerable source of power to operate (eg. laptops, fax, etc.)
  - personal (hand-terminal): the antenna can transmit up to 2, it is the "mobile phone"

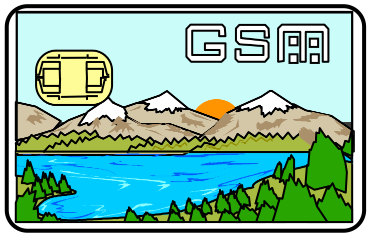
(Mobile Station - MS)

Classe	Potenza massima nominale [W]		Potenza media nominale [mW]	
	GSM 900 MHz	DCS 1800 MHz	GSM 900 MHz	DCS 1800 MHz
1	.	1	.	120
2	8	0,25	960	30
3	5	4	600	480
4	2	.	240	.
5	0,8	.	96	.

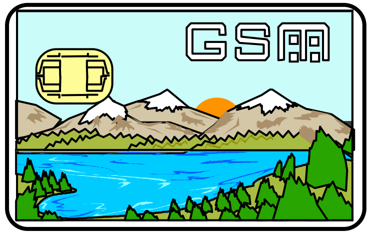
- Features
  - MS multi-band: can operate on different frequency bands (900, 1800, 1900, …)
  - MS multi-slot: can operate over different channels, in different slots (only for GPRS)
- MS is composed of an ME (Mobile Equipment) and a SIM (Subscriber Identity Module)
  - ME is the terminal through which we access the cellular network (HW, radio interface HW/SW, interface to the final user). It is identified by the *IMEI (International Mobile Equipment Identifier)*
  - SIM activates the terminal for a given user and stores all the needed information: it identifies the user, enables terminal personalization

(Subscriber Identity Module - SIM

- Smart card (with processor and memory) which is needed to activate/operate an ME
- It mustbe inserted in ME reader
- There are different formats (from credit card like to small plug-in SIM)



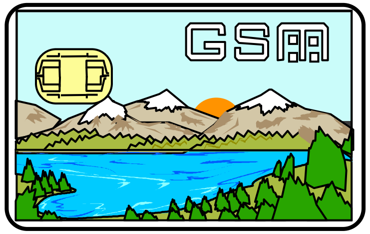
Information stored in the SIM



- *Serial number*
  - Uniquely Identifies SIM card (and card holder)
- *International Mobile Subscriber Identity (IMSI)*
  - Uniquely identifies the user in the network
- Security authentication and cyphering information
  - *A3* and *A8* algorithm (procedures to perform authentication and encryption)
  - K_i, K_c (keys for authentication and encryption)
- Temporary Network information
  - *LAI (Location Area Identifier)*, last visited location area identifier
  - *TMSI (Temporary Mobile Subscriber Identity)*, temporary identifier assigned by the network; TMSI is transmitted to identify the user instead of the IMSI

Information stored in the SIM

- Lista os services to which the user subscribed
- Personal Identification Number (PIN)
- Personal Unblocking Number (PUK)
- Access rights
- Prohibited networks
- Call messages
- Phone numbers



A Mobile Equipment without SIM is enabled to make only emergency calls

A Mobile Equipmentis identified by a unique IMEI identifier (International Mobile Equipment Identity) that can be used to identify stolen mobile terminals.