Mobile Wireless Networks

Chapter 4: Radio Network Planning

Prof. **Andrea Detti**
Univ. of Rome Tor Vergata
Electronic Engineering Dept.
Andrea.detti@uniroma2.it

Sources:

1. Vijay K. Garg, ''Wireless Communications and Networking'', avallabile at http://www.slideshare.net/shirazthegreat/wireless-communicationsandnetworking
2. Prof. Dr.-Ing. Jochen H. Schiller www.jochenschiller.de, MC – 2015, available at http://www.mi.fu-berlin.de/inf/groups/ag-tech/teaching/resources/Mobile_Communications/course_Material/
3. Christopher Cox, An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications: Second Edition, 2

Two approaches

To create a radio network that provides the users with seamless wireless services.

Coverage Planning **Worst case win** ***Capacity Planning***

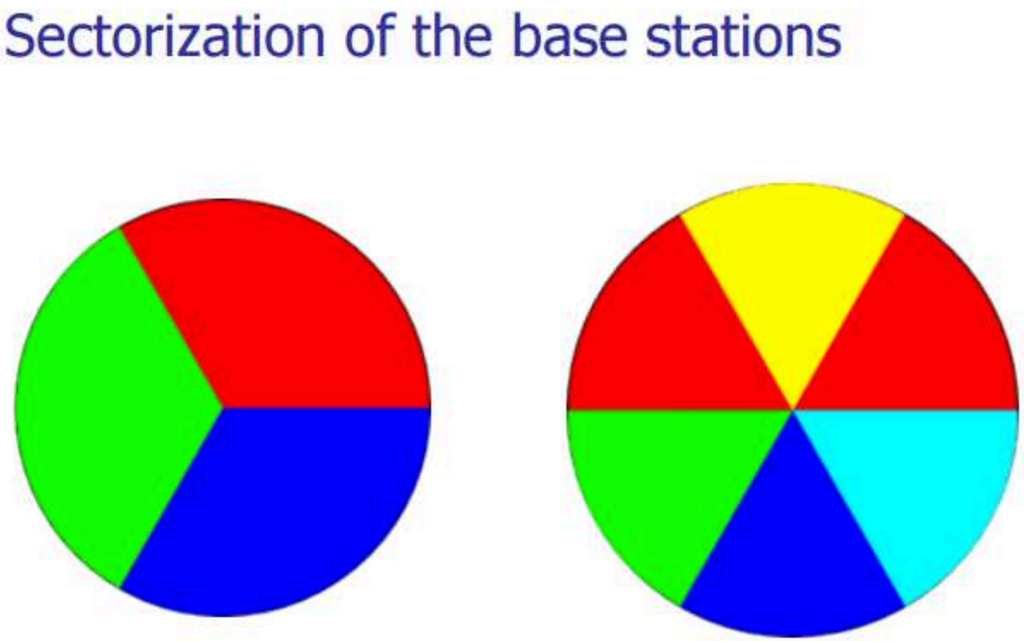
- to provide sufficient signal strength in the whole planning area.
- to provide sufficient radio resources for all users to be served.

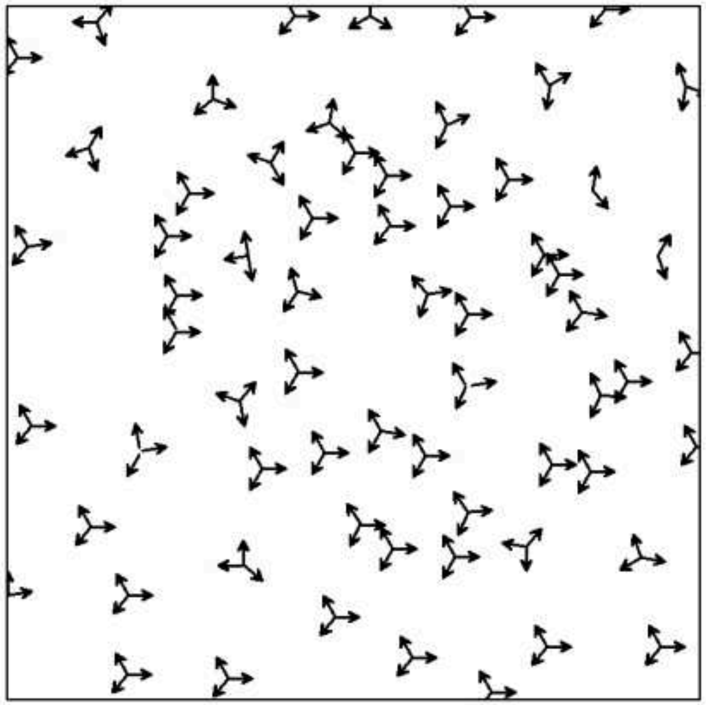
Degree of freedom:

- **Base Station Placement**
- **Antenna Configuration**
- **Radio Resource Management**

Base Station Placement

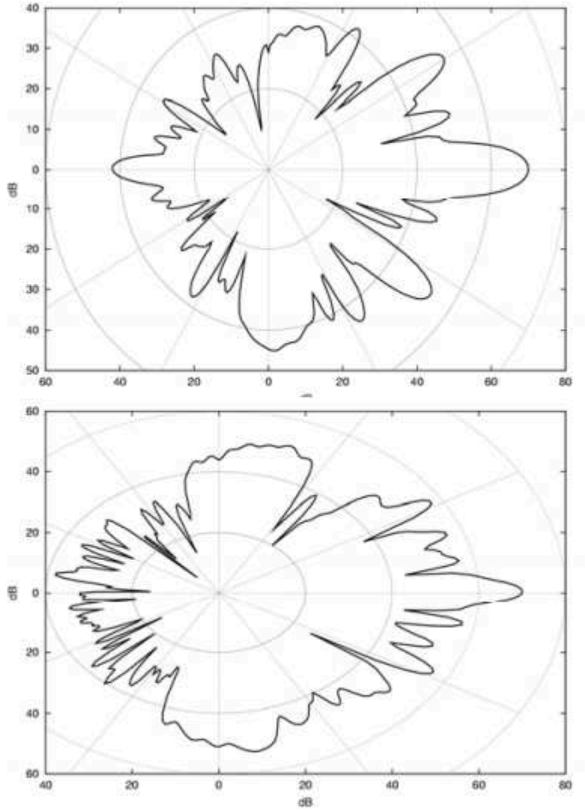
- Given a set of possible locations, select those where to place base stations and define the transmission powers (cell range, electro-magnetic field EMF limitations, etc.)

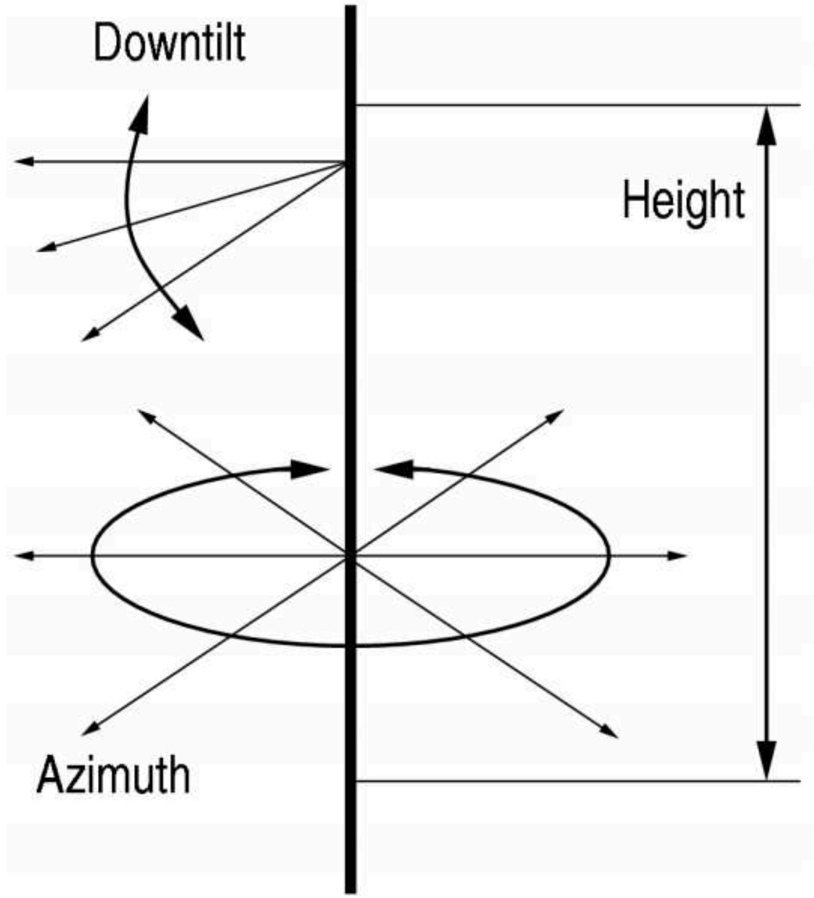




Antenna Configuration

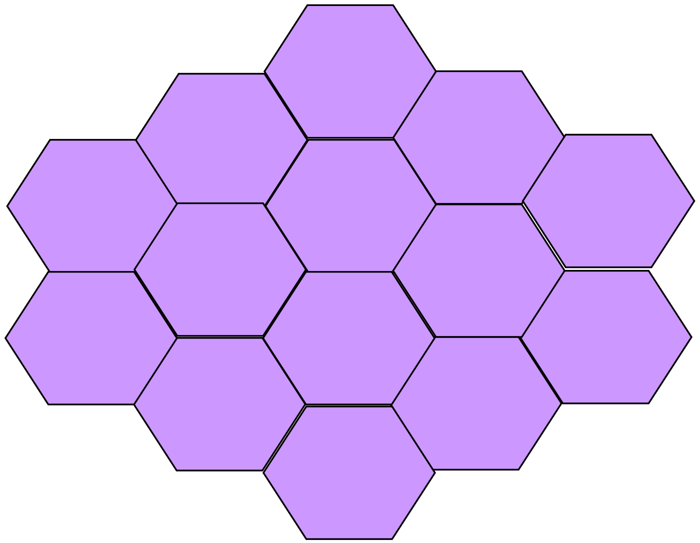
Antenna Type



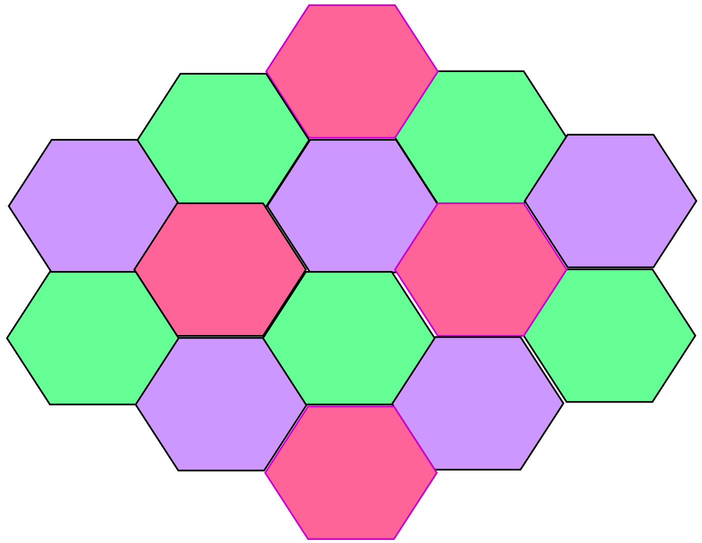


Frequency Planning

Every cell gets all radio bandwidth

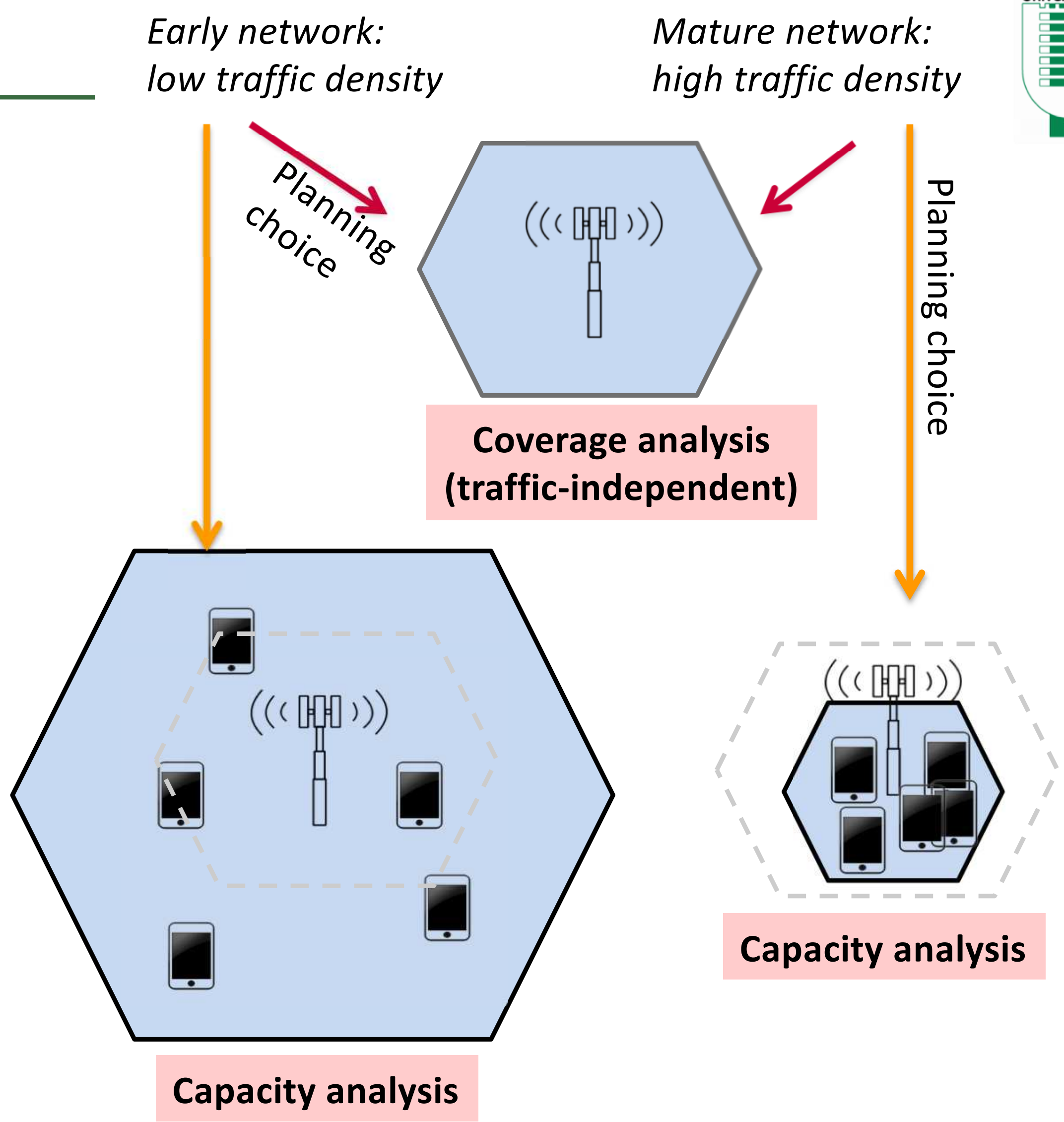


A cell gets 1/3 of radio bandwidth



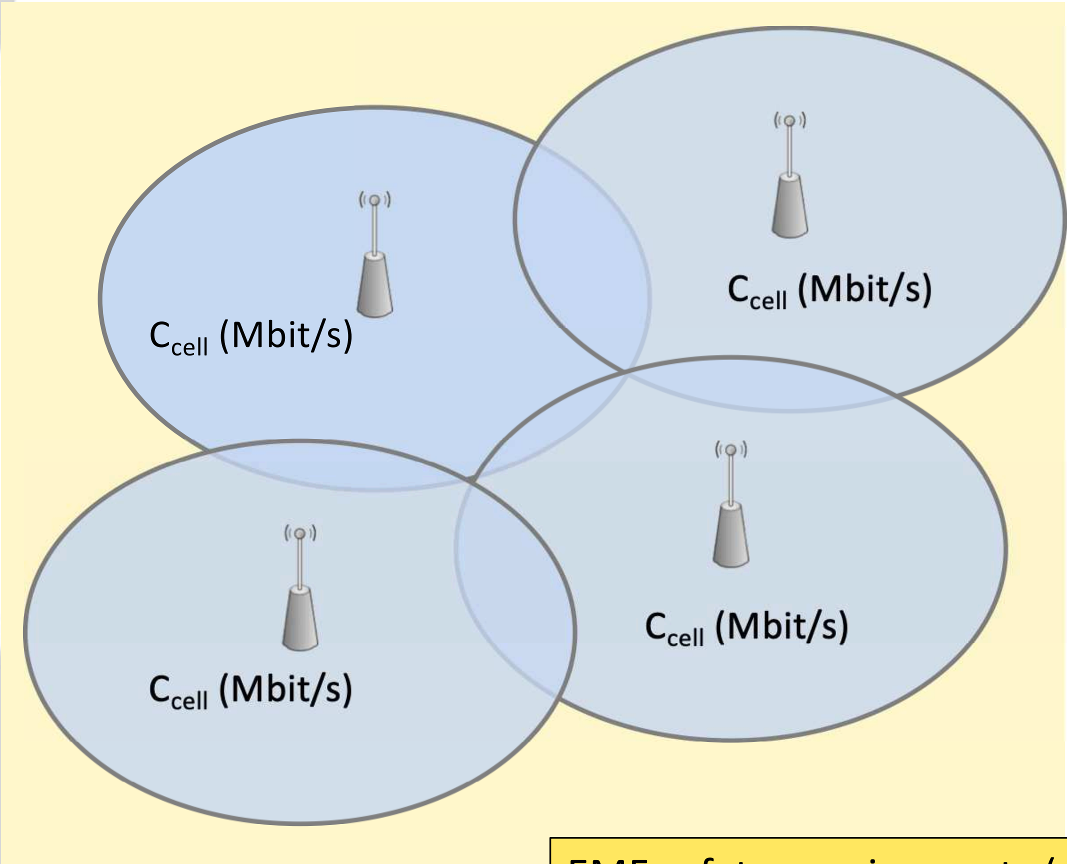
Coverage vs Capacity

- Both analysis end up with a cell size.
- For coverage planning, cell size is the greatest possible one. Power transmission is at the maximum value (including EMF constraints, e.g. 6 V/m).
- In case of capacity planning, the cell size is the maximum one so that the cell capacity (bit/s), shared among users, provide them with a minimum bit rate
- Smallest cell is the planning choice

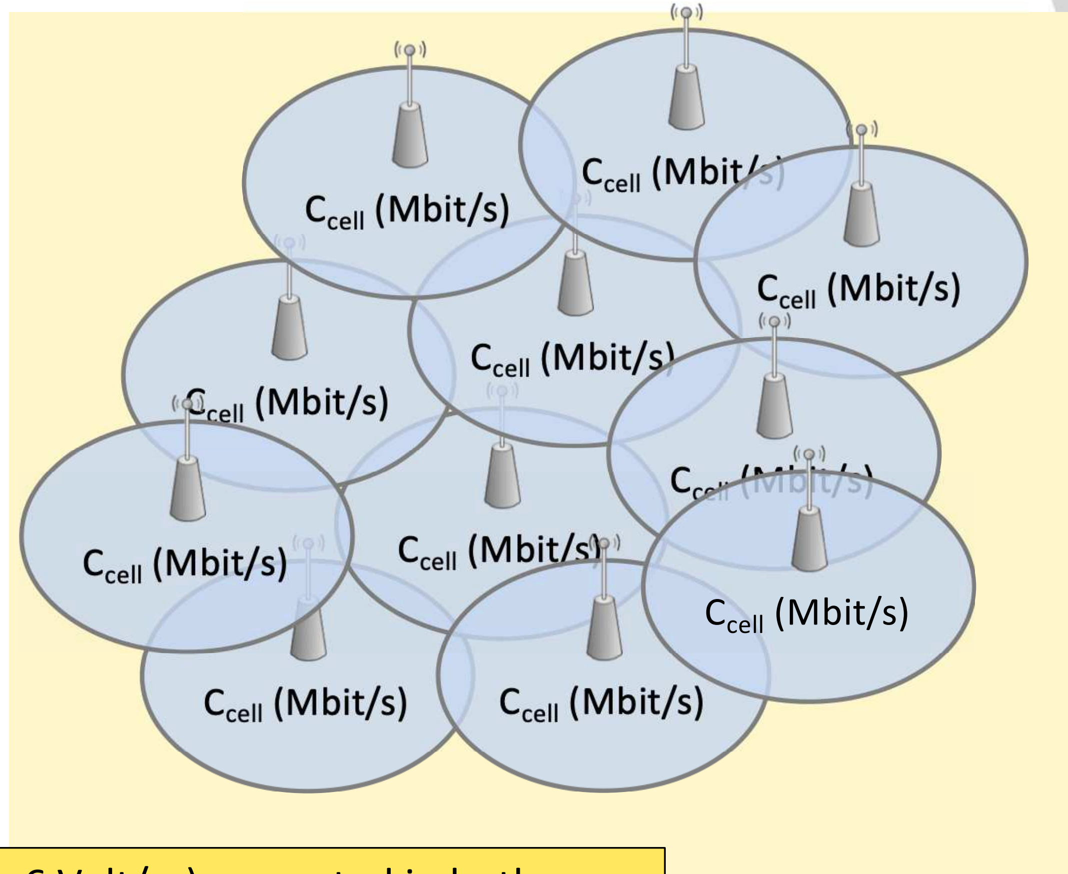


Network Spectral Efficiency: more cells, more capacity

Net Capacity = $4*C_{cell}$ Net Spectral Efficiency = $4*C_{cell}/B_{tot}$



Net Capacity = $11*C_{cell}$ Net Spectral Efficiency = $11*C_{cell}/B_{tot}$



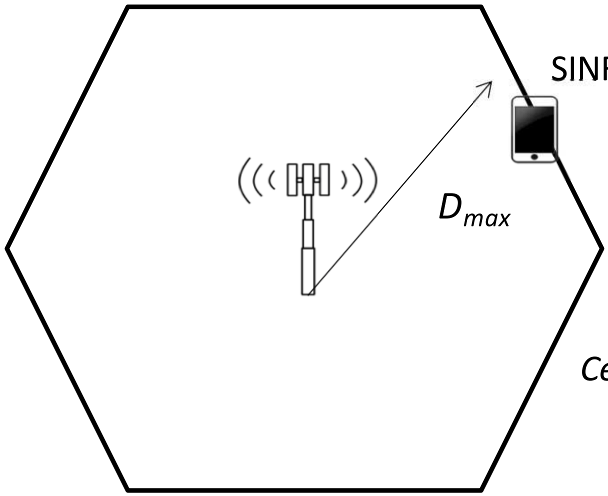
EMF safety requirements (e.g. 6 Volt/m) respected in both cases

Andrea Detti

COVERAGE PLANNING
(NO INTERFERENCE, SINGLE CELL)

RADIO COVERAGE

- Given a transmission power, where is the cell edge or which is the cell radius D_{max}?
- Cell edge is made by the most distant points on the territory where both of the following conditions occur:
  - **SINR (*signal quality*, RSRQ) is greater or equal to a minimum value $SINR_{min}$ (e.g. 0 dB)**
  - **Received power (*signal strength*, RSRP) is greater or equal to receiver sensitivity P_{rs} (e.g. -110 dBm)**
- Actually, **SINR matters** more than sensitivity because if you have good SINR, you also have good received power
- But measuring both provides insights about where problems are…power or interference
- If received power > sensitivity but SINR is bad → high inter-cell interference



From SINR to required signal power (S) via receiver sensitivity (*mostly used*)

- Without interference, **minimum signal power S_{min}** we must have in any point of the cell to have coverage is equal to the sensitivity.

$$S_{min} = P_{RS}$$

- Sensitivity depends SNR_{min} at reference temperature

$$S_{min} = P_{RS} = SNRmin * N = X * N$$

- SNR_{min} is the number of times (X) the signal power must be greater than noise to have good reception
- In presence of interference, “X times” must hold as well…but it is the SINR and not SNR

$$S_{min} = SINR_{min} * (N+I) = X * (N+I) = P_{RS} * (N+I/N) = P_{RS} * I_M \Rightarrow S_{min}\_dBm = P_{RS}\_dBm + I_M\_dB$$

- The Interference Margin (aka Noise rise) I_M is the increase of the AWGN disturbance due to the Interference with respect to only Noise
- With interference, the minimum signal power we must have in any point of the cell is equal to the sensitivity plus the interference margin
  - Sensitivity allows us to “win” versus thermal noise, interference margin versus interference

From SINR to required signal strength (*S*) via Shannon

- Constraints: user goodput R_b with bandwidth B_{eu}
- In case of an ideal modulation and coding scheme the minimum SINR to provide a lossless throughput (aka goodput) R_b can be computed inverting the attenuated Shannon formula

$$R_b = \alpha\, B_{eu} \log_2(1 + SINR_{min})$$

$$SINR_{min}\_dB = 10 \log_{10}\left(2^{\frac{R_b}{\alpha\, Beu}} - 1\right)$$

$$S_{min}\_dBm = \boldsymbol{SINR_{min}\_dB} + \boldsymbol{N}\_dBm + I_M\_dB$$

From SINR to required signal strength (S) via tables

Table 7.1 Lookup table for mapping SINR estimate to modulation scheme and coding rate

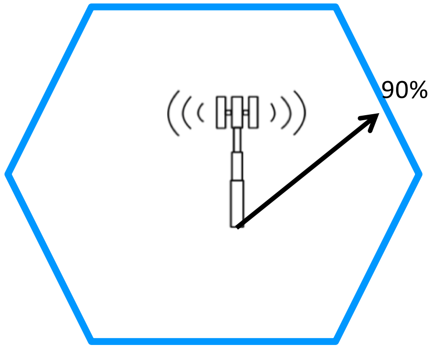
CQI index	Modulation	Coding rate	Spectral efficiency (bps/Hz)	SINR estimate (dB)
1	QPSK	0.0762	0.1523	−6.7
2	QPSK	0.1172	0.2344	−4.7
3	QPSK	0.1885	0.3770	−2.3
4	QPSK	0.3008	0.6016	0.2
5	QPSK	0.4385	0.8770	2.4
6	QPSK	0.5879	1.1758	4.3
7	16QAM	0.3691	1.4766	5.9
8	16QAM	0.4785	1.9141	8.1
9	16QAM	0.6016	2.4063	10.3
10	64QAM	0.4551	2.7305	11.7
11	64QAM	0.5537	3.3223	14.1
12	64QAM	0.6504	3.9023	16.3
13	64QAM	0.7539	4.5234	18.7
14	64QAM	0.8525	5.1152	21.0
15	64QAM	0.9258	5.5547	22.7

$$R_b = \eta_{min}\, B_{eu}$$

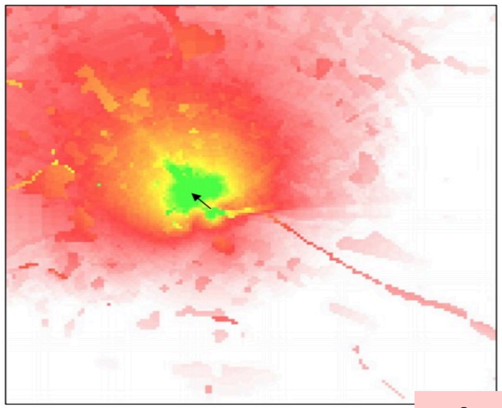
Solving equation for η_{min} , then use the table

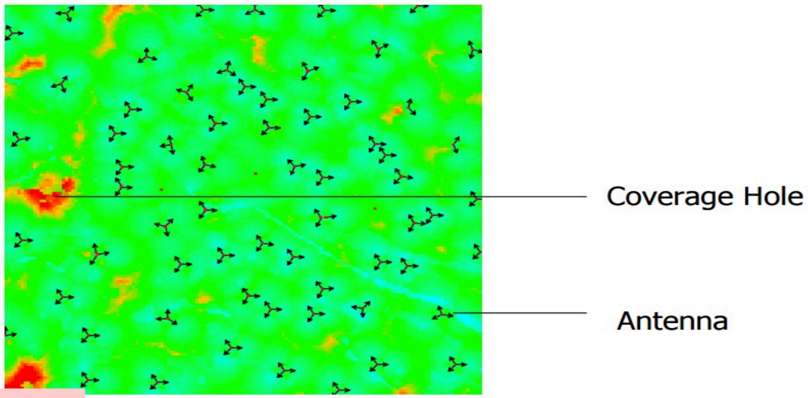
RADIO COVERAGE

- Due to the randomness of propagation impairments (e.g. shadowing), the cell edge can be identified in probabilistic terms, i.e. points covered the 90% of time
- Initially, radio coverage can be sketched up through analytic means
- Finally, radio coverage is usually determined by complex simulation tool, which for any location accounts for the environment, the traversed obstacles from transmitter to receiver, etc.…resulting coverage area has an irregular form
  - Color are related to signal power or SINR



Analytical





Simulation

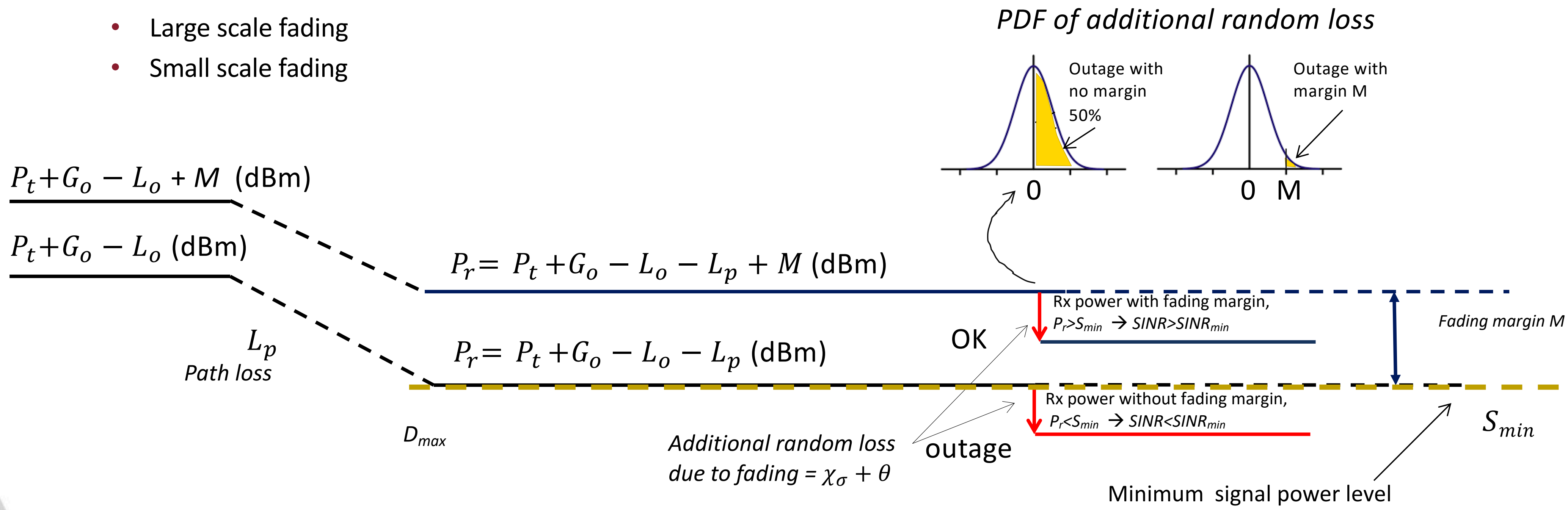
Single cell **Whole network**

Required signal power *S* example

- Computation example via $SINR_{min}$
- a: B_{eu} = 2*12*15 kHz = 55.6 dB Hz (2 * 4G/5G RBs @ 15kHz of scs)
- b: Noise spectral density kT_0 = -174 dBm Hz^{-1}
- c: Noise figure F = 3.5 dB
- d: Interference Margin = 3 dB
- e: SINRmin = -6.7 dB
- f: Required Signal Power S_{min} = a+b+c+d+e= -118.6 dBm

Fading margin

- In presence of random fading, the average received power at cell edge must be greater than *S* of an amount named *fading margin*
- The fading margin can be seen as a **budget of additional receiving power** that we use to cope with **additional random signal loss** due to fading
  - Large scale fading
  - Small scale fading



Fading margin

- How many dB for *M* ?
- Fading is a random phenomena, thus the more *M*, the higher the probability that received signal power is above S_{min} and SINR requirements are satisfied
- An amount *M* of fading margin provides a coverage probability *F* at cell edge, and generally at a given distance *d*
- Dimensioning problem: which value of *M* is required to have a coverage probability *F* at cell edge ?

Fade margin

- Radio coverage at cell edge is guaranteed if the margin *M* is greater than fading losses

$$M > \chi_\sigma + \theta$$

- Where χ_σ is the random loss due to large-scale fading (shadowing)
- And θ is the random loss due to small-scale fading

Small and Large scale fading margins

- To simplify the coverage design we assume to ideally split the extra power *M* in two contributions:

  - Large-scale fade margin M_L
  - Small-scale fade margin M_s

- Where $M = M_s + M_L$

- Sufficient (<u>but not necessary</u>) conditions to have coverage are

$$M_L \geq \chi_\sigma$$
$$M_s \geq \theta$$

- This is a conservative condition because, $M_s + M_L \geq \chi_\sigma + \theta$ is necessary to have coverage

Small and Large scale fading margin

- Small scale and large scale fading phenomena do not depend on the distance. Indeed, there are Rayleigh and Log-normal distributed
  - Path loss depend on distance, not small and large scale fading
- Accordingly, we can solve the following equations to obtain the margins required at the cell edge, namely

$$\Pr[M_L \geq \chi_\sigma] = F \rightarrow M_L^*$$
$$\Pr[M_s \geq \theta] = F \rightarrow M_s^*$$

- E.g. M_L^* = 8 dB and M_s^* = 2 dB to have *F*=0.95 (95% of coverage probability)

Link Budget and Cell radius

- Once margins are determined, we can compute the cell radius D_{max} using a **link budget**
- At the cell edge we need:

$$\begin{cases} P_{RS}\_dBm + I_M\_dB \\ SINR_{min}\_dB + N\_dBm + I_M\_dB \end{cases}$$

$$P_r(D_{max})\_dBm = S_{min}\_dBm + M_L^*\_dB + M_s^*\_dB$$
$$= P_t\_dBm + G_o\_dB - L_o\_dB - L_p(D_{max})\_dB$$

- The only variables that depends on distance D_{max} is the path loss L_p
- Thus to determine D_{max} we need to solve the following eq.

$$L_p(D_{max}) = P_t + G_o - L_o - M_L^* - M_S^* - S$$

Small-scale fading margin computation

- Usually the **small-scale fading** loss θ is faced with dedicated **receiver intelligence**, which completely or partially cut down the power loss effect
  - Channel equalization, cyclic prefix, Rake receiver, multiple antenna, etc.
- Moreover severe small-scale fading conditions usually last few milliseconds due to user movements (short time fading) and, in case retransmissions (data services) or concealing techniques (voice service) can recover the small-scale fading “damages”
- According, we can neglect the presence of the small-scale fading, or in the worst case taking into account of it with by requiring a constant small margin M_S^* (e.g. **2.0–5.0 dB**)
  - receiving **intelligence can temporary fail** and this can be crucial for slowly moving users
- Without receiver intelligence required small-scale fading margin would be severe (20-30 dB) so as making cells extremely small and deployment extremely costly

Large-scale fading margin computation

- Large-scale fading, i.e. shadowing, can not be recovered by receiver intelligence since is a flat reduction of the signal power that last for a long time (e.g. all the time I am in my house)
- We can compute the margin M_L^* required at the cell edge by leveraging on the log-normal characterization of large-scale fading and solving the following equation

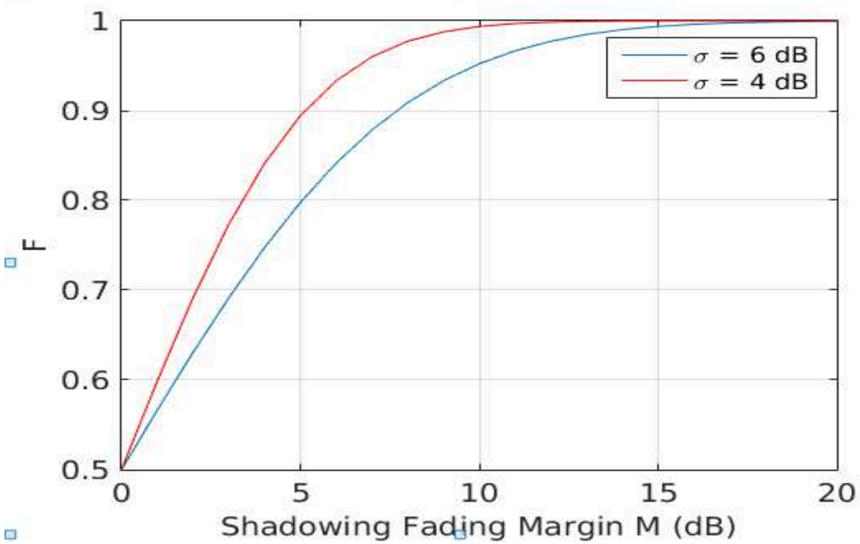
$$F = P[\chi_\sigma \leq M_L^*] = \int_0^{M_L^*} f(x)dx = \frac{1}{2} erfc\left[-\frac{M_L^*}{\sigma\sqrt{2}}\right]$$

$$\mathrm{f}(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{x^2}{2\sigma^2}\right]$$

Large-scale fading margin computation

- Equation can be solved using erfc tables/plot
  - e.g. M_L^*=5 dB for *F*=0.8 for σ = 6dB
- The stronger the large-scale fading (greater σ) and/or the higher the coverage probability *F* , the greater the required margin M_L^*

$$\frac{1}{2}\,\mathrm{erfc}\left[-\frac{M}{\sigma\sqrt{2}}\right] = F$$



Cell radius - example

- Standard deviation of shadowing is 6 dB, small-scale fading completely recovered by the receiver, required signal *S* at cell edge -110 dBm, tx-rx antenna gain 10 dB, other losses rather than path loss 2dB, log-distance path loss with index γ = 3, transmit power 20 dBm, path loss at 1 km = 100 dB, coverage probability 0.8 ($\mathrm{M}_{\mathrm{L}}^{*}$=5)

Tx power (P_t)	20 dBm
Other gains (G_0)	10 dB
Other losses (L_0)	2 dB
Shadowing margin (M_L^*)	5 dB
Rx min (S):	-110 dBm
Allowed path loss $L_p(D_{max})$	20+10-2-5-(-110) = 133 dB
Coverage radius D_{max} (km)	solve eq. 133=100+10*3*log10(Dmax/1) --> 12 km

$$L_p = \overline{L_p}(d_0) + 10\,\gamma\,\log\left(\frac{d}{d_0}\right)\ \mathrm{dB}$$

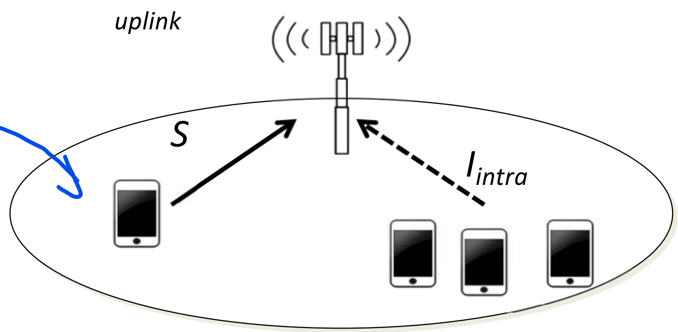
COVERAGE PLANNING (INTERFERENCE, MULTIPLE CELLS)

Interference

- A cellular system works in an interfered environment, since the same radio resource is **re-used** in close cells
- Interference impacts SINR, thus we need to account it in the coverage planning
- The ability to limit the amount of interference or to limit its effects without loosing system capacity is a key asset of a cellular technology
  - 2G, 3G, 4G, 5G are more and more able to handle interference effects
- We could classify interference as
  - **Intra-cell** : the interference generated by transmitters inside the cell
  - **Inter-cell** : the interference generated by transmitters of near cells

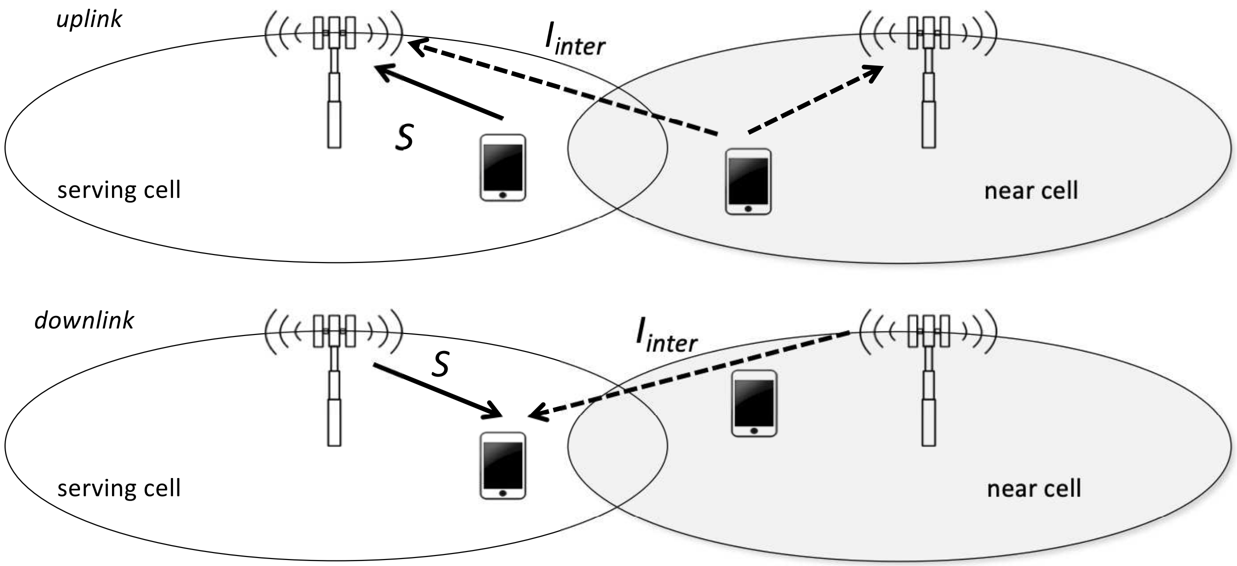
Intra-cell Interference

- Transmissions inside a cell may not be orthogonal, e.g.
  - in case of CDMA system not using orthogonal codes, e.g. UMTS (3G) uplink
  - In case of OFDMA systems with phase errors (may be limited)
  - In case of TDMA system with wrong timing sync (may be limited with timing advance)
- Usually occurs in the uplink direction
- To limit intra-cell interference, cell load should be limited
- Intra cell interference may dramatically change SINR while changing the cell traffic.
  - Cell Breathing



Inter-cell Interference

- Transmissions generated within near cells may not be orthogonal, e.g.
  - in case of CDMA systems not using orthogonal codes, e.g. UMTS (3G) uplink and downlink
  - In case of FDMA, OFDMA systems reusing frequency in near cells



Inter-Cell Interference reduction for FDMA/OFDMA multiple access

RESOURCE REUSE

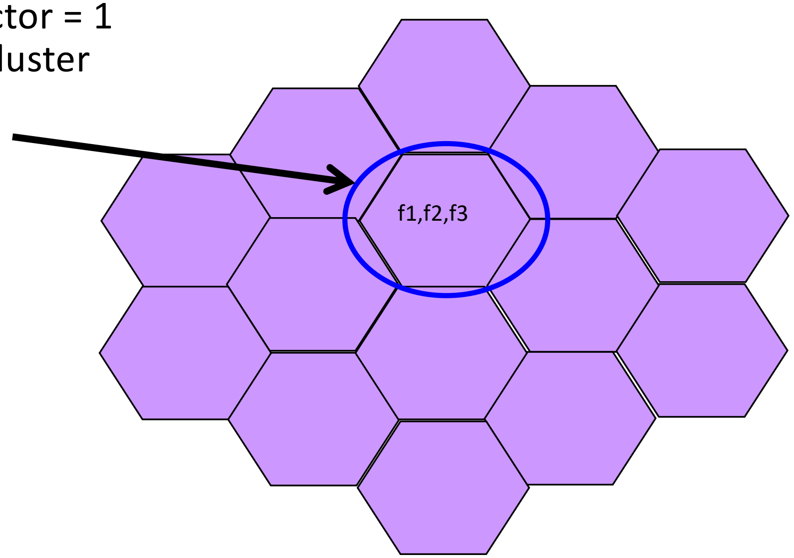
Inter-cell interference

- To reduce inter-cell interference different “channels” should be used in close cells
  - Channels is a generic terms depending on the access scheme (frequency, time, code, etc)
- Channel allocation can be:
  - A Fixed pattern of resource assigned to network cells
  - A Dynamic pattern, depending on the traffic condition of neighbor cells (Inter-Cell Interference Cancellation ICIC)
- Note: we are considering FDMA/OFDMA schemes where only one transmitter per cell can create interference
  - Neglecting MU-MIMO
  - In case of CDMA access all transmitters of a cell create interference, albeit reduced by the processing gain

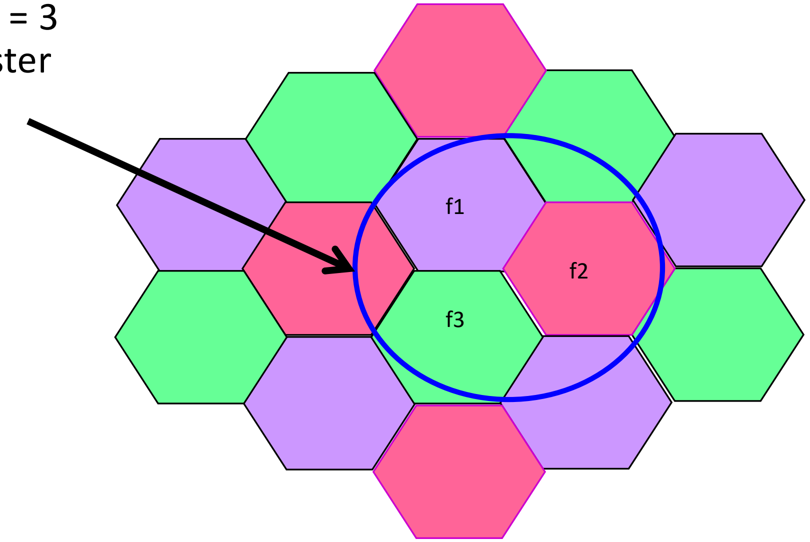
Fixed Channel Allocation (FCA)

- Representing the cell as an hexagon. Channel = bulk of frequencies
- Let us define **cluster** a cell pattern in which the whole spectrum bandwidth B_{tot} is used only one time
- The reuse factor ***N*** is defined as the number of cells in the cluster
- Frequency planning defines which frequencies in which cell of the cluster

Reuse factor = 1
1 Cell x Cluster
$B_{cell} = B_{tot}$

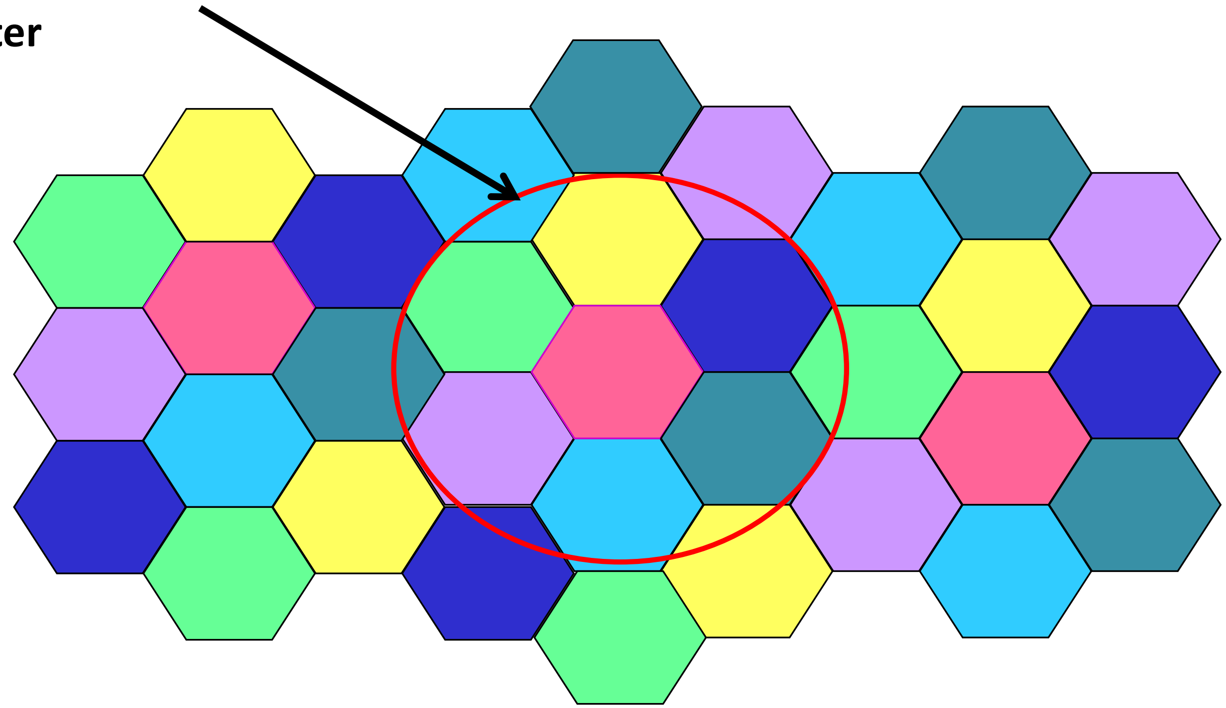


Reuse factor = 3
3 Cells x Cluster
$B_{cell} = B_{tot}/3$



Fixed Channel Allocation

Reuse factor = 7
7 Cell x Cluster
$B_{cell} = B_{tot} / 7$



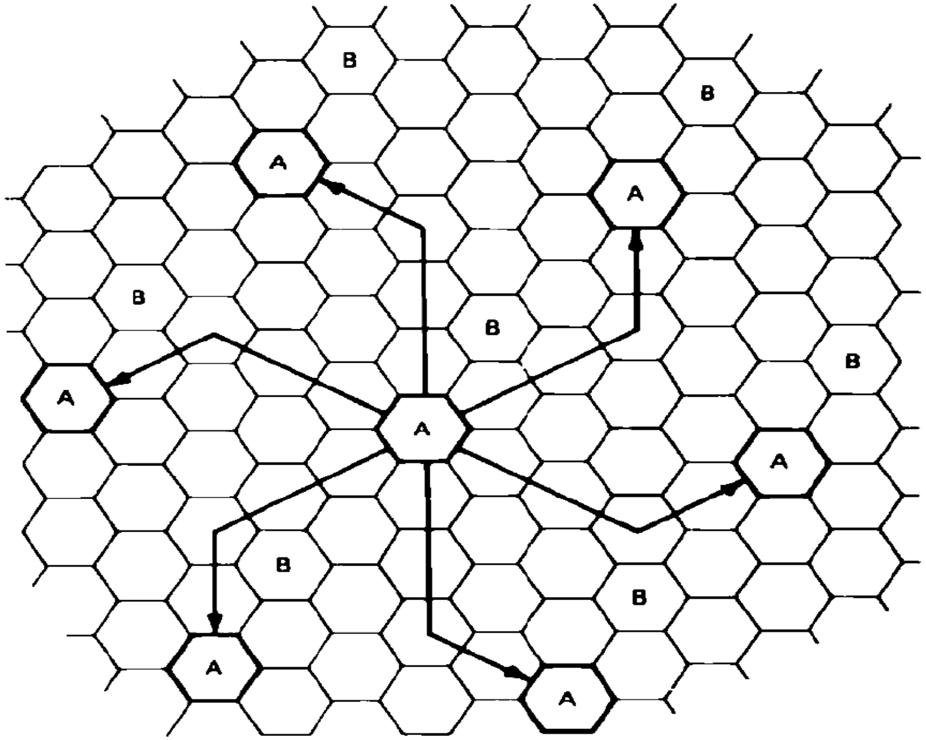
Fixed Channel Allocation - Algorithm

Mac Donald, Verne H. "Advanced mobile phone service: The cellular concept." Bell System Technical Journal, The 58.1 (1979): 15-41.

To lay out a cellular system in the sense of determining which channel set should be assigned to each cell, we begin with two integers i and j ($i \geq j$), called "shift parameters," which are predetermined in some manner. From the cellular pattern of Fig. 4, note that six "chains" of hexagons emanate from each hexagon, extending in different directions. Starting with any cell as a reference, we find the nearest "co-channel" cells, that is, those cells that should use the same channel set, as follows:

> Move i cells along any chain of hexagons; turn counter-clockwise 60 degrees; move j cells along the chain that lies on this new heading.

$$N = i^2 + ij + j^2.$$



SHIFT PARAMETERS: i = 3, j = 2

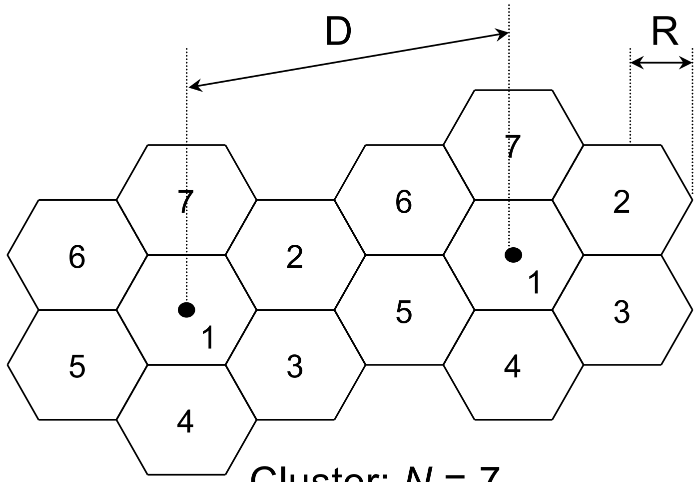
Computation of Inter-Cell Interference – FCA

Reuse distance *D*: distance between two antennas that use the same set of frequencies

R = cell radius distance between the center of the hexagon and one of the vertexes

N = reuse scheme/factor (cluster size)

Not all values of *N* are possible (1,3,4,7,9,12,13,16,19,...)



Cluster: *N* = 7

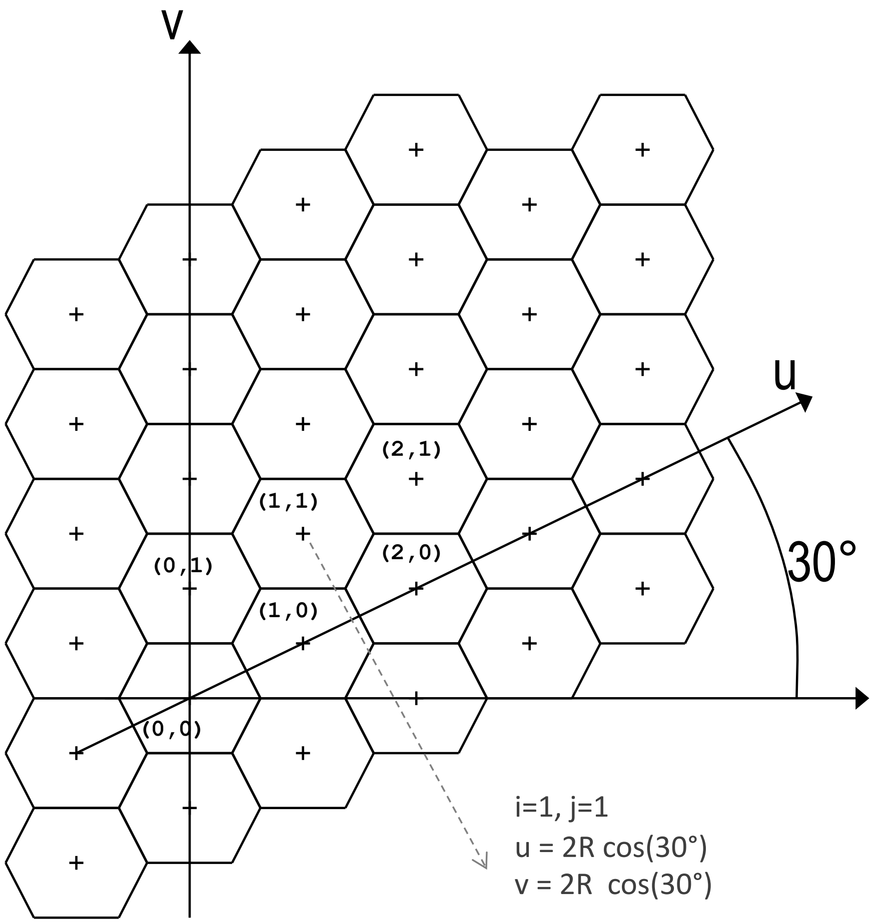
Computation of Inter-Cell Interference – FCA

- Let us consider a non-orthogonal reference system (u,v), whose axes traverse cell centers
- Let us define cell (i,j), the cell whose center coordinates are $u = i \cdot 2R \cos(30°)$, $v = j \cdot 2R \cos(30°)$ on the (u,v) reference axes
- Using trigonometric rules, we can derive the distance D_{ij} between the cell (0,0) and the cell (i,j) as

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

- Moreover, if the reuse scheme is N the reuse distance is

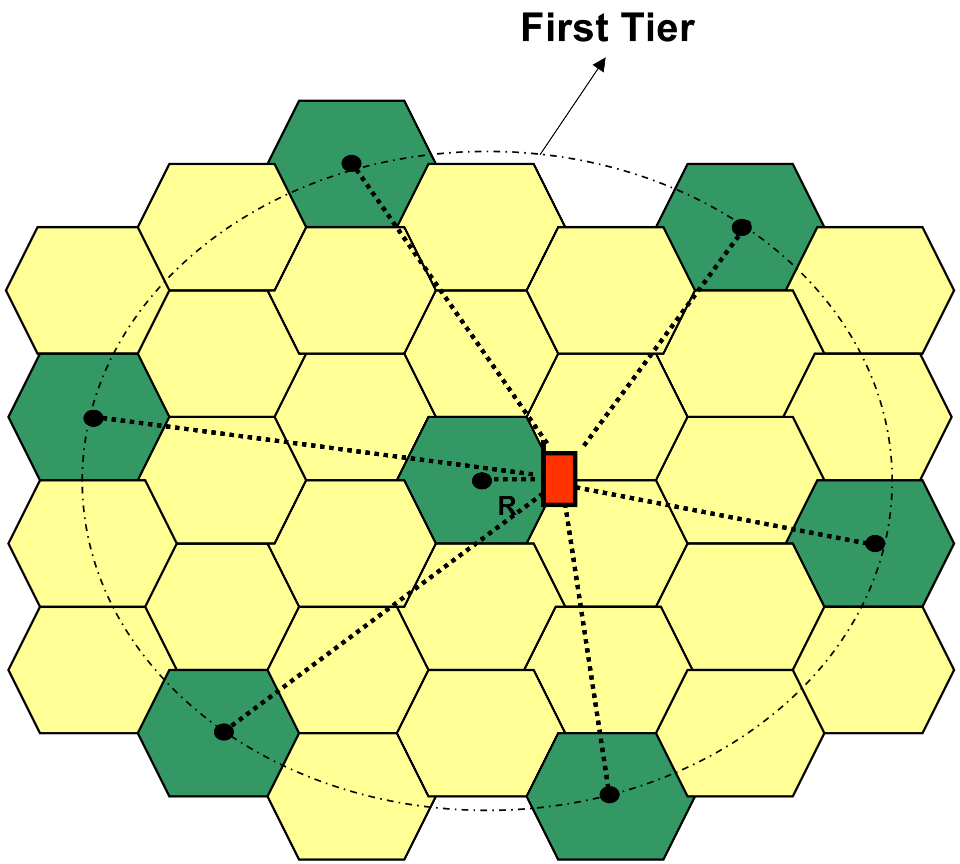
$$D = R\sqrt{3N}$$



Given these assumptions, the analysis likely aims to evaluate the performance of a cellular network under typical deployment scenarios where interference from neighboring cells plays a significant role. The log-distance path-loss model is a common way to represent how the signal strength attenuates with distance, and the consideration of equal power transmission without power control simplifies the analysis while providing insights into the impact of interference in the network.

Computation of Inter-Cell Interference – FCA–Downlink – Omnidirectional Antennas

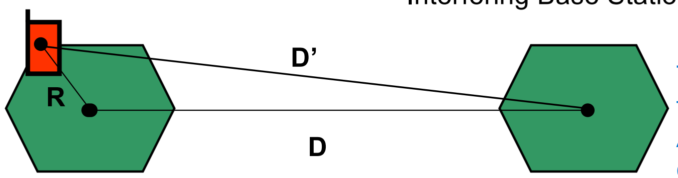
- Assumptions:
  - All cells equal
  - Reference mobile at cell edge
  - Log-distance path-loss model $L_p(d)=L_0*(d/d_0)^\gamma$
  - Base stations transmit with equal power towards all mobiles (no power control)
  - Inter-cell interference only coming from first-tier cells reusing the same channels
    - N_i = 6, number of interfering cells



Computation of Inter-Cell Interference – FCA–Downlink – Omnidirectional Antennas

Approximated model:

- Distance between interfering base station and reference mobile = *D*



$$D' \cong D$$

Reuse Factor (N):

The reuse factor (N) determines how frequently the same frequency channels are reused across the network.
A lower reuse factor means that the same frequency channels are reused more frequently, leading to higher interference.
Therefore, a lower reuse factor results in a lower SINR due to increased inter-cell interference.

$$SIR_{inter} = \frac{S}{I_{inter}} = \frac{R^{-\gamma}}{N_i \ D^{-\gamma}} = \frac{1}{N_i}\left(\sqrt{3N}\right)^{\gamma} = \frac{1}{6}\left(\sqrt{3N}\right)^{\gamma}$$

- Signal to Inter-cell interference does not depend on cell size, but only on reuse factor N, number of interfering cells Ni and path loss exponent

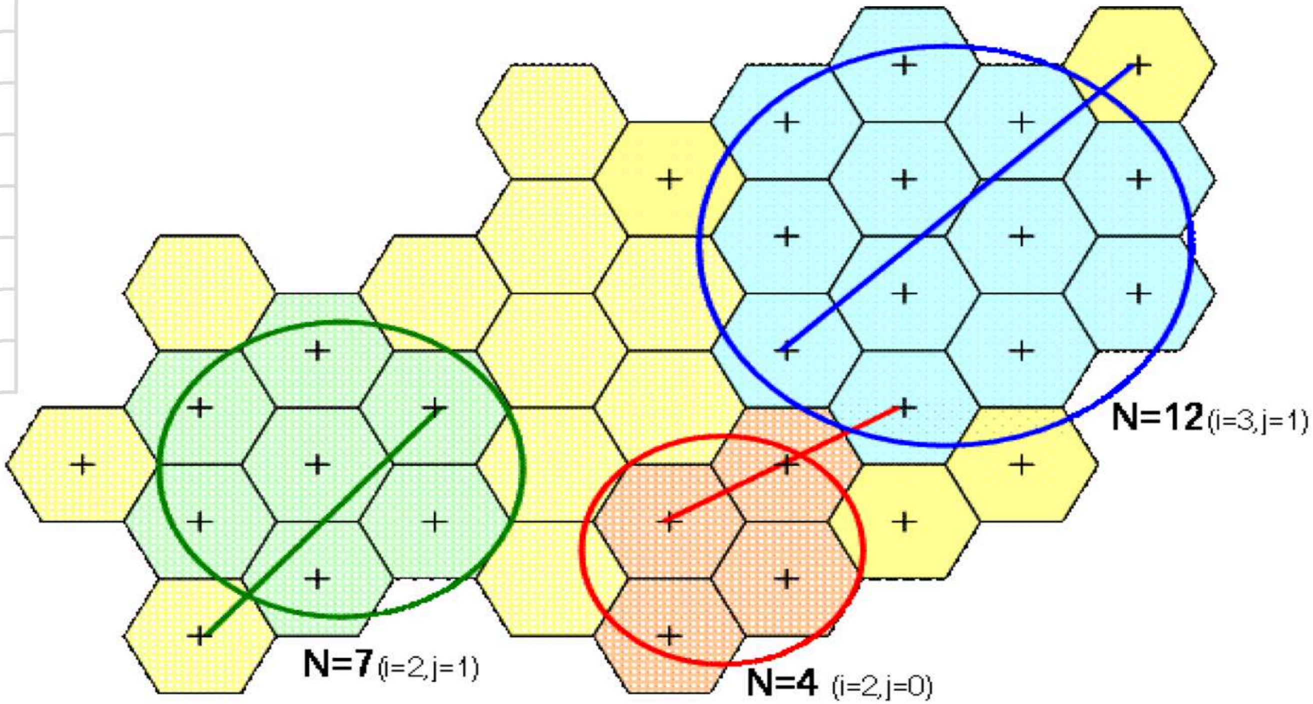
In summary, in a cellular network with equal-sized cells and equal power transmission, the SINR primarily depends on factors such as the number of interfering cells, path loss exponent, and reuse factor, rather than the size of individual cells. These factors collectively determine the interference levels and thus the SINR experienced by mobile receivers in the network.

Computation of Inter-Cell Interference – FCA – Downlink – Omnidirectional Antennas

Assumptions : $\gamma = 4$

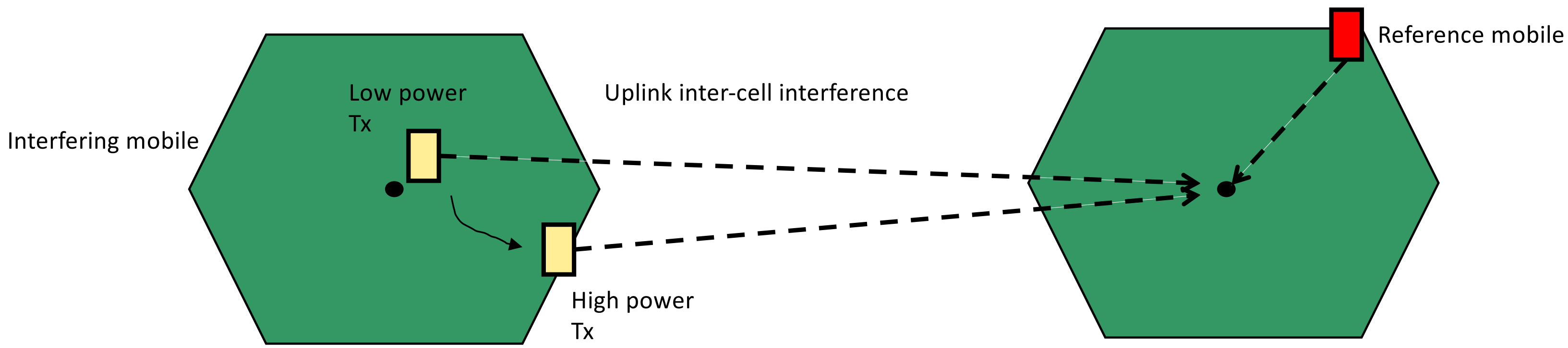
N	SIR	SIR dB	
1	1.5	1.8	
3	13.5	11.3	
4	24.0	13.8	
7	73.5	18.7	
9	121.5	20.8	
12	216.0	23.3	
13	253.5	24.0	
16	384.0	25.8	
19	541.5	27.3	
21	661.5	28.2	

The more the reuse the more the SIR



Computation of Inter-Cell Interference – FCA – Uplink – Omnidirectional Antennas

- Uplink interference, i.e. interference at base station coming from a mobile in other cells is difficult to be analytically evaluated since:
  - mobiles are not in fixed locations and
  - depending on the mobile location, the power control mechanism leads to different transmitting power thus different interference (base station usually uses fixed power)
- In any case, the more the reuse is, the lower is the interference because distance is greather

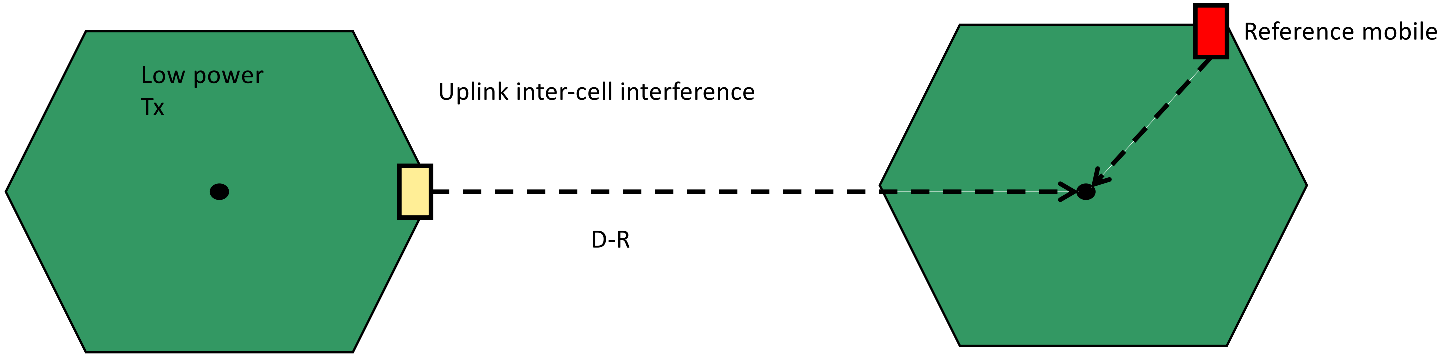


In summary, while higher reuse factors may lead to greater distances between co-channel cells, which can reduce interference to some degree, accurately evaluating uplink interference analytically remains challenging due to the dynamic nature of mobile locations and the complexities introduced by power control mechanisms. Practical interference management often involves a combination of techniques such as power control, interference coordination, and frequency planning to optimize network performance.

Computation of Inter-Cell Interference – FCA – Uplink – Omnidirectional Antennas

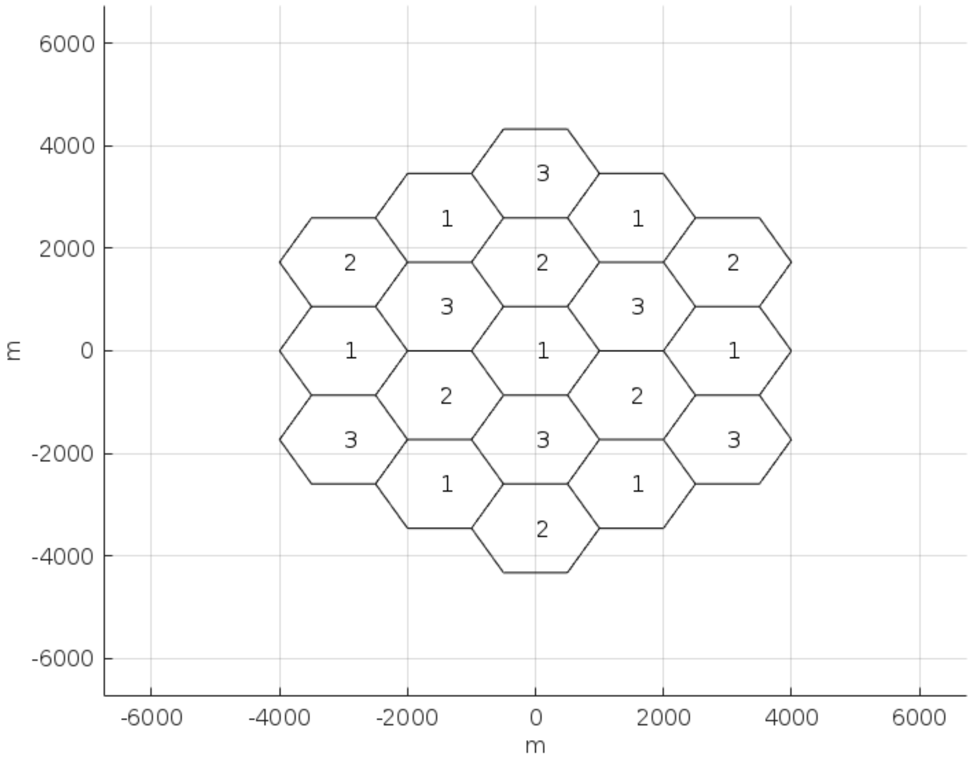
- Approximated model: interfering mobile in the bs-bs direction and at cell edge. Reference mobile at cell edge. No power control.
- Reusing the formula for downlink, assuming interfering at cell edge and reference mobile at cell edge

$$SIR_{inter} = \frac{S}{I_{inter}} = \frac{R^{-\gamma}}{N_i \ (D-R)^{-\gamma}} = \frac{1}{N_i}\left(\sqrt{3N} - 1\right)^{\gamma}$$



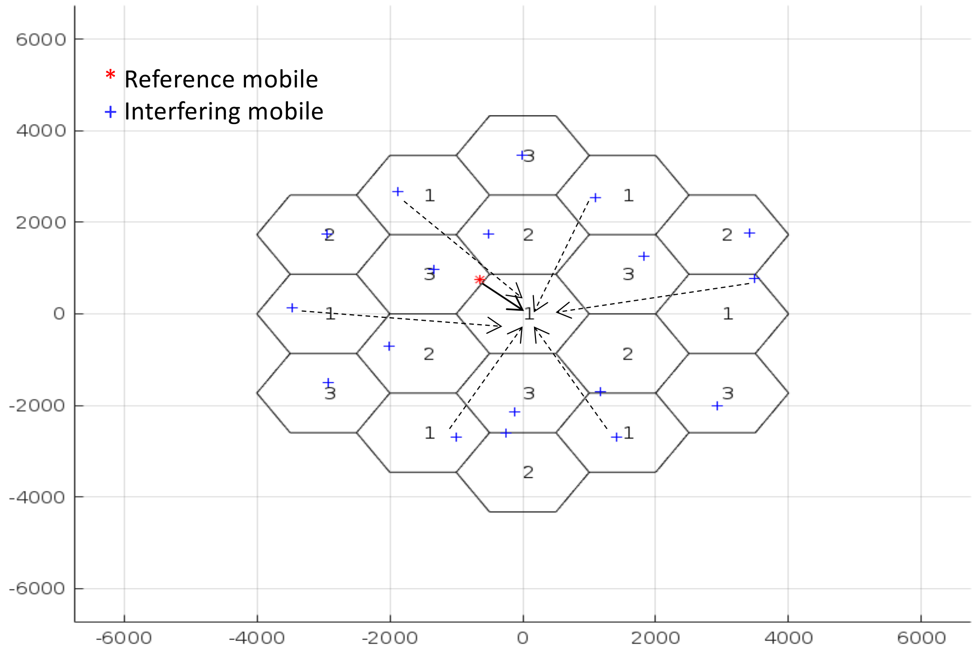
Inter Cell Interferences: Simple Simulator

- Simple Matlab Simulator developed by Andrea Detti for MWN
- Deploy base stations in a grid geometry
- Cell radius R (not relevant for SIR)
- Fixed Channel Assignment using a reuse factor *N*
- Consider only base stations of the first tier
- Reference base station at (0,0)
- Reference mobile at cell edge with random angle



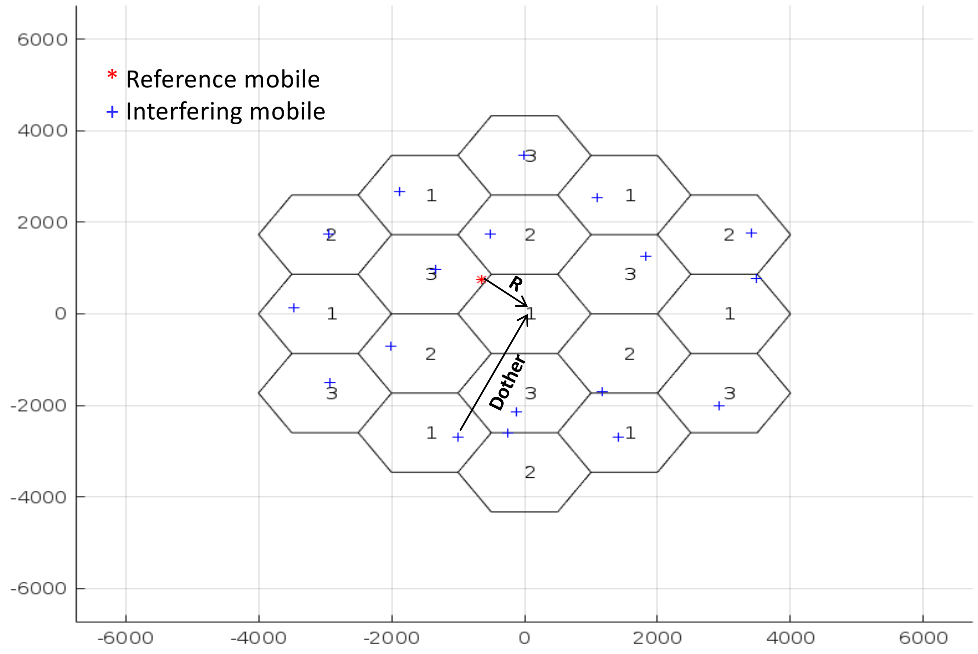
Inter Cell Interferences: Uplink simulation

- Deploy a single interfering mobile in a random position within each cell
- Compute Rx power of reference mobile and interfering mobiles at base station of reference mobile



Inter Cell Interferences: Uplink Simulation

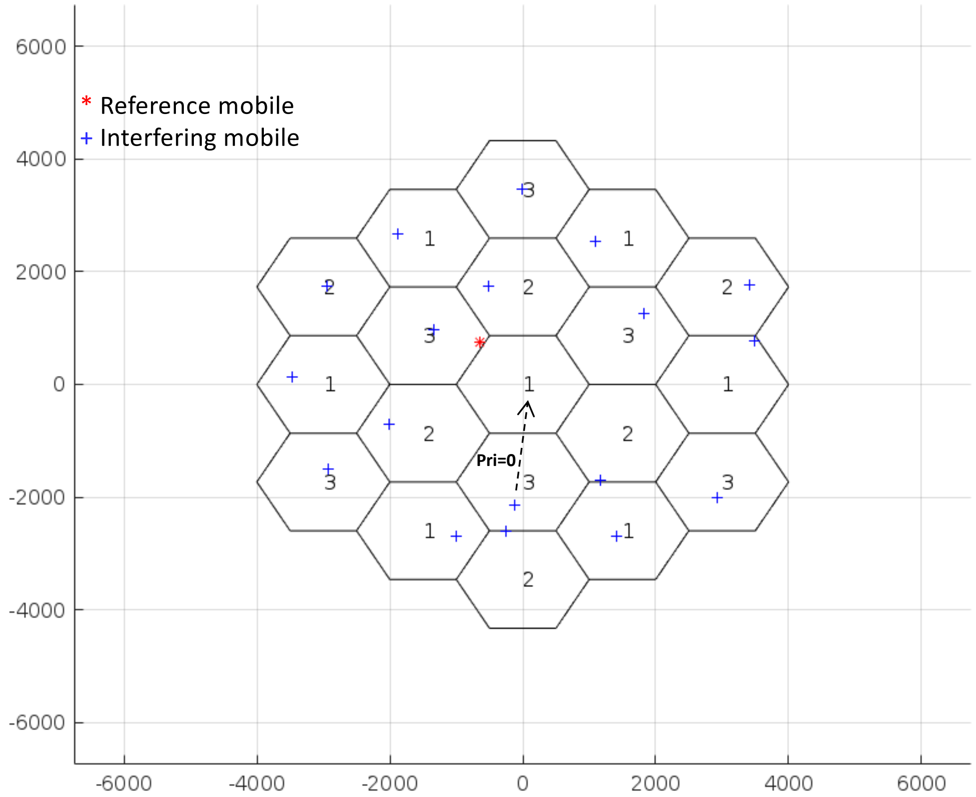
- No power control ***Ptx*=const=*Prx_t* * (*R*)**$^{\gamma}$, equal for each mobile
  - The value is so as achieving a *target* received power *Prx_t* when mobile is located at cell edge (R)
  - When closer, the received power is greater than this target
- With power control ***Ptx* = *Prx_t* * (*r*)**$^{\gamma}$
  - Ptx controlled to have the target Prx_t when mobile is in any position (*r*)
- Rx power from reference mobile: ***Prx= Ptx* (*R*)** $^{-\gamma}$
- Rx power from interfering mobile (Pri) at reference BS, ***Pri = Ptx* (*Dother*)** $^{-\gamma}$
- With log-distance model, the values of *Prx_t* and *d0* are not relevant to compute a power ratio: SIR



Inter Cell Interferences: Uplink Simulation

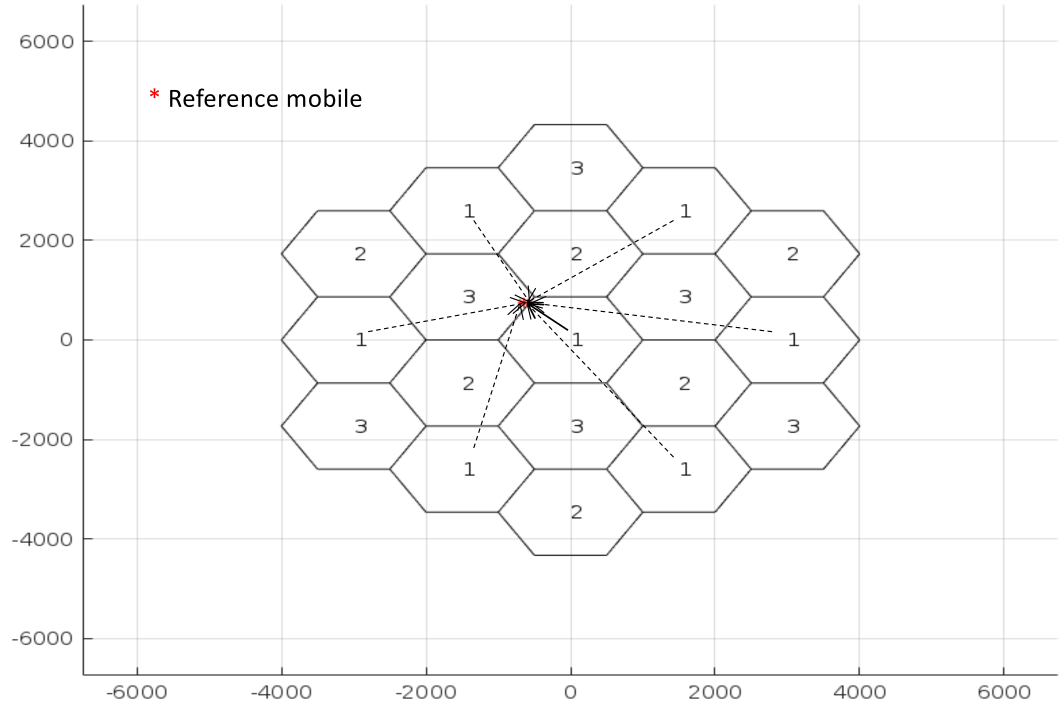
- $SIR_{inter} = Prx / \Sigma Pri$

- Pri = 0 if interfering and reference stations use different
    - Channels, sectors,
    - or no load (see later)



Inter Cell Interferences: Downlink simulation

- Deploy reference mobile at cell edge, random angle
- Compute Prx power of reference and interfering base stations at reference mobile

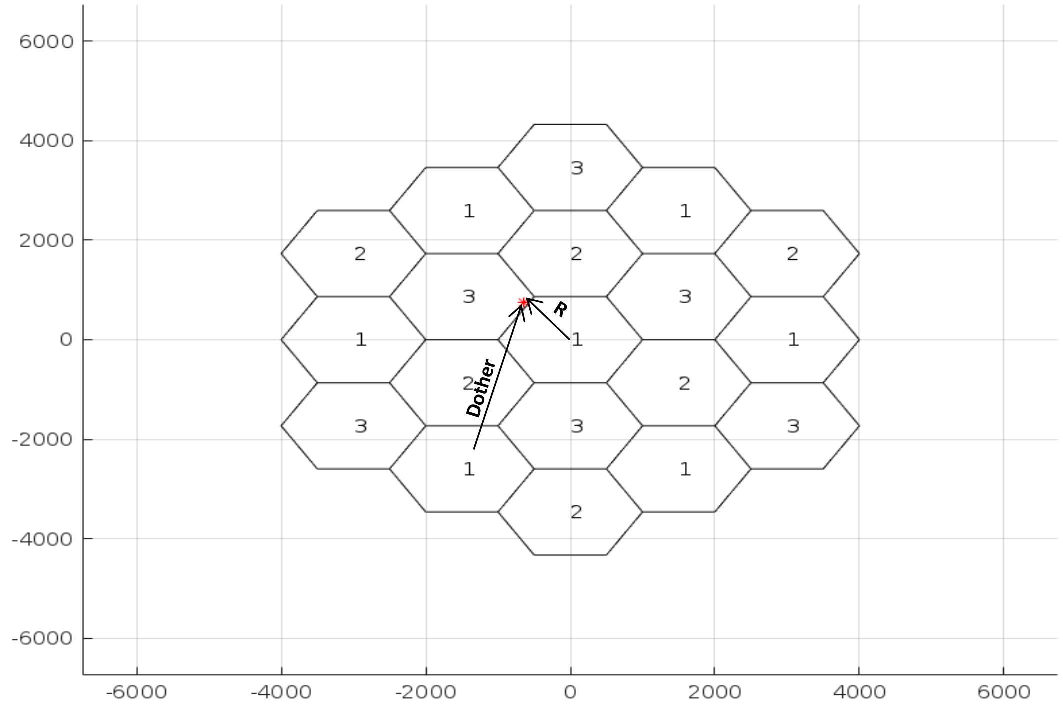


Interfering mobile

Inter Cell Interferences: Downlink simulation

- No power control case **Ptx = Prx_t (R)**$^{\gamma}$
- With power control **Ptx = Prx_t (r)**$^{\gamma}$
- Rx power from reference mobile: ***Prx= Ptx (R)*** $^{-\gamma}$
- Rx power from interfering mobile (Pri) at reference BS, ***Pri = Ptx (Dother)*** $^{-\gamma}$

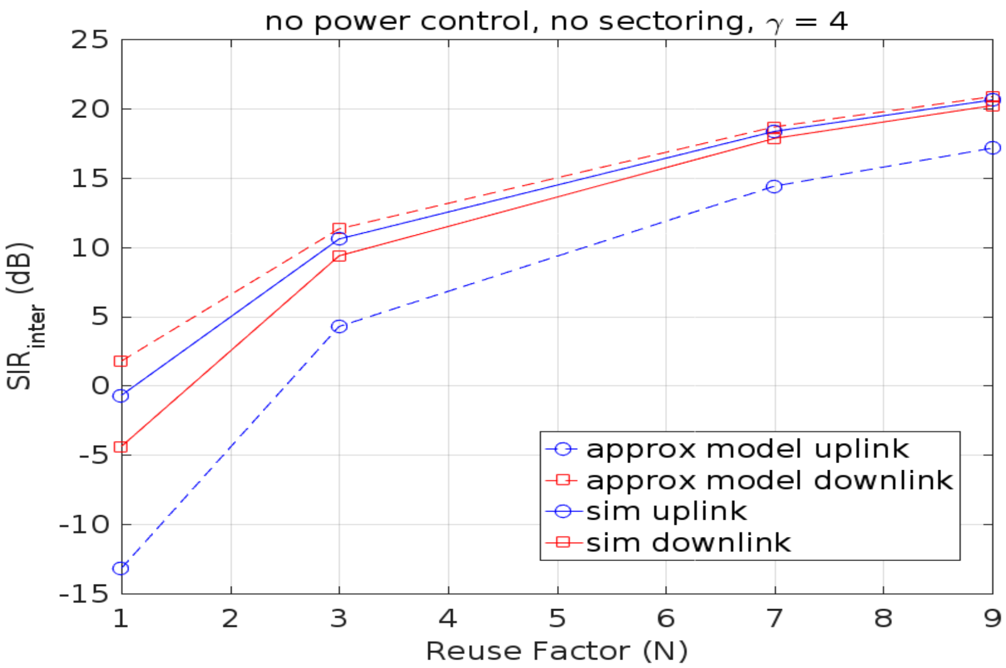
- $SIR_{inter} = Prx / \Sigma Pri$
- Pri = 0 if interfering and reference stations use different
  - Channels, sectors,
  - or no load (see later)

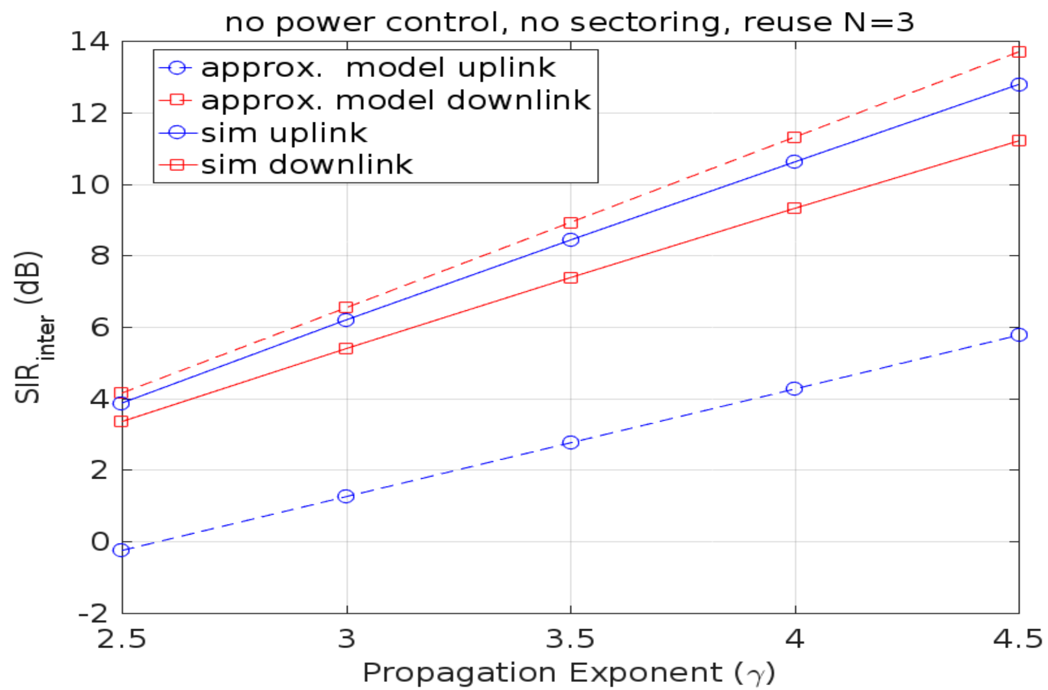


Interfering mobile

Simulation Results

- Approximated downlink model is close to simulations and a little bit better
- Approximated uplink model too much worse, simulation required or better to use downlink approximated model also for uplink
- Model tight for N>1 (for N=1 sim better)





Simulation Tables for Exercises

SIR_inter (dB), Omnidirectional, no sectoring, no power control, simulation up

	Reuse Factor (N)			
	1.00	3.00	7.00	9.00
Gamma				
2.5	-4.54	3.35	8.42	9.85
3	-4.50	5.39	11.58	13.32
3.5	-4.60	7.37	14.71	16.77
4	-4.80	9.31	17.83	20.20
4.5	-5.07	11.20	20.91	23.61

SIR_inter (dB), Omnidirectional, no sectoring, no power control, simulation up

	Reuse Factor (N)			
	1.00	3.00	7.00	9.00
Gamma				
2.5	-2.74	3.87	8.63	10.03
3	-1.91	6.13	11.89	13.57
3.5	-1.33	8.37	15.15	17.09
4	-0.83	10.61	18.39	20.63
4.5	-0.38	12.82	21.61	24.15

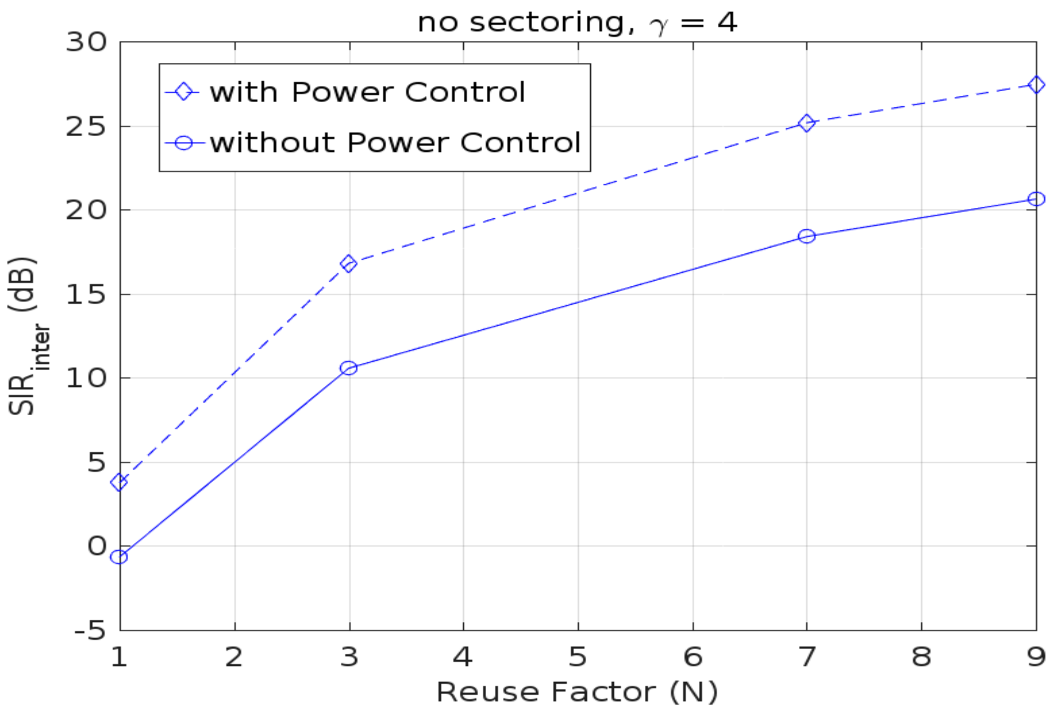
Power control

- Power control is mainly used in uplink to save phone energy, etc.
- Power control strategy impacts interference, energy consumption and spectral efficiency (Shannon)
- A power control strategy may have different objectives, e.g.
  - The most energy saving and interference limitation is achieved when each mobile controls its tx power so as reaching the base station antenna with a same Rx power (and SINR too). This also implies that any mobile will get almost same spectral efficiency (flat fairness). Strategy solving near-far problem.
  - Higher tx power provides different tradeoff between mobile spectral efficiency and energy consumption/interference

Simulation Results

- Uplink power control leads to a SIR increase of 4-7 dB at cell edge

- Due to power control SIR values are almost independent of the mobile position



SIR Improvement at Cell Edge:

At the cell edge, where received signal power is typically weakest, uplink power control leads to a notable increase in SIR.
By adjusting the transmit power based on the mobile device's distance from the base station, power control helps ensure that the desired signal power remains relatively higher compared to interference and noise, resulting in an improved SIR.
The 4-7 dB increase in SIR indicates a substantial enhancement in the quality of the uplink communication at the cell edge.

Simulation Tables for Exercises

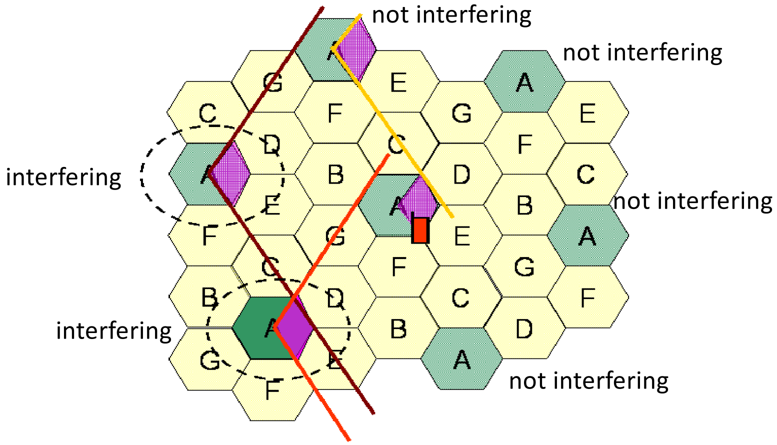
SIR_inter (dB), Omnidirectional, no sectoring, with power control, simulation up

	Reuse Factor (N)			
	1.00	3.00	7.00	9.00
Gamma				
2.5	1.95	9.15	14.03	15.39
3	2.85	11.78	17.77	19.42
3.5	3.57	14.63	21.45	23.51
4	4.11	16.84	25.04	27.45
4.5	4.30	19.12	28.60	31.20

Site Sectoring - Downlink

- Directional antennas improve coverage (antenna gain) and also reduce inter-cell interference
  - 18 dBi for directional antenna (3-sector)
  - 19.5 dBi for directional high gain antenna (6-sector)
  - 8 dBi for “omni”-directional antenna, vertically bounded
- Usually 3 or 6 sectors per base station
- Assumption: sectors uses different sub-channels statically configured. Otherwise, no interference reduction
- Advantage of sectoring: directional antenna reduces the number of interfering cells Ni from 6 to
  - K=3 sectors , Ni = 2
  - K= 6 sectors, Ni=1
- Disadvantage: we are dividing resources and loosing multiplexing gain. Moreover, n. of handovers increase

FDMA/OFDMA

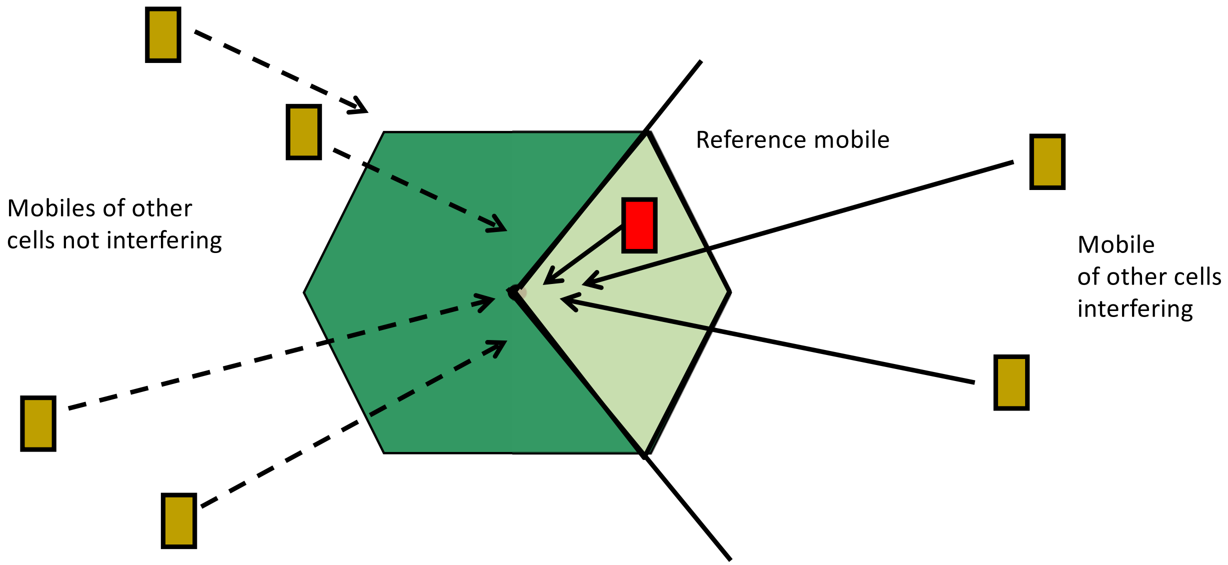


$$SIR_{inter-sec} = SIR_{inter-omni} * K$$

Note: usually a sectored cell is called “site” and the sector is called cell. However, in this course we use the terms cell (to indicate a site) and sector (to indicate a site sector)

Site Sectoring - Uplink

- Directional antennas always reduce the n. of interfering mobiles seen by the BS antenna of a factor equal to number of sectors *K*, with respect to the omnidirectional case
  - This is true also if sectors use the same radio resources



$$SIR_{inter-sec} = SIR_{inter-omni} * K$$

Cell Load

- In a cell, radio resources (e.g. OFDMA sub-carriers) are actually used depending on the traffic demand
- Considering full loaded cells may be too much pessimistic
- Cell-load ρ can be defined as the average percentage [0,1] of used resources of a cell
- The amount of inter-cell interference coming from a cell must be multiplied by ρ, because interference actually occurs if the resource is actually used in the neighbor cell
- The lower the load is, the lower is the inter-cell interference

$$SIR_{inter-load} = SIR_{inter-full} * \frac{1}{\rho}$$

SIR and Interference Margin

- The Interference Margin = I_M is used for link budget to cope with interference

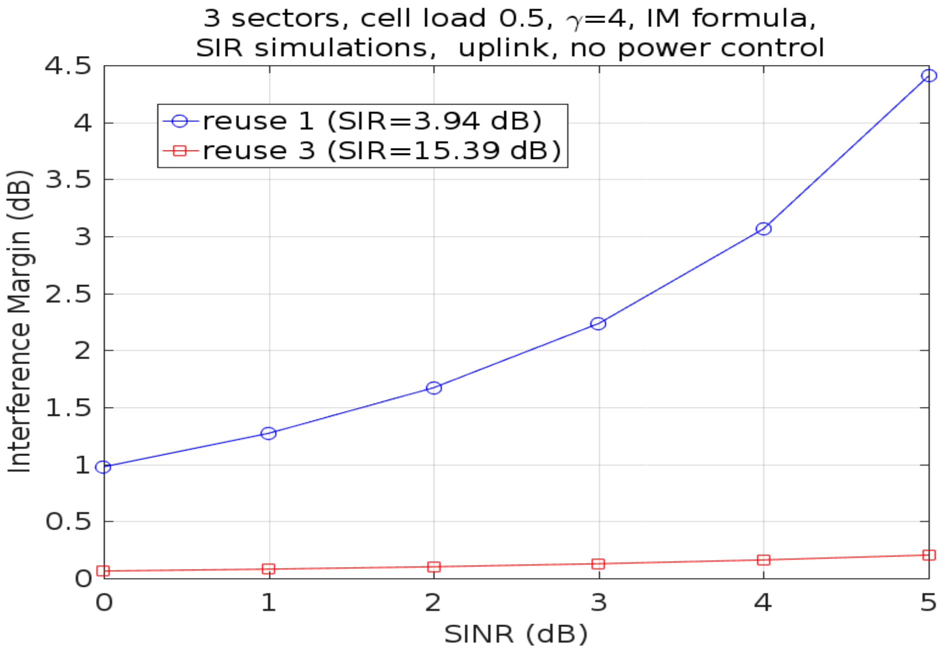
$$I_M = \frac{N+I}{N} = \frac{N+\ I_{inter}}{N} = \frac{N+\ I_{inter}}{N}\frac{S}{S} = \frac{SNR}{SINR_{min}}$$

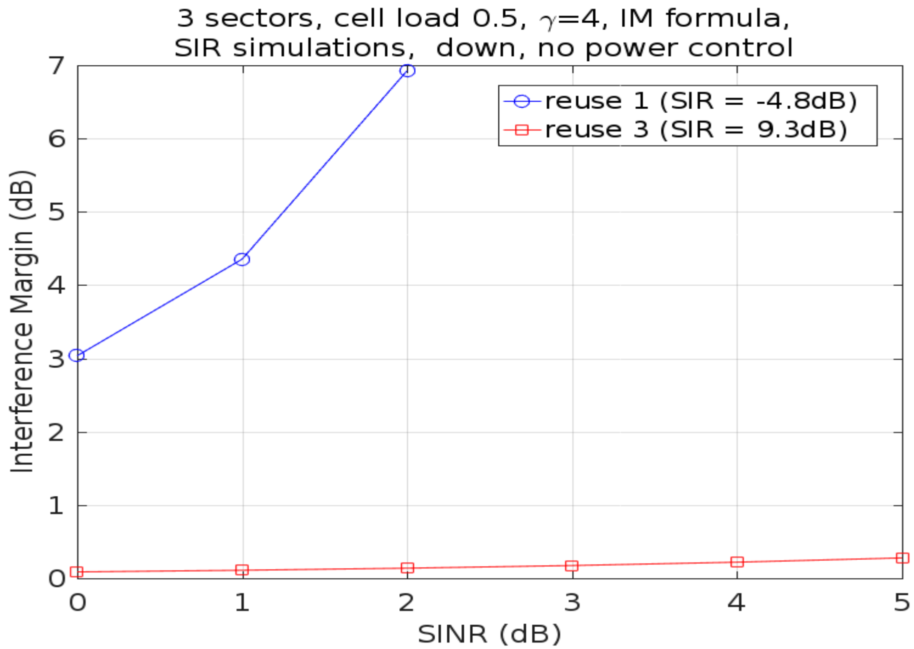
$$SINR_{min} = \frac{S}{N+I_{inter}} = \frac{1}{\frac{1}{SNR}+\frac{1}{SIR_{inter}}} = \frac{1}{\frac{1}{I_M\ SINRmin}+\frac{1}{SIR_{inter}}}$$

- Solving for I_M

$$I_M = \frac{1}{1-\frac{SINR_{min}}{SIR_{inter}}}$$

Simulation Results



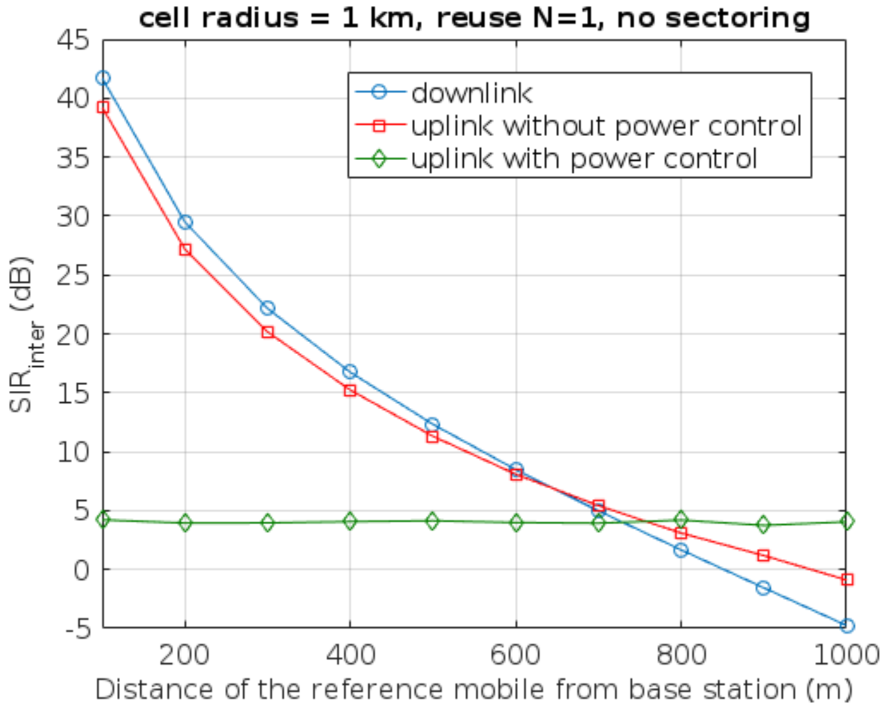


FRACTIONAL/SOFT FREQUENCY REUSE

GIAMBENE, GIOVANNI. "PERFORMANCE EVALUATION OF DIFFERENT FRACTIONAL FREQUENCY REUSE SCHEMES FOR LTE." EURO MED TELCO CONFERENCE (EMTC), 2014. IEEE, 2014.

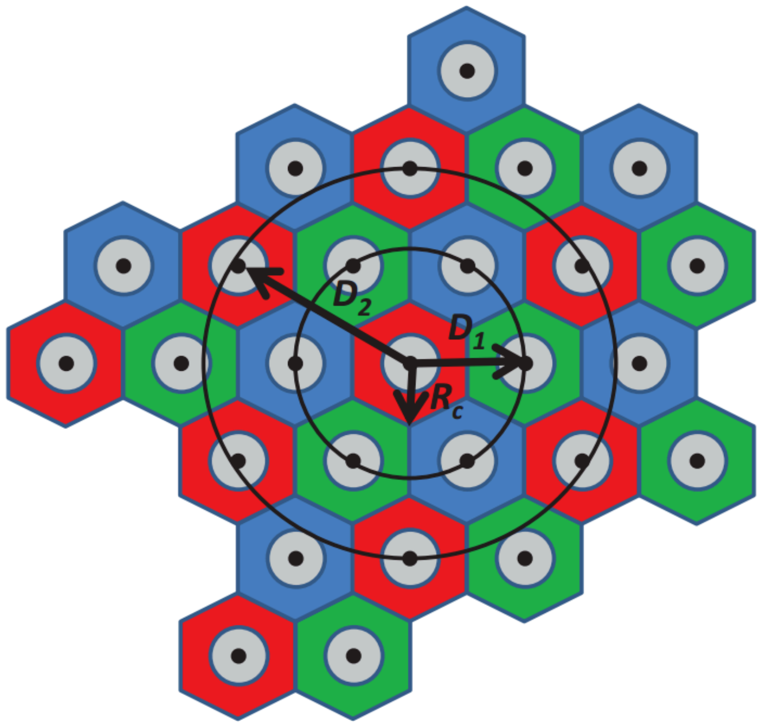
Concept

- Reuse factor *N*=1 makes possible to maximize utilization
  - Shannon: bandwidth better than SINR
- But inter-cell interference "at the cell border" is extremely high and mobiles located there my suffer too much
- *N*=1 may be feasible at the cell center, but not at the edge
  - Without power control, received signal power of the reference mobile located at cell center is higher and higher is the *SIR*
- For instance, if we require a min SIR = 5 dB, from the figure we see reuse 1 is not good for mobiles more distant than 700m, but it is good for the other (no power control)



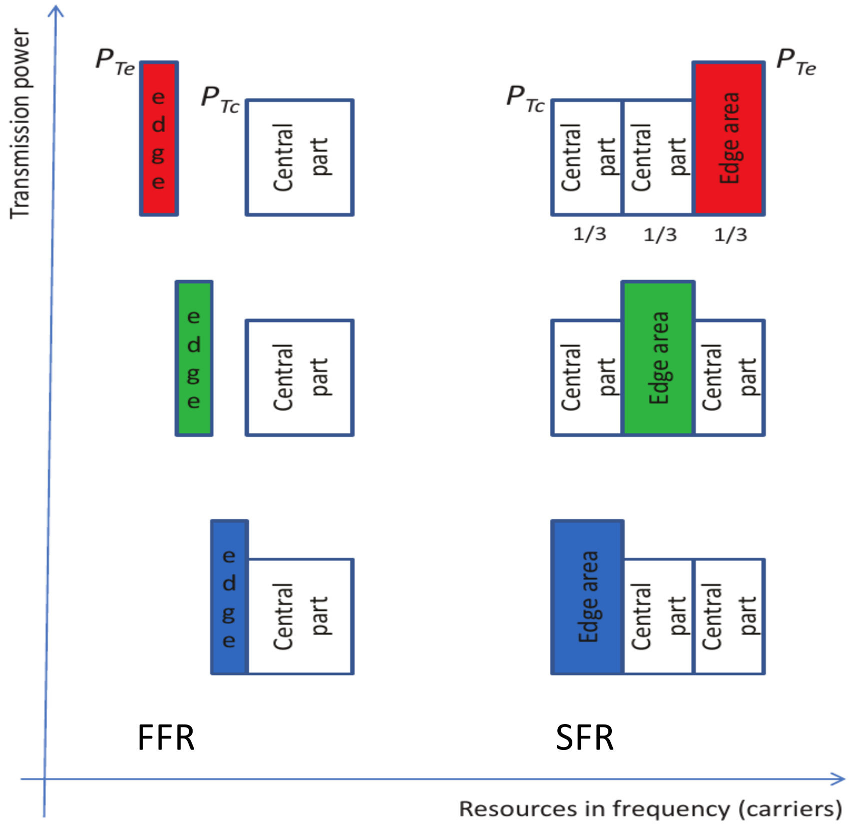
Fractional/Soft Frequency Reuse

- Cell spitted in two zones: central and edge
- Reuse factor 1 in the central zone
- Reuse factor > 1 in the edge zone
- Different transmission power levels for zones



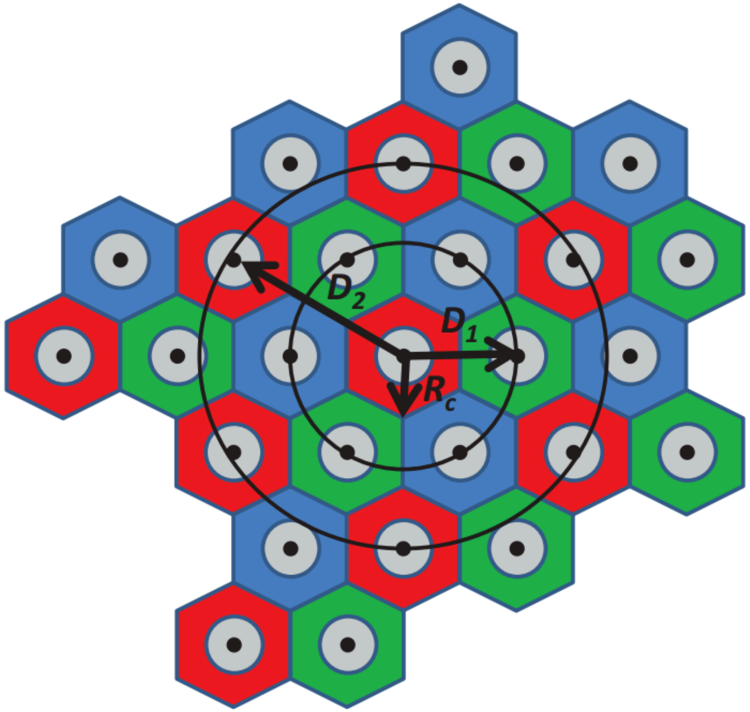
Fractional and Soft schemes

- Fractional Frequency Reuse (FFR):
  - Set of channels used in the center is separated from the ones used at edge
  - edge channels set divided in *N* (reuse factor) parts. Each cell/sector can use only a part. Parts allocated to cell/sector according to the reuse scheme
- Soft Frequency Reuse (SFR)
  - In a cell, edge channels set is 1/N of the whole channels set; remaining channels is used in the central part



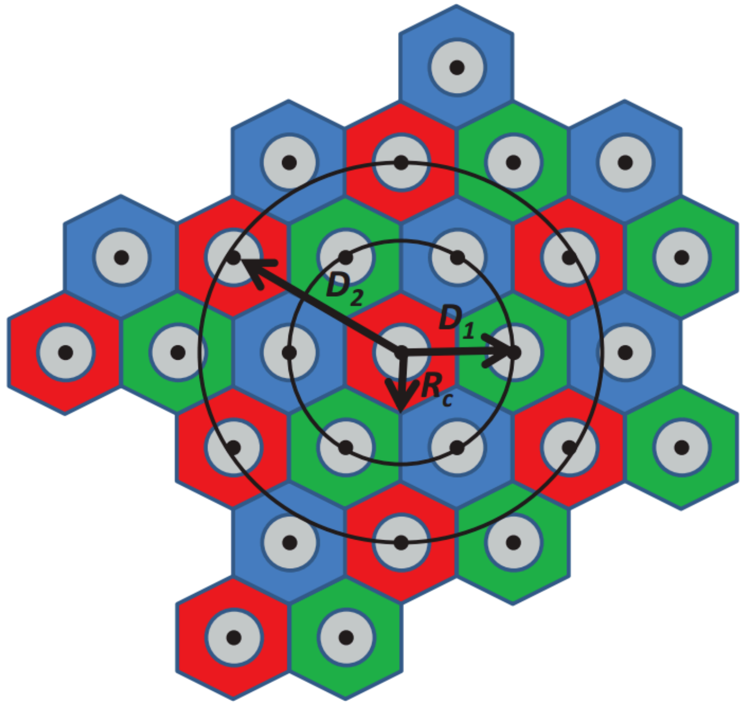
Inter Cell Interference: Variables

- P_{Txc} : Tx power for mobiles in the central part
- P_{Txe} : Tx power for mobiles in the edge part
- $\Omega = P_{Txe} / P_{Txc}$ (>1)
- R_c : radius of the central part
- D_{own} : distance bs-mobile
- R : cell radius
- D_1 distance with neighbour cells
- D_2 distance with first tier cells



Inter Cell Interference: FFR approx.

- First tier approx. for both edge and central
  - We consider only closest interfering edge and central devices
- D_{own} distance base station - mobile
- SIR at edge equal to the case of full frequency reuse with *N* reuse factor
- SIR in the central part equal to the case of full frequency reuse with *N*=1



Downlink/Uplink (using dw approx also for uplink)

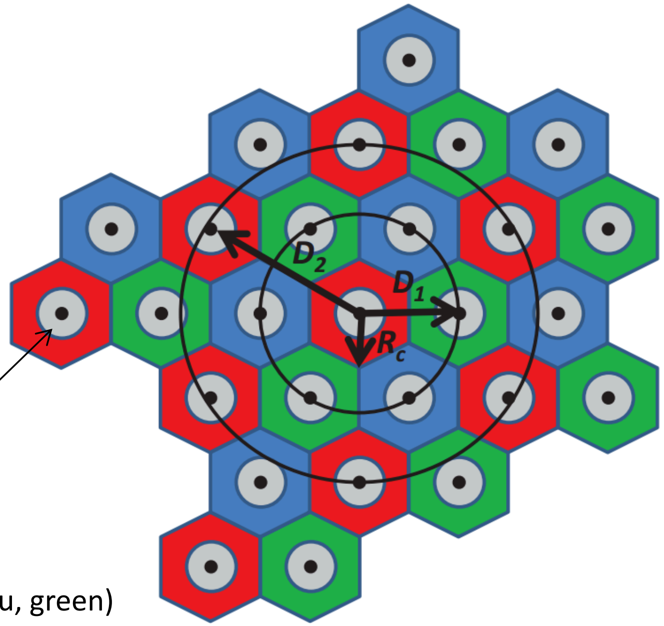
$$SIR_{inter\_e} = \left(\frac{D_{own}}{R}\right)^{-\gamma} \frac{1}{6}\left(\sqrt{3N}\right)^{\gamma}$$

$$SIR_{inter\_c} = \left(\frac{D_{own}}{R}\right)^{-\gamma} \frac{1}{6}\left(\sqrt{3}\right)^{\gamma}$$

$\left(\frac{D_{own}}{R}\right)^{-\gamma}$ Rx power increase moving the mobile from *R* to D_{own} (log-normal distance model)

Inter Cell Interference: SFR approx.

- First tier approx. for both edge and central
- Reuse factor *N* = 3
- In the central part a mobile (e.g. using green channel) is interfered by central channels of 3 neighbor cells and edge channels of 3 neighbor cells

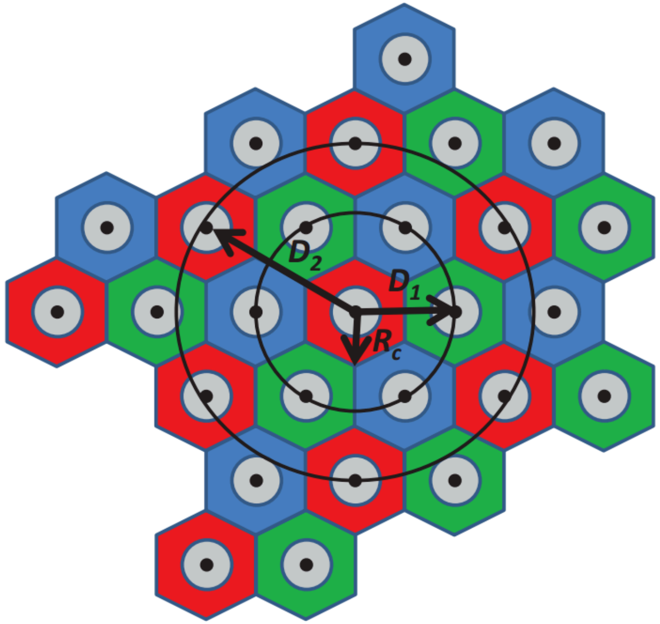


This cell use here remaining *colors* (blu, green)
A mobile use one of them, e.g. green

$$SIR_{inter\_c} = \frac{P_{Txc} {D_{own}}^{-\gamma}}{3\left(P_{Txc} {D_1}^{-\gamma} + P_{Txe} {D_1}^{-\gamma}\right)} = \left(\frac{D_{own}}{R}\right)^{-\gamma} \frac{\left(\sqrt{3}\right)^{\gamma}}{3(1+\Omega)}$$

Inter Cell Interference: SFR approx.

- In the edge part a mobile (e.g. using red channel) is interfered by central channels of 6 neighbor cells and edge channels in 6 first-tier neighbors



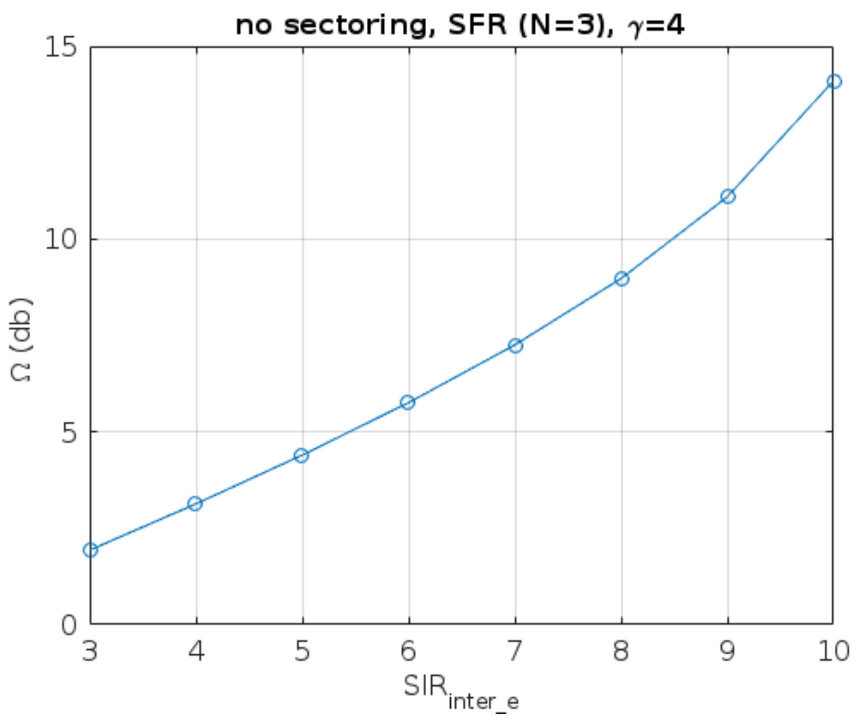
$$SIR_{inter\_e} = \frac{P_{Txe} {D_{own}}^{-\gamma}}{6(P_{Txc} {D_1}^{-\gamma} + P_{Txe} {D_2}^{-\gamma})} = \left(\frac{D_{own}}{R}\right)^{-\gamma} \frac{1}{\frac{6}{\Omega}\left(\sqrt{3}\right)^{-\gamma} + 6\left(\sqrt{3N}\right)^{-\gamma}}$$

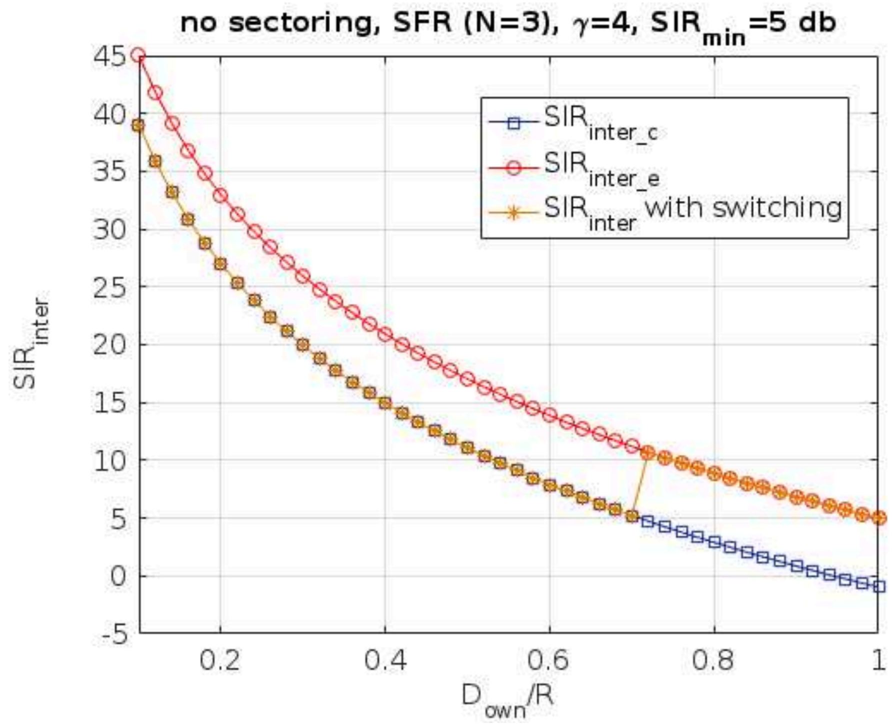
$$\Omega = \frac{6\left(\sqrt{3}\right)^{-\gamma}}{{SIR_{inter\_e}}^{-1} - 6\left(\sqrt{3N}\right)^{-\gamma}}$$

Formula for deriving necessary value of Ω to have a SIR at cell edge D_{own}=R

Inter Cell Interference: SFR approx.

- Channel switching:
  - If on central channel and SIR > SIR_{min} switch on edge channels, and vice versa





CAPACITY PLANNING

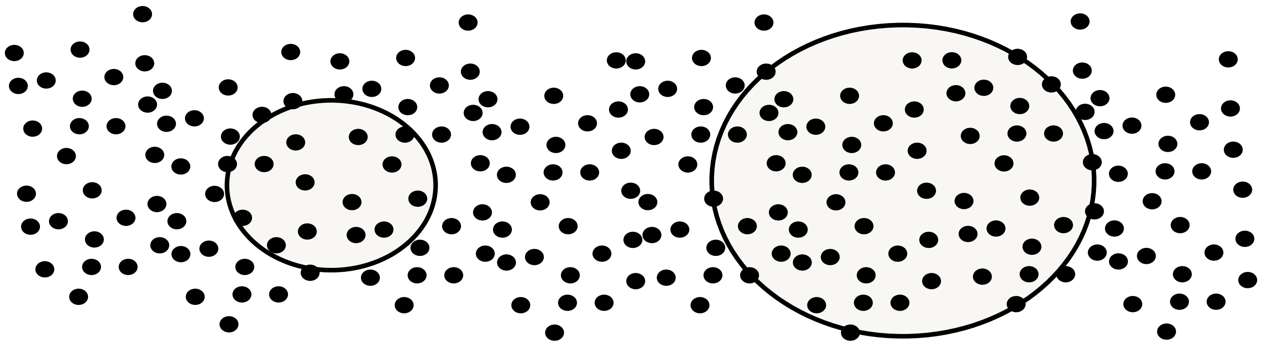
Objective

- Capacity planning computes cell size in order to serve the enclosed population with given performance targets, e.g. average bit-rate
- In a cell the radio resources are limited, thus cell size coming out from capacity planning depends on the traffic demand and available radio resources.
- In the initial phase of the network, there is low traffic demand thus the cell size resulting from capacity planning can be greater than the one resulting from coverage planning, in this case deployment follows coverage planning
- In a mature network, with high traffic demand, capacity planning can require cells smaller than the coverage planning ones, in this case new sites need to be deployed reducing the tx power for making smaller the cell

Cell size

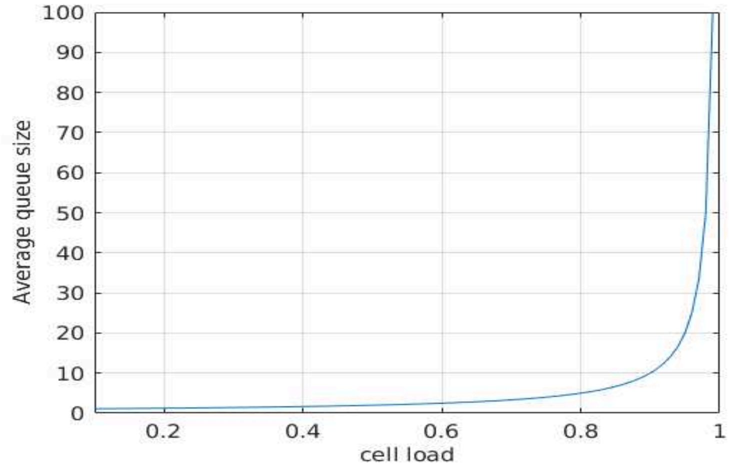
- All users of a cell require an average bit rate A_o (bit/s)
- The greater the cell radius (R), the greater the number of served users and A_o
- Each user requires A_{o_u} , user density δ (user/km²)

$$A_o(R) = A_{o\_u}\, \delta\, \pi R^2$$



Cell size

- Cell radio resource should provide A_o/ρ, bit/s (cell capacity) where $0<\rho<1$ is the cell load, used both for reducing interference but also for achieving low queuing latency and packet loss both in uplink and downlink
  - E.g. assuming to model the data transfer in a cell as an M/M/1 queuing model, the average queue length is $1/(1-\rho)$



- Radio bandwidth available in the cell is B_{cell}
- The required **average cell spectral efficiency** of the cell must be greater than $\longrightarrow$ $\eta_c \geq \frac{A_o(R)/\rho}{B_{cell}}$
- Average cell spectral efficiency is a measure almost independent of the cell size, thus solving the eq. provides greatest *R*

Average Cell Spectral Efficiency

- Within a cell the average spectral efficiency can be computed as the value of the efficiency provided by the Shannon formula in the point *x,y* of the cell multiplied for the probability *Pr(x,y)* of having mobile located at the *x,y* point

$$\eta_c = \iint \alpha \; \log_2(1 + SINR(x,y)) \Pr(x,y) \, dxdy$$

- Since SINR depends (i) on the D_{own} (bs-ms) distance and (ii) on cell radius *R*, assuming uniform distribution of the mobiles in the cell we can rewrite cell spectral efficiency as follows

$$\eta_c = \int_0^R \alpha \log_2\big(1 + SINR(D_{own}, R)\big) \left(\frac{2\pi D_{own}}{\pi R^2}\right) dD_{own}$$

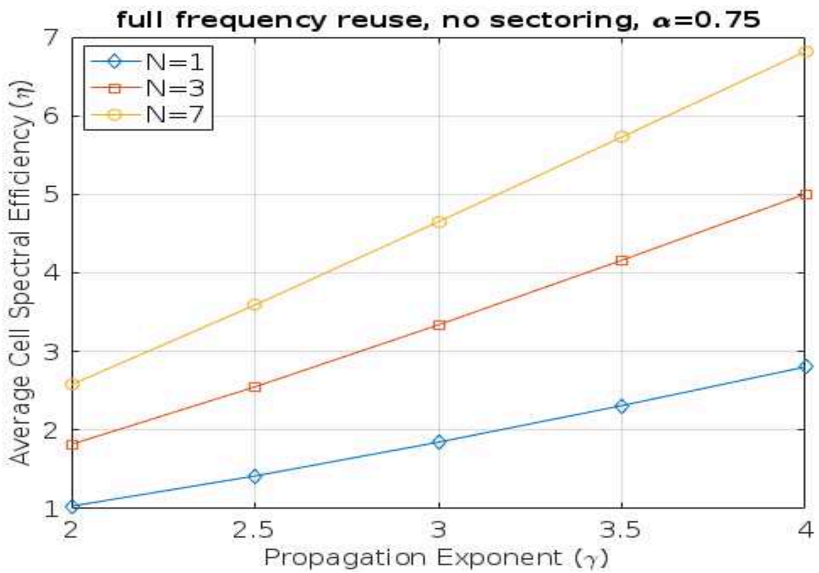
Average Cell Spectral Efficiency when SINR about equal to SIR

- In case of full frequency reuse (no sectoring, full load) and assuming SINR ≅ SIR , we have (numeric integration),
- Almost independent of R

$$\eta_c \cong \alpha \int_0^R \log_2\left(1 + \left(\frac{D_{own}}{R}\right)^{-\gamma} \frac{1}{6}\left(\sqrt{3N}\right)^{\gamma}\right)\left(\frac{2\pi D_{own}}{\pi R^2}\right) dD_{own}$$

Average spectral efficiency, no sectoring, full reuse

	Reuse Factor (N)		
	1.00	3.00	7.00
Gamma			
2	1.03	1.82	2.58
2.5	1.42	2.55	3.59
3	1.85	3.34	4.65
3.5	2.31	4.16	5.73
4	2.80	5.00	6.82



Efficiency is improving but….
cell bandwidth is decreasing more, by a factor 1/N
average capacity of the cell $B_{cell}\,\eta_c$ is decreasing by increasing the reuse factor

Average Cell Spectral Efficiency from SINR at the edge

- SINR(R) is the value of the SINR that is guaranteed by link budget at cell edge
- Almost independent of R

$$\eta_c \cong \alpha \int_0^R \log_2\left(1 + \left(\frac{D_{own}}{R}\right)^{-\gamma} SINR(R)\right)\left(\frac{2\pi D_{own}}{\pi R^2}\right) dD_{own}$$

Example

- Users of Rome are about 2.5 Millions
- Rome area is about $AREA_{tot}$=1285 km^2
- Assuming that an operator aims to control 1/3 of users i.e. about 830000 users
- Each user in a month consumes on average
  - 2GB of Internet
  - 500 min of calls (12.65 kbps; AMR-WB)
  - All traffic generated during 12 hours of peak traffic time (worst case)
- During peak traffic time the rate of each user is :
  (2*8*1e9+500*60*12.65e3)/31/12/3600 ≅ 12 kbits/s

Example

- Available System Bandwidth B_{tot} = 15 MHz
- Propagation Exponent $\gamma = 4$
- Full Reuse Factor N = 3
- No sectoring
- Cell load $\rho = 0.5$
- Attenuated Shannon $\alpha = 0.75$
- Assuming SINR=SIR
- Determine capacity cell radius

Example - sol

- Cell Spectral Efficiency η_c, Matlab numerical computation assuming a range R^* = 1000 m
  - eta = @(D,R, N, gamma,ro) 0.75*log2(1+((1/ro)*(1/6) * ((D./R).^-gamma).*(sqrt(3*N)^gamma))).*(2*pi*D./(pi*R^2));
  - eta_c=integral(@(D) eta(D,1000,3,4,0.5),1,1000)

$$\eta_c = \alpha \int_0^{R^*} \log_2\left(1 + \frac{1}{\rho}\left(\frac{D_{own}}{R^*}\right)^{-\gamma} \frac{1}{6}\left(\sqrt{3N}\right)^{\gamma}\right)\left(\frac{2\pi D_{own}}{\pi {R^*}^2}\right) dD_{own} = 5.74$$

Example - sol

- Total average bitrate required from users = 830.000*12e3
- User density δ = 830.000 / 1285 = 646 user/km^2
- Required cell capacity

$$A_o(R) = A_{o\_u}\,\delta\,\pi R^2 = 12e3\;646\;\pi R^2$$

- Largest cell radius …

$$\eta_c = 5.74 = \frac{A_o(R)/\rho}{B_{cell}} = \frac{2\quad 12\text{e}3\quad 646\pi R^2}{15e6/3}$$

$$\mathrm{R} = 0.76\ \mathrm{km}$$