Reti cellulari GSM

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Allocazione delle frequenze: organizzazione a celle
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

1 Base Station
N=12 channels
*(e.g. 1 channel = 1 frequency)*

\[ \text{Signal OK if } P_{rx} > -X \text{ dBm} \]
\[ P_{rx} = c \cdot P_{tx} \cdot d^{-4} \]
greater \( P_{tx} \) → greater \( d \)

N=12 simultaneous calls

Covering a large geographical area NOT possible
Cellular coverage

**target:** cover the same area with a larger number of BSs

- 19 Base Station
- 12 frequencies
- 4 frequencies/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 frequencies)
  - (4 freq/cell)

Disadvantage:
- Mobility management
- Additional infrastructure costs
• 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 frequencies
    ✓ Larger spectrum occupation
  – frequency reuse pattern
  – Cell size
    ✓ Smaller cell (cell → microcell → picocell → femtocell) = greater capacity
    ✓ Smaller cell = lower transmission power
    ✓ Smaller cell = increased handover management burden
- Hexagon:
  - Good approximation for circle
  - Ideal coverage pattern
    - no “holes”
    - no cell superposition

> Example case:
⇒ Reuse pattern = 4
• 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,...
K=3
Dimensione dei cluster

K=4
Dimensione dei cluster

K=7
- General formula
- Valid for hexagonal geometry
- \( D = \text{reuse distance} \)
- \( R = \text{cell radius} \)
- \( K = \text{cluster size} \)
- \( q = D/R = \text{frequency reuse factor} \)

\[
D = R \sqrt{3K}
\]

<table>
<thead>
<tr>
<th>K</th>
<th>q = D/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3,00</td>
</tr>
<tr>
<td>4</td>
<td>3,46</td>
</tr>
<tr>
<td>7</td>
<td>4,58</td>
</tr>
<tr>
<td>9</td>
<td>5,20</td>
</tr>
<tr>
<td>12</td>
<td>6,00</td>
</tr>
<tr>
<td>13</td>
<td>6,24</td>
</tr>
</tbody>
</table>
Distance between two cell centers:

- \((u_1, v_1) \leftrightarrow (u_2, v_2)\)

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

- Simplifies to:

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

- 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:

\[
D = R\sqrt{3K}
\]
• Distance between two cell centers:
  \[(u_1, v_1) \leftrightarrow (u_2, v_2)\]
  \[D = \sqrt{(u_2 - u_1) \cos 30^\circ} + \sqrt{(v_2 - v_1) + (u_2 - u_1) \sin 30^\circ}\]
  \[\text{Simplifies to:}\]
  \[D = \sqrt{(u_2 - u_1)^2 + (v_2 - v_1)^2 + (u_2 - u_1)(v_2 - v_1)}\]
  \[\text{Distance of cell (i,j) from (0,0):}\]
  \[D = \sqrt{i^2 + j^2 + ij \sqrt{3}R}\]
  \[D_R = \sqrt{i^2 + j^2 + ij}\]
  \[K = D_R^2 = i^2 + j^2 + ij\]
  \[\text{hence:}\]
  \[D = R \sqrt{3K}\]
• Distance between two cell centers:
  \((u_1, v_1) \leftrightarrow (u_2, v_2)\)

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

– 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 \((0,0)\):

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  - \((u_1, v_1) \leftrightarrow (u_2, v_2)\)
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  D = \sqrt{(u_2 - u_1) \cos 30^\circ} + \left((v_2 - v_1) + (u_2 - u_1) \sin 30^\circ\right)
  \]
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  \]
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  \[
  D = \sqrt{i^2 + j^2 + ij\sqrt{3}R}
  \]
  - Cluster: easy to see that
  \[
  K = D_R^2 = i^2 + j^2 + ij
  \]
  \[
  D = R\sqrt{3K}
  \]
Se $R$ è il raggio di un esagono, la metà della distanza tra due celle adiacenti è

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

Quindi la distanza tra due celle adiacenti è 2 volte questa quantità!
• Distance between two cell centers:
  \[ (u_1, v_1) \leftrightarrow (u_2, v_2) \]

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

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

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

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

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

(definition of \(D_R\))

\[
K = D_R^2 = i^2 + j^2 + ij
\]

\[
K = D^2 / 3R^2
\]

\[
D = R \sqrt{3K}
\]
• Se considero una cella che usa un determinato gruppo di frequenze A dato che voglio ricoprire l’area con cluster i centri delle celle interferenti saranno a distanza D

• Posso approssimare l’area di ciascun cluster con l’area di un esagono il cui raggio e’ dato da $D/\sqrt{3}$
• Posso approssimare l’area di ciascun cluster con l’area di un esagono il cui raggio è dato da 
\[ D / \sqrt{3} \]
Se il raggio di una cella esagonale è \( r \) la distanza tra i centri di due esagoni adiacenti è 
\[ d = \sqrt{3}r \]
Nel caso di cluster adiacenti la distanza tra i loro centri è \( D \)
Quindi il raggio dell’esagono che contiene il cluster è \( r = D / \sqrt{3} \)
• L’area occupata da un cluster $A_{\text{cluster}}$ è quindi data da:

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

• Quanti esagoni di area $\frac{3}{2} (R)^2 \sqrt{3}$ possono stare in un’area pari a $K$?

• Risposta:

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

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

$D = \sqrt{3KR^2} = R \sqrt{3K}$
• L’area occupata da un cluster $A_{\text{cluster}}$ è quindi data da:

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

• Quanti esagoni di area $\frac{3}{2} (R)^2 \sqrt{3}$ possono stare in un’area pari a $\frac{3}{2} \left( \frac{D}{\sqrt{3}} \right)^2 \sqrt{3}$?

• Risposta:

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

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

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

dato che:

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

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

\[ K = D^2_R = i^2 + j^2 + ij \]
Possible clusters
all integer $i,j$ values

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

Dim.ammissibili dei cluster 1,3,4,7,9,12,13,16,...
Frequency reuse implies that remote cells interfere with tagged one.

Co-Channel Interference (CCI)
- sum of interference from remote cells

\[
S = \frac{\text{signal power (S)}}{N \cdot \text{noise power (N}_s\text{)} + \text{interfering signal power (I)}}
\]

\[
S = \frac{\text{signal power (S)}}{I \cdot \text{interfering signal power (I)}}
\]

\[
S \approx \frac{S}{I} \quad \text{as } N_s \text{ small}
\]
Assumptions

- $N_I=6$ interfering cells
  - $N_I=6$: first ring interferers only
  - we neglect second-ring interferers
- Negligible Noise $N_S$
  - $S/N \sim S/I$
- $d^{-\eta}$ propagation law
  - $\eta=4$ (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 $D$

\[ D_{int} \sim D \]
\[ S \approx \frac{S}{N} = \frac{S}{I} = \frac{\text{cost} \cdot R^{-\eta}}{\sum_{k=1}^{N_I} \text{cost} \cdot D^{-\eta}} = \frac{1}{N_I} \left( \frac{R}{D} \right)^{-\eta} = \frac{1}{N_I} \left( \frac{D}{R} \right)^{\eta} = \frac{1}{N_I} q^{\eta} \]

By using the assumptions of same cost and same D:

Results depend on ratio \( q = \frac{D}{R} \)

(\( q = \text{frequency reuse factor} \))

Alternative expression: recalling that

\[ D = R \sqrt{3K} \]

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

\( N_I = 6, \eta = 4 \rightarrow \frac{S}{I} = \left( \frac{3K}{R \sqrt{3K}} \right)^{\eta/2} = \frac{(3K)^{\eta/2}}{6} \)

\[ \frac{S}{I} = \frac{(3K)^{\eta/2}}{6} = \frac{3}{2} K^2 \]

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

- **target conditions:**
  - \( S/I = 9 \text{ dB} \)
  - \( \eta = 4 \)
- **Solution:**

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

\[
\frac{S}{I} = \left(\frac{3K}{6}\right)^{\eta/2} \quad \Rightarrow \quad K = \sqrt{\frac{2}{3}} \cdot \frac{S}{I}
\]

\[
K \geq 2.3 \quad \Rightarrow \quad K = 3
\]

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

- **target conditions:**
  - \( S/I = 18 \text{ dB} \)
  - \( \eta = 4.2 \)
- **Solution:**

\[
\frac{S}{I} \left[dB\right] = 5\eta \log(3K) - 10 \log 6
\]
\[
\log(3K) = \frac{18 + 7.78}{21} = 1.23
\]
\[
K \geq \frac{10^{1.23}}{3} = 5.63 \quad \Rightarrow \quad K = 7
\]
**S/I computation**

assuming 6 interferers only (first ring)

<table>
<thead>
<tr>
<th>K</th>
<th>q=D/R</th>
<th>S/I</th>
<th>S/I dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3,00</td>
<td>13,5</td>
<td>11,3</td>
</tr>
<tr>
<td>4</td>
<td>3,46</td>
<td>24,0</td>
<td>13,8</td>
</tr>
<tr>
<td>7</td>
<td>4,58</td>
<td>73,5</td>
<td>18,7</td>
</tr>
<tr>
<td>9</td>
<td>5,20</td>
<td>121,5</td>
<td>20,8</td>
</tr>
<tr>
<td>12</td>
<td>6,00</td>
<td>216,0</td>
<td>23,3</td>
</tr>
<tr>
<td>13</td>
<td>6,24</td>
<td>253,5</td>
<td>24,0</td>
</tr>
<tr>
<td>16</td>
<td>6,93</td>
<td>384,0</td>
<td>25,8</td>
</tr>
<tr>
<td>19</td>
<td>7,55</td>
<td>541,5</td>
<td>27,3</td>
</tr>
<tr>
<td>21</td>
<td>7,94</td>
<td>661,5</td>
<td>28,2</td>
</tr>
<tr>
<td>25</td>
<td>8,66</td>
<td>937,5</td>
<td>29,7</td>
</tr>
</tbody>
</table>
• 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
- Primo livello di interferenti a distanza D, secondo a distanza 2D, terzo a distanza 3D etc.

- Spesso gli interferenti oltre il primo livello hanno impatto non significativo

- Formula generale

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

\[N_{Ii} = \text{numero di celle interferenti a livello } i\]
- stesse antenne e stessa potenza

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

- caso peggiore \( d = r \)
- approssimazione \( d_i = D - R \)

\[ SIR = \frac{R^{-\eta}}{\delta(D-R)^{-\eta}} \]
• 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 performance impairments
Inference from 2 cells, only
- Instead of 6 cells

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

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

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

Conclusion: 3 sectors = 4.77 dB improvement
• 60° Directional antennas

• CCI reduction:
  – 1 interferer only
  – 6 x S/I in the omni case
  – Improvement: 7.78 dB
Unica BS che disturba le ricezioni/trasmissioni verso/dalle MU nella cella di riferimento
Pianificazione di sistemi cellulari
• Fundamental formula for telephone networks planning
  – $A_o =$ offered traffic in Erlangs

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

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

Efficient recursive computation available

blocking probability

offered load (erlangs)
• 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 $B_{\text{target}}$
  – $C$ (number of channels) is obtained from numerical inversion of

$$B_{\text{target}} = E_{1,C}(A_o)$$
Offered load (erl) $A_o$ → C channels → Carried load (erl) $A_c = A_o(1 - B)$

Blocked traffic $A_o B$

Efficiency: $\rho = \frac{A_c}{C} = \frac{A_o(1 - E_{1,C}(A_o))}{C} \approx \frac{A_o}{C}$ if small blocking

Fundamental property: for same GOS, efficiency increases as $C$ grows!!
GOS = 1% maximum blocking.

Resulting system dimensioning and efficiency:

<table>
<thead>
<tr>
<th>Traffic Load (erl)</th>
<th>Capacity C</th>
<th>Efficiency ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>C &gt;= 53</td>
<td>ρ = 74.9%</td>
</tr>
<tr>
<td>60</td>
<td>C &gt;= 75</td>
<td>ρ = 79.3%</td>
</tr>
<tr>
<td>80</td>
<td>C &gt;= 96</td>
<td>ρ = 82.6%</td>
</tr>
<tr>
<td>100</td>
<td>C &gt;= 117</td>
<td>ρ = 84.6%</td>
</tr>
</tbody>
</table>
Trunking Efficiency

FIGURE 4.21 Trunking efficiency plots.
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

ErlangB Online calculator:

http://mmc.et.tudelft.nl/~frits/Erlang.htm
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
    - $A_i=4\times2/60=0.1333$ erl/user
- Evaluate max num of users in cell
  - $M=40.25/0.1333 \approx 302$

**Meglio con area dell’estagono!**

**Third step:**
- Given density of users
  - $\delta=500$ users/km$^2$
- Evaluate cell radius
  - $R = \sqrt{\frac{M}{\pi\delta}}$

*Second question: if the user density is 500 users/km$^2$ how should we set the cell radius?*
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_t=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_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

**Provider C:**
- 20 channels/cell
- at 2%: A_0=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
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Compare case A with C! The reason is the lower efficiency of 20 channels/cell.

il fatto
di avere più celle
con pochi canali
(ad esempio perché' ho scelto un K
diverso)
non porta
ad un vantaggio
in termini di capacità del sistema
• 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

• 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 \( A_0 = 1 \times 46.95 = 46.95 \text{ erl} \), \( \rho = 77.46\% \)
  – 120°: 60/3=20 channels \( A_0 = 3 \times 12.03 = 36.09 \text{ erl} \), \( \rho = 59.54\% \)
  – 60°: 60/6=10 channels \( A_0 = 6 \times 4.46 = 26.76 \text{ erl} \), \( \rho = 44.15\% \)
Cells in real world

Shaped by terrain, shadowing, etc

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