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Cellular Network Planning and Optimization
Part IX: WCDMA load equations

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General

- Computation of theoretical WCDMA load is straightforward in uplink and downlink
- Load equations can be used to make semi-analytic coverage and capacity estimates.
- Load equations are semi-analytic since link level SIR performance needs to be simulated while system level performance is obtained analytically.
- As such load equations are very useful for quick system level evaluations.
- Load equations are also interesting since they provide a explicit mapping from link level performance to system level performance and link level results are usually more easily available than system level results.

Uplink wideband power (1)

- We start with the received wideband signal in base station. At time *t* it admit the form

(1) $$r(t) = \sum_{n=1}^{N_{own}} y_n(t) + \sum_{n=1}^{N_{other}} z_n(t) + n(t)$$

where first sum refers to signals that are coming from users that are connected to the considered cell, second sum refers to signals that are coming from users that are connected to other cells and last term refers to AWGN noise

Uplink wideband power (2)

- The wideband power is given by

(2) $$E\{|r(t)|^2\} = I_{total} = I_{own} + I_{other} + P_N$$

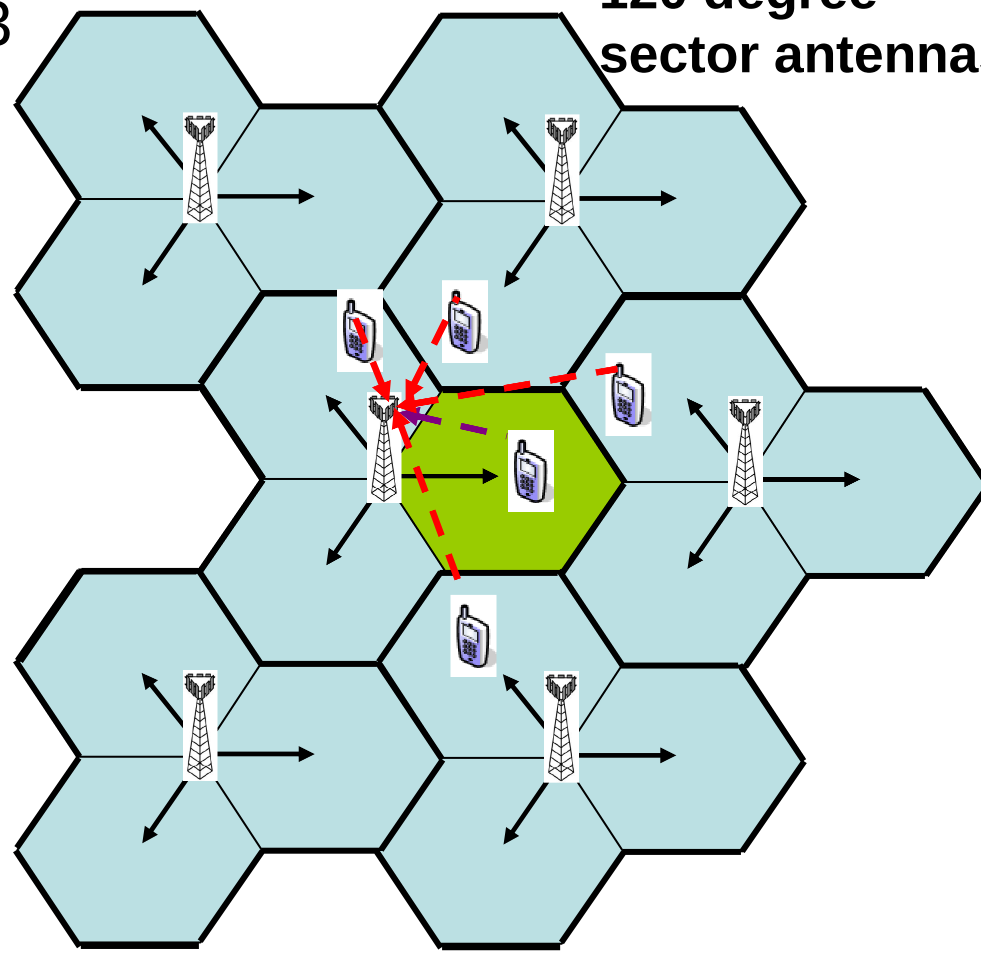
where last term is the AWGN noise power and

$$I_{own} = \sum_{n=1}^{N_{own}} E\{|y_n(t)|^2\},\ I_{other} = \sum_{n=1}^{N_{other}} E\{|z_n(t)|^2\}$$

Remark: Here *E*{ . } refers to expectation.
Exercise: Go through all intermediate steps between (1) and (2)

Uplink wideband power (3)

- Illustration: 3 sectors = 3 cells in each site.
- Blue cell = ‘other’ cells, green cell = ‘own’ cell
- All users are separated by scrambling codes
- Signals from different users are uncorrelated
- Path loss and antenna gain attenuates signals from ‘other’ cells



Uplink load equation (1)

- Important measure that is used in system level investigations is the noise rise (denoted by *NR*) that is defined as a ratio between total received wideband power and AWGN noise power

(3) $$NR = \frac{I_{total}}{P_N}$$ **Definition of uplink noise rise**

our goal is to deduce a formula (load equation) that provides a connection between noise rise and link level parameters.

Uplink load equation (2)

- Consider a single link and denote by Eb/No the received energy per user bit divided by the noise spectral density (SIR). We have

$$E_b / N_0 = \left(\text{Processing gain}\right) \cdot \frac{\text{Signal power}}{\text{Total received power excluding own signal power}}$$

  Hence, the minimum requirement for Eb/No is defined by the processing gain + power that is needed to overcome the interference from other users.

- Eb/No is an important variable since it actually maps the link level performance to the system level performance.

Uplink load equation (3)

- Let us formulate Eb/No mathematically. For a user *j* there holds

(4) $$\left(E_b / N_0\right)_j = \frac{W}{\nu_j R_j} \cdot \frac{P_j}{I_{total} - P_j}$$

where

$W = \text{System chip rate}$

$P_j = \text{Signal power of user j}$

$\nu_j = \text{Activity factor of user j}$

$R_j = \text{Bit rate of user j}$

$I_{total} = \text{Total received wideband power} + \text{thermal noise in base station}$

We consider these variables more carefully later.

Uplink load equation (4)

- The load generated by *j*th user is

(5) $$\eta_j = \frac{P_j}{I_{total}}$$

- After combining (4) and (5) we find that

(6) $$\eta_j = \frac{1}{1 + W/(\nu_j R_j \cdot (E_b / N_0)_j)}$$

This is uplink load generated by a single user

Uplink load equation (5)

- The load generated by N users in the cell is obtained by summing over (6)

Uplink load equation in isolated cell

(7) $$\eta_{own} = \sum_{j=1}^{N} \eta_j = \sum_{j=1}^{N} \frac{1}{1 + W / (\nu_j R_j \cdot (E_b / N_0)_j)}$$

Note: If there are e.g. 2 services used in the cell, then load equation is of the form

$$\eta_{own} = \frac{N_1}{1 + W / (\nu_1 R_1 \cdot (E_b / N_0)_1)} + \frac{N_2}{1 + W / (\nu_2 R_2 \cdot (E_b / N_0)_2)}$$

Uplink load equation (6)

- Formula (7) gives only the 'own cell' load which is generated by users that connected to considered (own) cell. In order to take into account also the load coming from other cells we introduce other-to-own cell interference factor

(8) $$\iota = \frac{\text{Other cell interference}}{\text{Own cell interference}} = \frac{I_{other}}{I_{own}}$$

- In practise other-to-own cell factor may greatly vary in different parts of the network. Now we can write the uplink load equation for non-isolated cell,

Uplink load equation for non-isolated cell

(9) $$\eta = (1+\iota)\eta_{own}$$

Uplink noise rise (1)

- It is common to discuss on noise rise instead of load. Noise rise (denoted by *NR*) is defined as a ratio between total received wideband power and AWGN noise power. Let us deduce the connection between noise rise and load. The total received wideband power admit the form

(10) $$I_{total} = (1+\iota)\sum_{j=1}^{N} P_j + P_N = \eta \cdot I_{total} + P_N$$

where last term is the AWGN noise power and we have used equation (2).

Uplink noise rise (2)

- After combining the definition of noise rise (3) and (10) we obtain the formula

(11) $$NR = \frac{I_{total}}{P_N} = \frac{1}{1-\eta}$$ **Noise rise in terms of load**

Noise rise is usually given in decibels. Thus

(12) $$NR_{dB} = -10\log(1-\eta)$$

Uplink noise rise (3)

- Noise rise of 3 dB is related to 50% load. This is usually limit value when deployment is coverage limited
- Noise rise of 6 dB is related to 75% load. This value is usual upper limit when deployment is capacity limited.
- Load and admission control is monitoring and controlling the noise rise in different cells

Load equation: Parameters

- Suitable value of Eb/No can be obtained from link simulations, measurements or from 3GPP performance requirements.
- Eb/No varies between services and its requirements are coming from the predefined receiver block error rate that is tolerated in order to meet the service QoS.
- Eb/No contains impact of soft handover and power control
  - Example values for multipath channel:
  - 12.2 kbps voice, Eb/No = 4.5 dB (3 km/h), Eb/No = 5.5 (120 km/h)
  - 128 kbps data, Eb/No = 1.5 dB (3 km/h), Eb/No = 2.5 (120 km/h)
  - 384 kbps data, Eb/No = 2.0 dB (3 km/h), Eb/No = 3.0 (120 km/h)

Load equation: Parameters

- **System chip rate W:**
  - 3.84 Mcps for WCDMA (5 MHz bandwidth)
- **Activity factor ν:**
  - Value 0.67 for speech (uplink recommendation)
  - Value 1.0 for data
- **Bit rate R:**
  - Depends on the service, usually up to 400-500 kbps
- **Other-to-own cell interference ι:**
  - Depends on the antenna configuration and network topology
    - Omni-directional antennas $\iota = 0.55$
    - Three-sector cells $\iota = 0.65$
    - ι may greatly vary due to load variations in adjacent cells

Uplink load equations: Example (1)

- **Example.** Plot uplink noise rise curves (in decibels) for
  - 12.2 kbps voice service (all users in the cell use the same service)
  - 128 kbps data services (all users in the cell use the same service)
- Give X-axis of the plot as a function of number of users. All sites in the network admit three sectors (cells) and user mobility is 3 km/h in the first and 120 km/h in the second case.

Uplink load equations: Example (2)

- **Solution.** We use equations

$$\eta_{own} = \sum_{j=1}^{N} \eta_j = \sum_{j=1}^{N} \frac{1}{1+W/(\nu_j R_j \cdot E_j)} = \frac{N}{1+W/(\nu \cdot R \cdot E)}$$

$$\eta = (1+\iota)\eta_{own} \qquad NR_{dB} = -10\log(1-\eta)$$

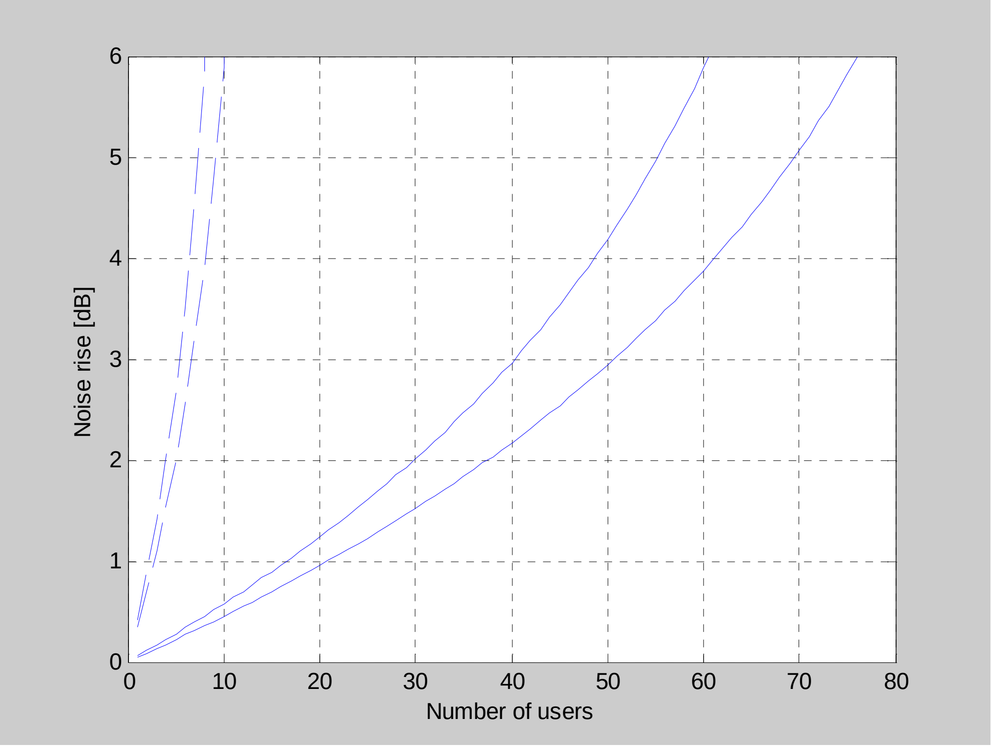
,

Required parameters are

$$W = 3.84 Mcps, \nu = 0.67, R_{voice} = 12.2 \text{ kbps}, R_{data} = 128 \text{ kbps},$$
$$(E_b/N_0)_{voice}(3km/h) = 4.5dB, (E_b/N_0)_{data}(3km/h) = 1.5dB,$$
$$(E_b/N_0)_{voice}(120km/h) = 5.5dB,$$
$$(E_b/N_0)_{data}(120km/h) = 2.5dB, \iota = 0.65$$

Uplink load equations: Example (3)

- Requested noise rise plot



12.2 kbps voice service (solid curve) and 128 kbps data service (dashed curve). Lower curves: 3km/h mobility, upper curves: 120 km/h mobility

Uplink load equations: Example (4)

- **Observations:**
- With 3 dB noise rise system can support in uplink
  - Round 50 (40) voice users when user mobility is 3 km/h (120 km/h)
  - Round 6 (5) data users when user mobility is 3 km/h (120 km/h)
- With 6 dB noise rise system can support in uplink
  - Round 75 (60) voice users when user mobility is 3 km/h (120 km/h)
  - Round 10 (8) data users when user mobility is 3 km/h (120 km/h)

Downlink load equation (1)

- We start the derivation of the downlink load equation from so-called pole equation.
- The baseline assumption is that fast power control is applied. Then UEs are able to obtain exactly the minimum required Eb/No.
- The link quality equation for the user j in cell m attain the form

Received interference power from 'other' node B's

$$(13)\quad (E_b/N_0)_j = \frac{W}{R_j}\cdot\frac{P_j}{L_{m,j}}\cdot\frac{1}{(1-\alpha_j)P/L_{m,j} + \sum_{n=1,n\neq m}^{N_{cells}} P/L_{n,j} + P_N}, \quad j = 1,2,\dots,N_{own}$$

Processing gain

AWGN noise power

Power for user *j*

Received interference power from 'own' node B

Downlink load equation (2)

- Parameters in link quality equation are

$W = \text{System chip rate}$

$P_j = \text{Required signal power of user j in base station transmission}$

$P = \text{Base station transmission power}$

$L_{m,j} = \text{Path loss between considered base station (index m) and UE}$

$R_j = \text{Bit rate of user j}$

$L_{n,j} = \text{Path loss between } n\text{th base station and UE}$

$N_{cells} = \text{Number of cells}$

Downlink load equation (3)

- In equation (13) first term is the processing gain multiplied by signal power after path loss.

$$\frac{W}{R_j} \cdot \frac{P_j}{L_{m,j}}$$

- The denominator of the second term defines the interference and AWGN noise.
  - First interference term contains the impact of imperfect code ortogonality (due to multi-path fading) which is multiplied by ‘own’ base station power after path loss.

$$(1-\alpha_j)P / L_{m,j}$$

  - The second interference term contains interference coming from other cells.

$$\sum_{n=1, n \neq m}^{N_{cells}} P / L_{n,j}$$

Note: It is assumed that all base stations admit the same transmission power *P*

On orthogonality factor

- In operational network, α is continuously changing
- α is estimated by base station based on UL multipath propagation According to experience, α for typical WCDMA environments:
    - 0,5 – 0,6 macro cells
    - 0,8 – 0,9 micro cells (smaller cells, less multipath)
- Too optimistic α can lead to coverage problems
- Too modest α can lead to inefficient utilisation of DL performance

Base station transmission power (1)

- Let us solve the power that is needed for user j from equation (13). We obtain

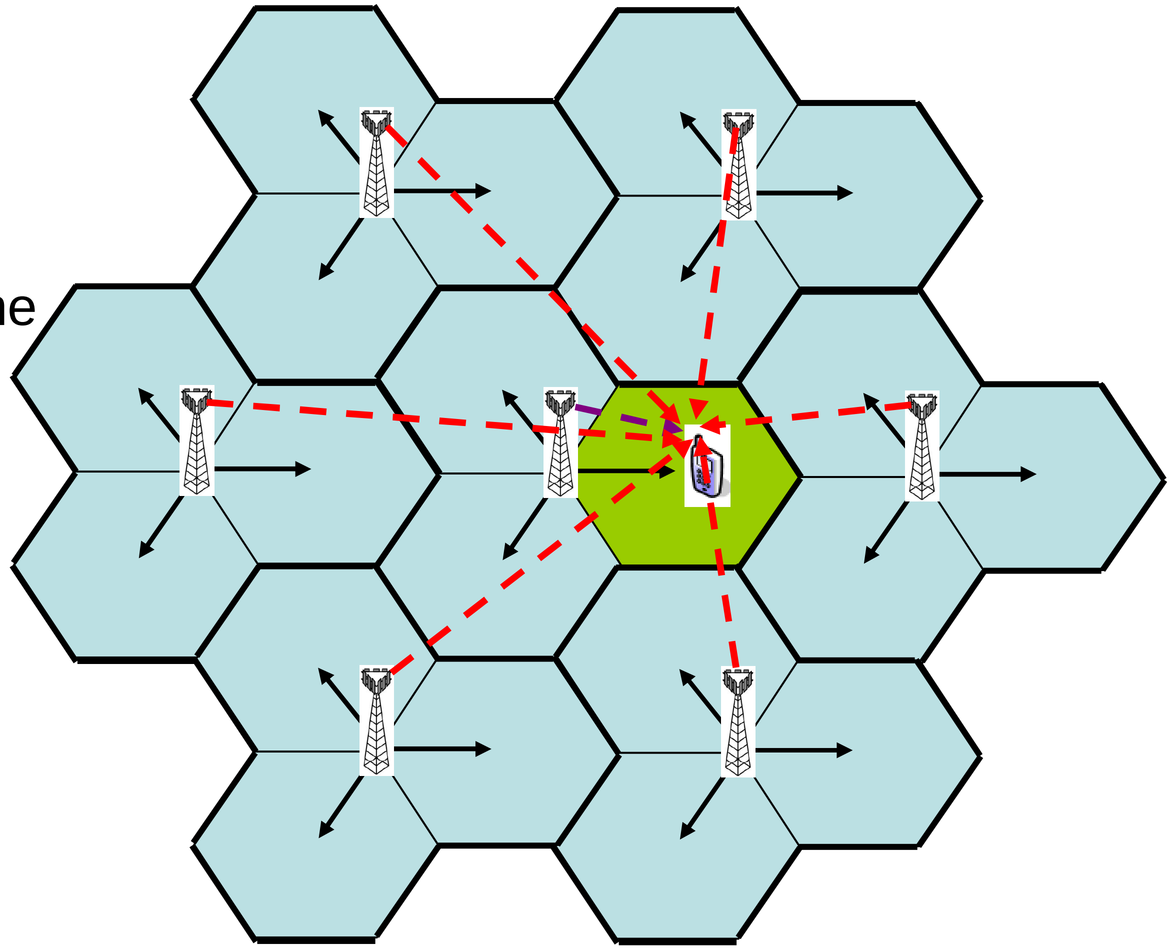
(14) $$P_j = \frac{(E_b/N_0)_j \cdot R_j}{W} \cdot \left(P \cdot (1-\alpha_j) + P \sum_{n=1, n\neq m}^{N_{cells}} L_{m,j}/L_{n,j} + P_N L_{m,j} \right), \quad j = 1,2,\ldots,N_{own}$$

We note that in downlink other-to-own cell interference is different for different users. We have

(15) $$\iota_j = \sum_{n=1, n\neq m}^{N_{cells}} \frac{P \cdot L_{m,j}}{P \cdot L_{n,j}} = \sum_{n=1, n\neq m}^{N_{cells}} \frac{L_{m,j}}{L_{n,j}}$$

Downlink other-to-own cell interference

- Illustration: 3 sectors = 3 cells in each site.
- Blue cells = ‘other’ cells, green cell = ‘own’ cell
- Other-to-own cell interference depends on the user location
- Cells are separated by scrambling codes
- Shadowing related to different base stations is correlated to some extent
- Path loss attenuates base station signals from ‘other’ cells



Base station transmission power (2)

- Next we sum up powers of different users and take into account the activity factor. Then we obtain the formula

$$(16)\quad P = P\sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} \cdot \left((1-\alpha_j)+\iota_j\right) + P_N \sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} L_{m,j}$$

From (16) we solve the required total base station transmission power

$$(17)\quad P = \frac{P_N \sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} L_{m,j}}{1-\sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} \cdot \left((1-\alpha_j)+\iota_j\right)}$$

Required base station transmission power in downlink

Downlink load equation (4)

- In (17) we denote the downlink load by

(18) $$\eta = \sum_{j=1}^{N_{own}} \frac{(E_b / N_0)_j R_j \nu_j}{W} \cdot \left((1-\alpha_j) + \iota_j\right)$$ **Downlink load equation**

and the downlink noise rise by

$$NR = \frac{1}{1-\eta} \qquad NR_{dB} = -10\log(1-\eta)$$

Base station transmission power (3)

- In decibels the required base station transmission power is of the form (see eq. (17))

(19) $$P_{dB} = (P_N)_{dB} + 10\log\left(\sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} L_{m,j} \right) + NR_{dB}$$

Required base station transmission power in decibels

- The factors that impact to the required transmission power in base station
  - AWGN noise (first term)
  - Transmission power that is needed to serve own cell users (second term)
  - Transmission power that is needed to overcome the interference (third term). Interference contains contribution from own cell (imperfect code orthogonality) and from other cells.

Base station transmission power (4)

- In downlink dimensioning it is important to estimate the required base station power.
- Link budget gives the maximum transmission power which is determined by the cell edge users
- However, dimensioning should be based on the average transmission power. This follows from the fact that users are spread all over the cell and wideband transmission is a sum over all signals. Hence, it contains signals to users on cell edge as well as signals to users near the base station.
- The difference between maximum and average path loss is typically 6 dB [1], p.195.

Downlink load equation (5)

- The average load in the cell is given by

(20) $$\overline{\eta} = E\{\eta\} = \sum_{j=1}^{N_{own}} \frac{(E_b/N_0)_j R_j \nu_j}{W} \cdot \left((1-\overline{\alpha}) + \overline{\iota}\right)$$ **Downlink average load equation**

- $\overline{\alpha}$ is the mean orthogonality factor.
  - In ITU Vehicular A channel $\overline{\alpha}$ is round 0.5
  - In ITU Pedestrian A channel $\overline{\alpha}$ is round 0.9
- $\overline{\iota}$ is the mean other-to-own cell interference factor
  - In macro-cell deployment with omnidirectional antennas $\overline{\iota}$ is round 0.55
  - In macro-cell deployment with 3-sector sites $\overline{\iota}$ is round 0.65

SIR/activity values for downlink

- Example values for Eb/No ([1], p.389) in downlink multi-path channel:
  - 12.2 kbps voice, Eb/No = 6.7 dB (3 km/h), Eb/No = 6.4 (120 km/h)
  - 128 kbps data, Eb/No = 5.3 dB (3 km/h), Eb/No = 5.0 (120 km/h)
  - 384 kbps data, Eb/No = 5.2 dB (3 km/h), Eb/No = 4.9 (120 km/h)
- Recommended activity factor in downlink:
  - Value 0.58 for speech
  - Value 1.0 for data.

Base station transmission power (5)

- In dimensioning the following mean total transmission power in base station is to be used

$$P_{BS} = \frac{N_{rf} \cdot W \cdot \overline{L} \cdot \sum_{j=1}^{N_{own}} \frac{(E_b / N_0)_j R_j \nu_j}{W}}{1 - \sum_{j=1}^{N_{own}} \frac{(E_b / N_0)_j R_j \nu_j}{W} \cdot \left((1-\overline{\alpha}) + \overline{\imath}\right)} \qquad (21)$$

Here N_{rf} is the noise spectral density of the receiver front end. There holds

$$N_{rf} = k \cdot T + NF \qquad (22)$$

Where k $= 1.381 \cdot 10^{-23}$ J/K is Boltzmann constant, T is temperature in Kelvin and NF is receiver noise figure that is usually between 5 to 9 dB.

Example

- Plot maximum allowed path loss as a function of number of users for 12.2 kbps voice service and for 64 kbps data service when
  - BS transmission power is 40W
  - BS transmission power is 10W

  All sites in the network admit three sectors (cells), users mean mobility is 3 km/h, average orthogonality factor is 0.5, average mobile noise figure is 7dB.

Example

- Solution. We solve mean path loss from equation

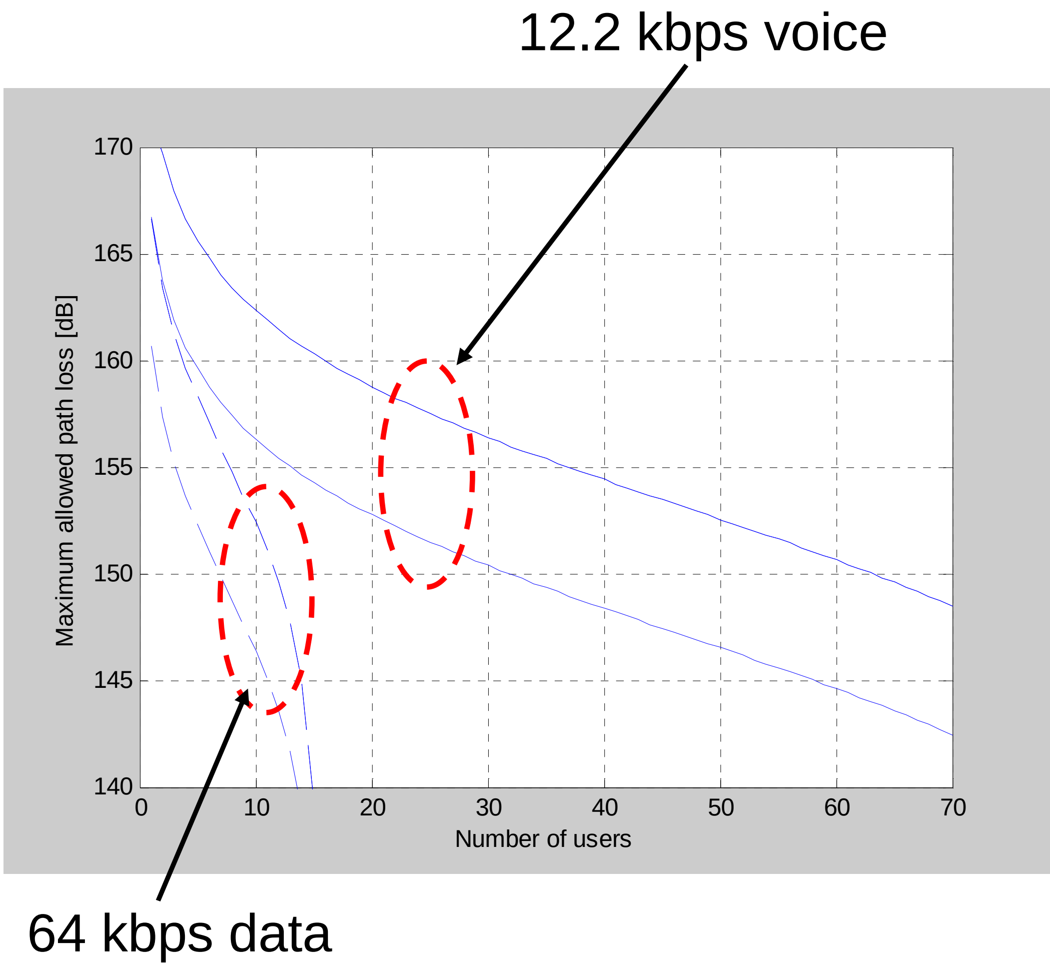
$$P_{BS} = \frac{N_{rf} \cdot W \cdot \overline{L} \cdot \sum_{j=1}^{N_{own}} \frac{(E_b / N_0)_j R_j \nu_j}{W}}{1 - \sum_{j=1}^{N_{own}} \frac{(E_b / N_0)_j R_j \nu_j}{W} \cdot ((1-\overline{\alpha}) + \overline{\iota})} = \frac{N_{rf} \cdot \overline{L} \cdot N_{own} \cdot (E_b / N_0) \cdot R \cdot \nu}{1 - \frac{N_{own} \cdot (E_b / N_0) \cdot R \cdot \nu}{W} ((1-\overline{\alpha}) + \overline{\iota})}$$

  and compute its numeric value for different number of users by substituting parameters
  - N_{rf} = -174+7dB, $\overline{\alpha}$ = 0.5, $\overline{\iota}$ = 0.65, ν = 0.58, W = 3.84 Mcps,
  - R = 12.2 kbps, R = 64 kbps, Eb/No = 6.7 dB (voice), Eb/No = 5.3 dB (data),
  - P_{BS}= 0.85*40W, P_{BS} = 0.85*10W (15% of BS power is spend on control channels)

  Finally, we add 6 dB margin to achieved mean path loss. The resulting values are plotted in the figure of the following slide

Example

- Observations:
- Number of downlink data users can be increased only slightly by increasing the base station transmission power
- Number of voice users can be significantly increased by increasing the base station transmission power



Practical WCDMA capacity

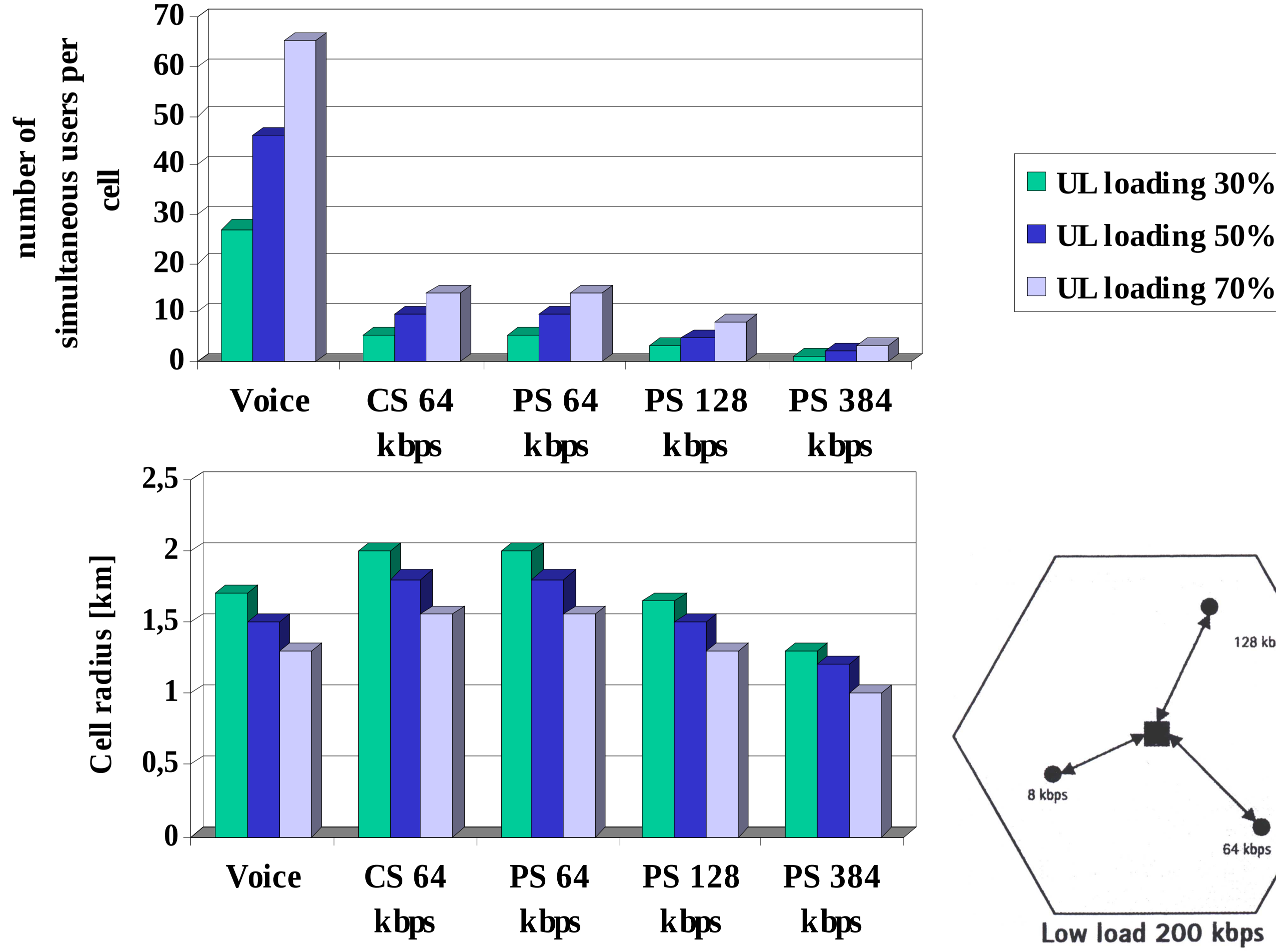
- Depends on
  - Base station HW channel & Iub capacity
  - Inter-cell interference (traffic, cell desing)
  - Parametrisation (mostly RRM issue)
  - System’s capabilities to utilise NRT capacity
  - SHO probability
  - External interference (most effect on coverage)

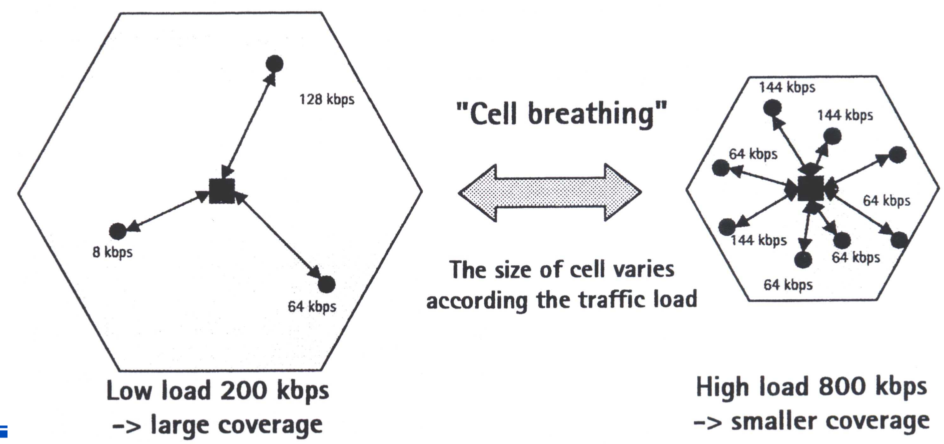
- Example: In early networks e.g. 4 simultaneous 384kbps connections/cell can be achieved near the base station

WCDMA capacity

- The interference in the cell directly effects the cell's capacity

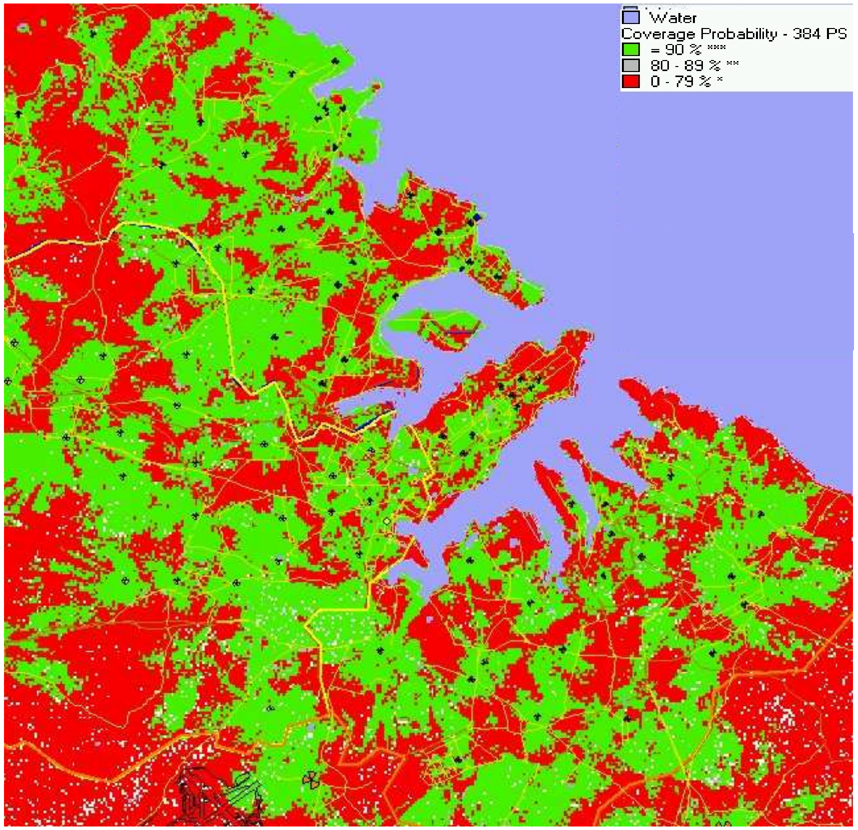
- In WCDMA also the coverage is then effected

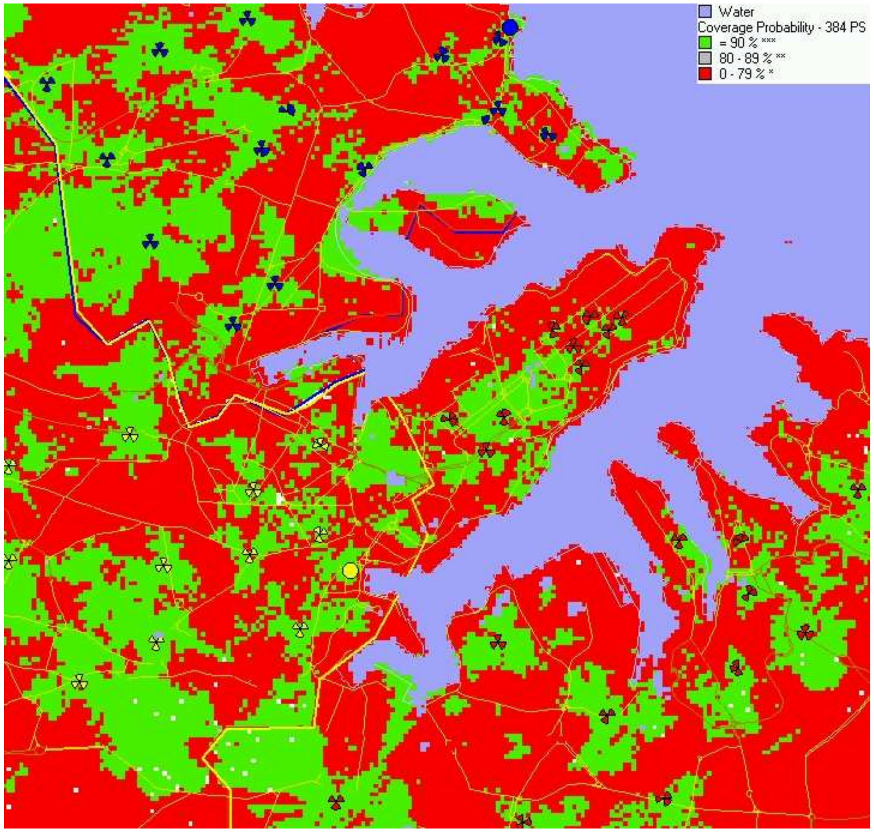




WCDMA capacity – simulations

43% 64/384 kbps PS service probability 28%



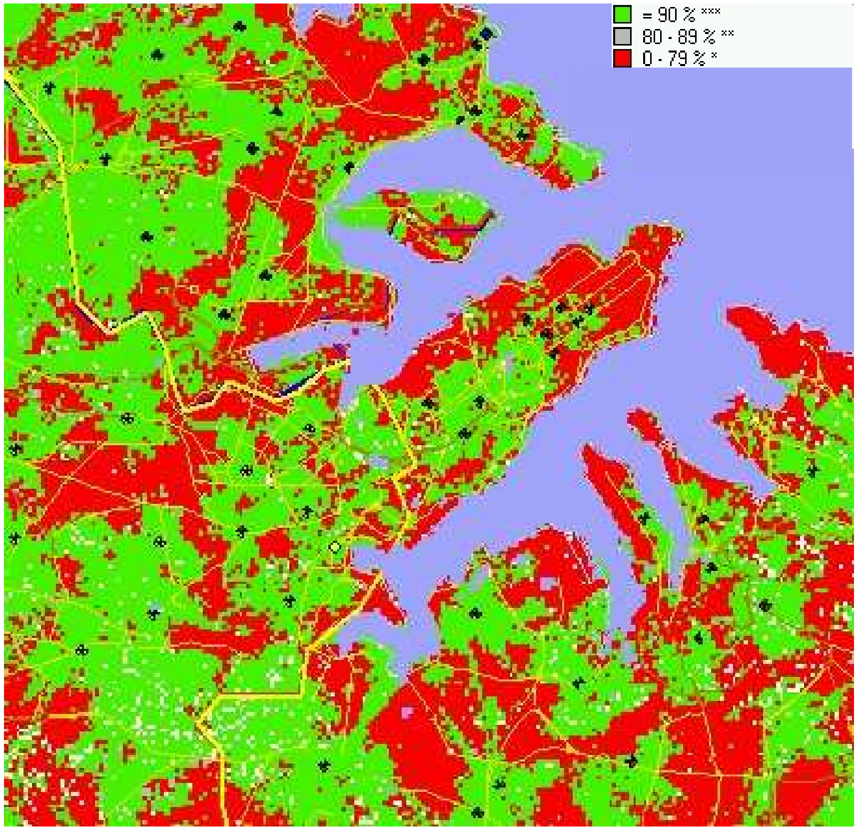


- **Traffic density: Amount of users increased by 25% homogeneously (other conditions remained the same, indoors)**

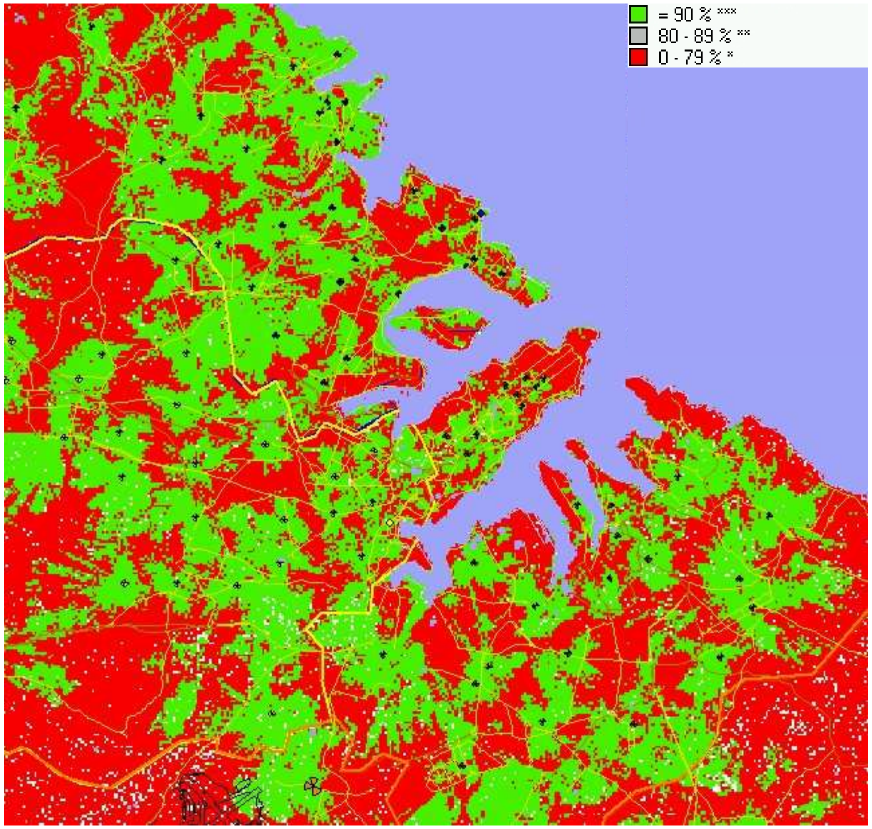
WCDMA capacity – simulations

64/128 => 128/128 kbps service probability

56%



40%



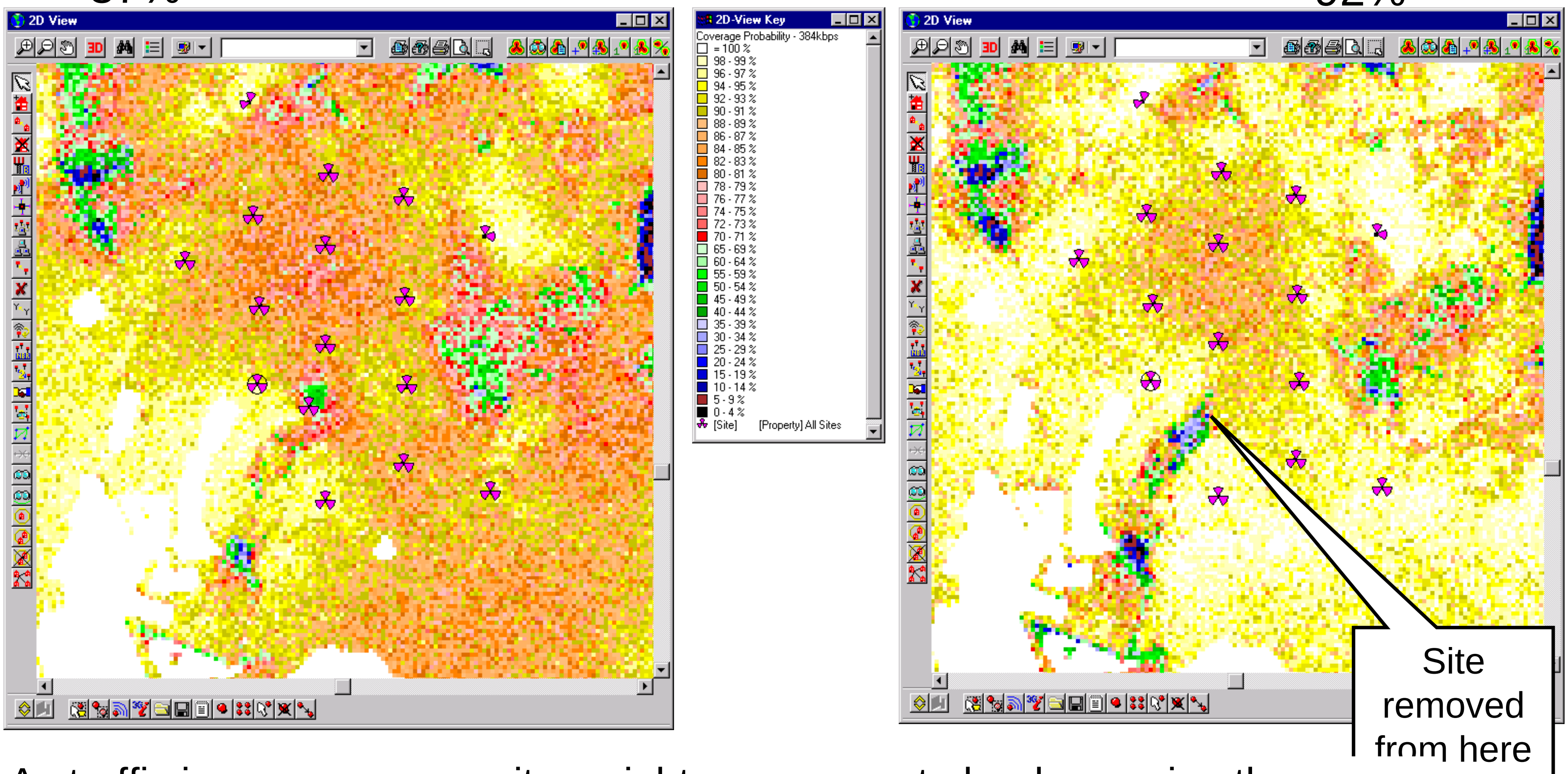
- **Traffic asymmetry: the users moved from using 64/128 kbps PS RAB to 128/128 RAB (other conditions remained the same, indoors)**

WCDMA capacity – simulation

64/128 kbps PS service probability

87%

92%

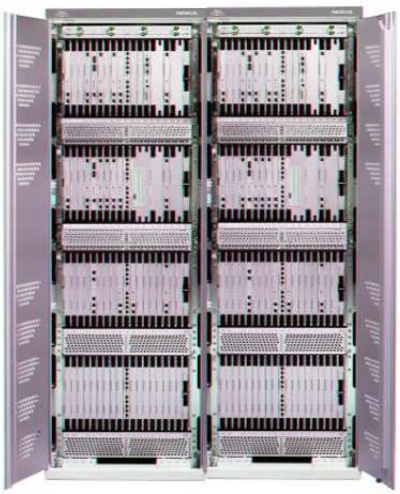


As traffic increases, some sites might even prove to be decreasing the service probability (or need modification) => simulations with varying traffic density, distribution and asymmetry needed

Network element dimensioning

RNC

- The network area is divided to areas supported by one RNC each
- RNC dimensioning: provide the number of RNCs needed to support the estimated traffic
- Three dimensions are identified when RNC is dimensioned:
  - Maximum number of cells supported
  - Maximum number of NodeB supported
  - Maximum Iub throughput
- Typically Iub throughput is selected as primary dimensioning (and financial) parameter, but support for enough cells/NodeB is always ensured



$$No\_of\_RNC = \frac{(A+B)*(1+SHO\_overhead)}{RNC\_capacity}$$

A= Total estimated voice traffic
B= Total estimated data traffic

Network element dimensioning

NodeB

- The amount of needed NodeBs is derived from coverage analysis
- The configurations of NodeBs need to be decided in terms of
  - HW channels
  - PA type and power
  - Iub transmission arrangements
- Enough HW channel elements (cards) are needed to support the offered traffic
- One HW channel typically support one AMR user and associated signalling (a 384kbps user can take up to 16 HW channels)
- The HW channels are organised as a pool common for all sectors
- Common channels need to be taken into account in the dimensioning

Network element dimensioning

NodeB

- The Power Amplifiers types available have a wide range
  - Single carrier PA
  - Multi-Carrier PA (MCPA)
  - PA's for TX diversity
- As the does the power options
  - 10W -> 60W
  - The nominal output power per sector is the key dimensioning parameter
- The most typical configuration in UMTS networks today is the 20W per sector multi-carrier PA.
- The problem with high-power MCPA is the possibility to lose code orthogonality when high interference is produced

Network element dimensioning

NodeB

- There are many ways to arrange the Iub transmission
  - Dedicated backhaul
  - Micro wave link
  - Leased line
- In GSM co-siting cases raise a few issues
  - Dedicated backhaul link for UMTS?
  - Sharing transmission with GSM?
- Dimensioning is based on traffic estimates, typical value
  - Macro sites: 1.5 Mbps/carrier

Code & frequency planning

- In principle the scrambling code planning in WCDMA is similar than frequency planning in GSM, atlhough simpler
  - Planning considers only Downlink (spreading codes and uplink scrambling codes are automatically assigned by the RNC)
  - For UL unique pools of scrambling codes need to assigned to each RNC (more than million codes available, two RNCs may not have the same code in their pool)
  - In total 512 DL scrambling codes usable for the network -> easy planning
- The 512 codes are divided to 64 groups
- Rule of thumbs:
  - The same scrambling code should not be seen by a UE more than once at any location of the network
  - The reuse distance between two cells using the same DL scrambling code inside one carrier should be higher than 4x inter-site distance
  - The same scrambling code should not be used in two cells of same site
- The plan can be made automatically with a 3G planning tool