EC 744 Wireless Communications Spring 2007

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Cellular systems

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Syllabus

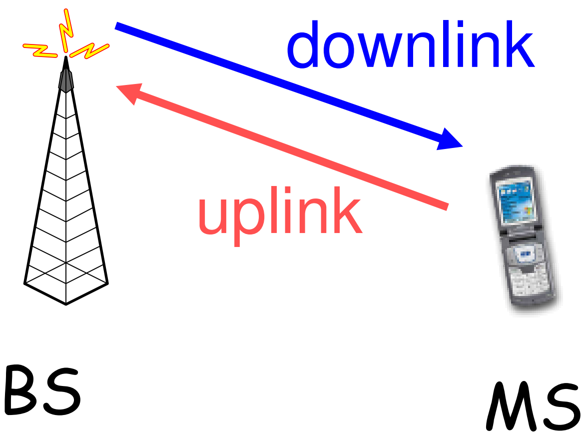
- Tentatively

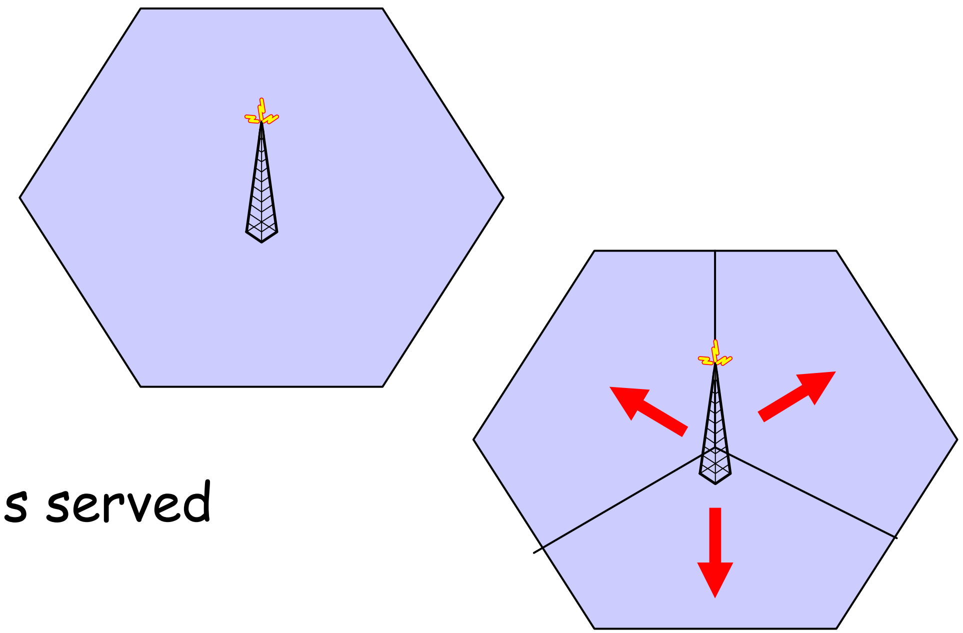
Week 1	Overview, Probabilities, Random variables, Random process
Week 2	Wireless channels, Statistical Channel modelling, Path loss models
Week 3	**Cellular concept and system design fundamentals**
Week 4	**Modulation techniques, single** and multi-carrier
Week 5	Diversity techniques
Week 6	Equalization techniques
Week 7	Mid Term exam
Week 8	802.11 and Mac evaluation
Week 9	Energy models in 802.11
Week 10	Wimax and Mac layer
Week 11	Presentations
Week 12	Presentations
Week 13	Presentations
Week 14	Presentations
Week 15	Final Exam

Cellular Basics

Terminologies: BS, MS, Cell, Sector

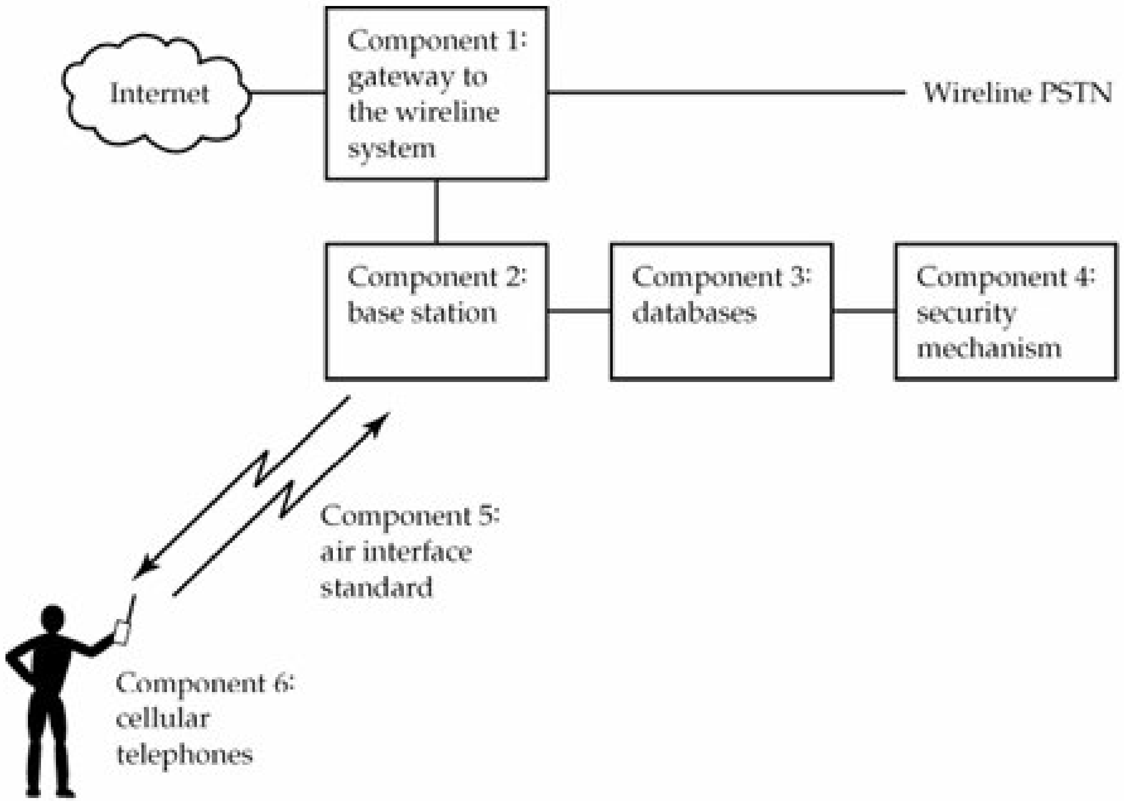
- Base station (BS)
  - Access point (AP)
- Mobile station (MS)
  - SS (Subscriber station)
  - MT (mobile terminal)
  - MN (mobile node)
- Downlink
  - Forward link
  - BS→MS
- Uplink
  - Reverse link
  - MS→BS
- Cell
  - Coverage area of a BS
- Sector
  - Partial area of a cell that is served by a directional antenna





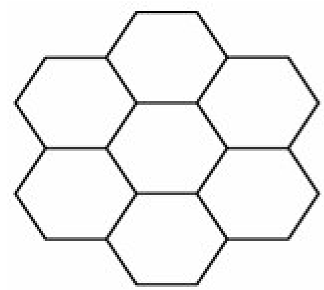
Abstract model for a cellular system

- Components
  - Gateway to the wireline system (backhaul)
  - Base station (BS)
  - Database
  - Security
  - Air interface
  - Cellular phone



Basic Cellular Concept

- "Cell"
  - Typically, cells are hexagonal
  - In practice, it depends on available cell sites and radio propagation conditions
- Spectrum reuse
  - Reuse the same EM spectrum in other geographical location
  - Frequency reuse factor



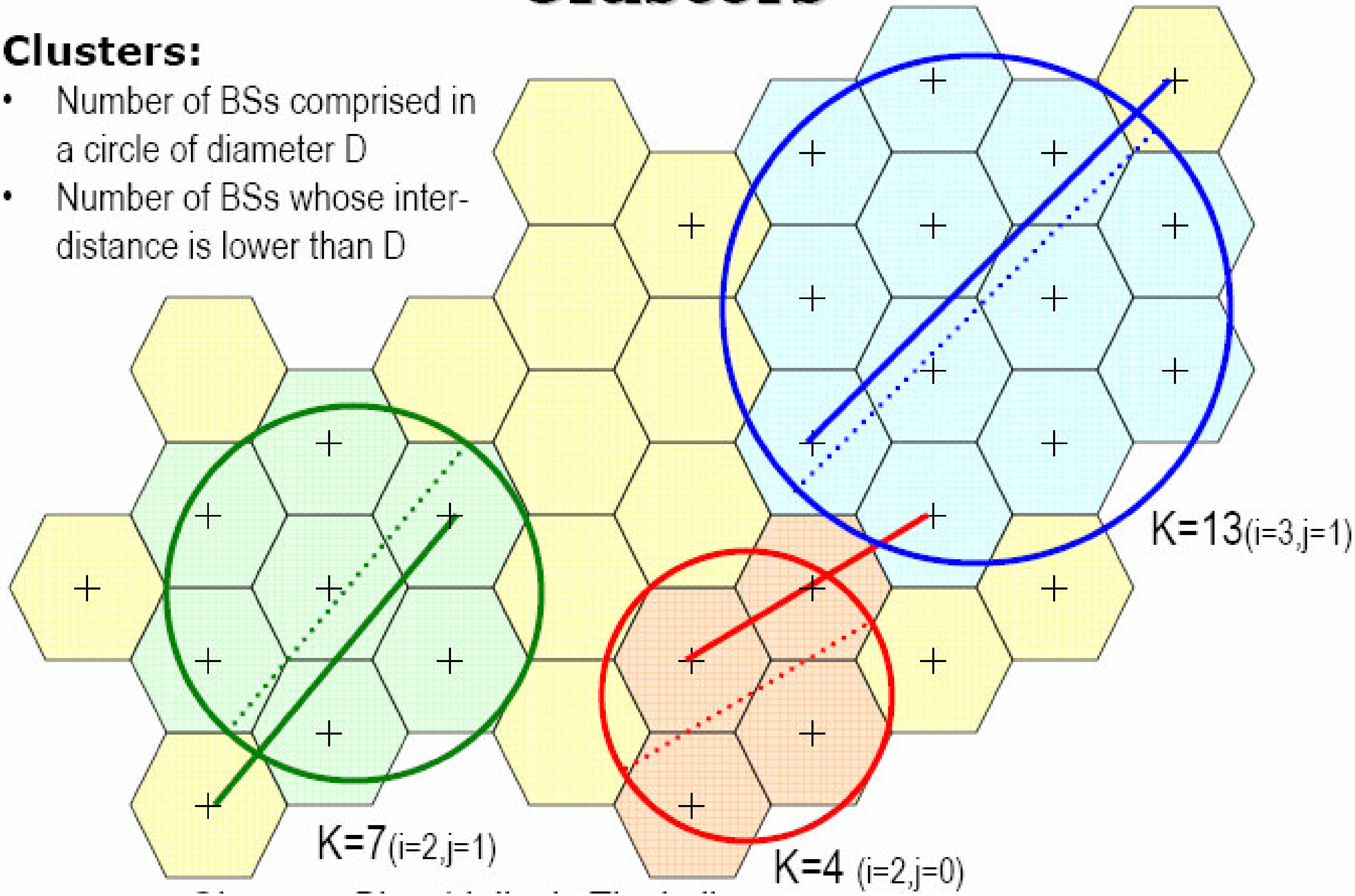
Frequency Reuse

- Cluster
  - A group of cells
- Frequency reuse factor
  - (Total # of channels in a cluster) / (Total # of channels in a cell)

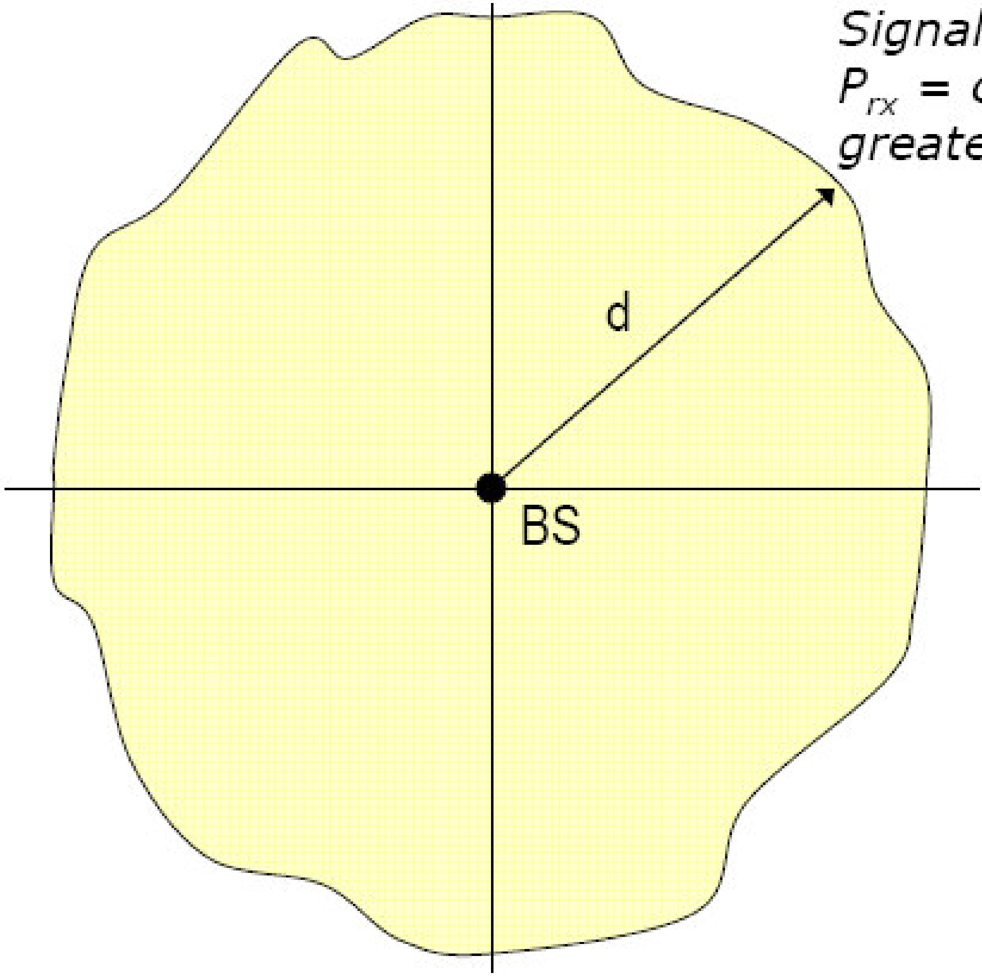
Clusters

Clusters:

- Number of BSs comprised in a circle of diameter D
- Number of BSs whose inter-distance is lower than D



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

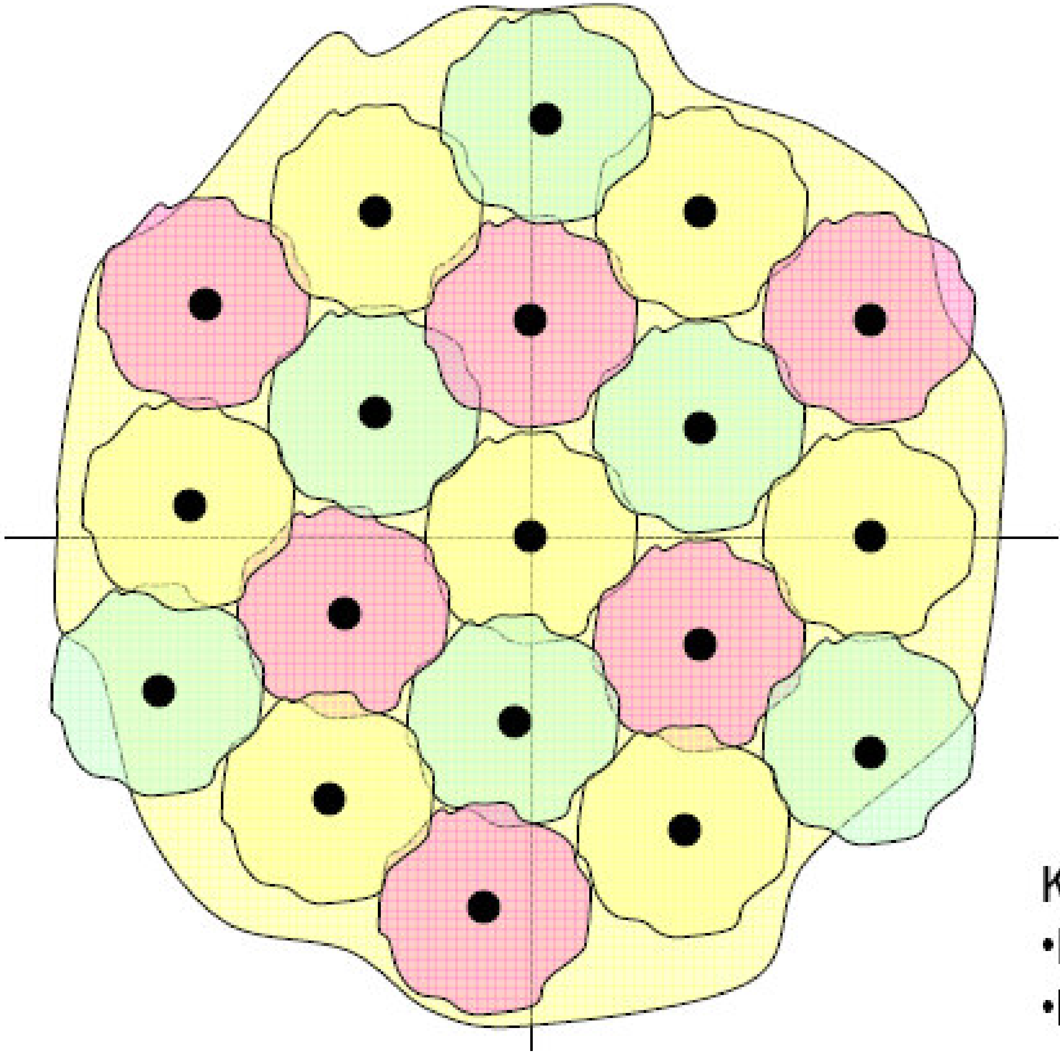
- (e.g. 1 channel = 1 frequency)

↓

N=12 simultaneous calls

Cellular coverage

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



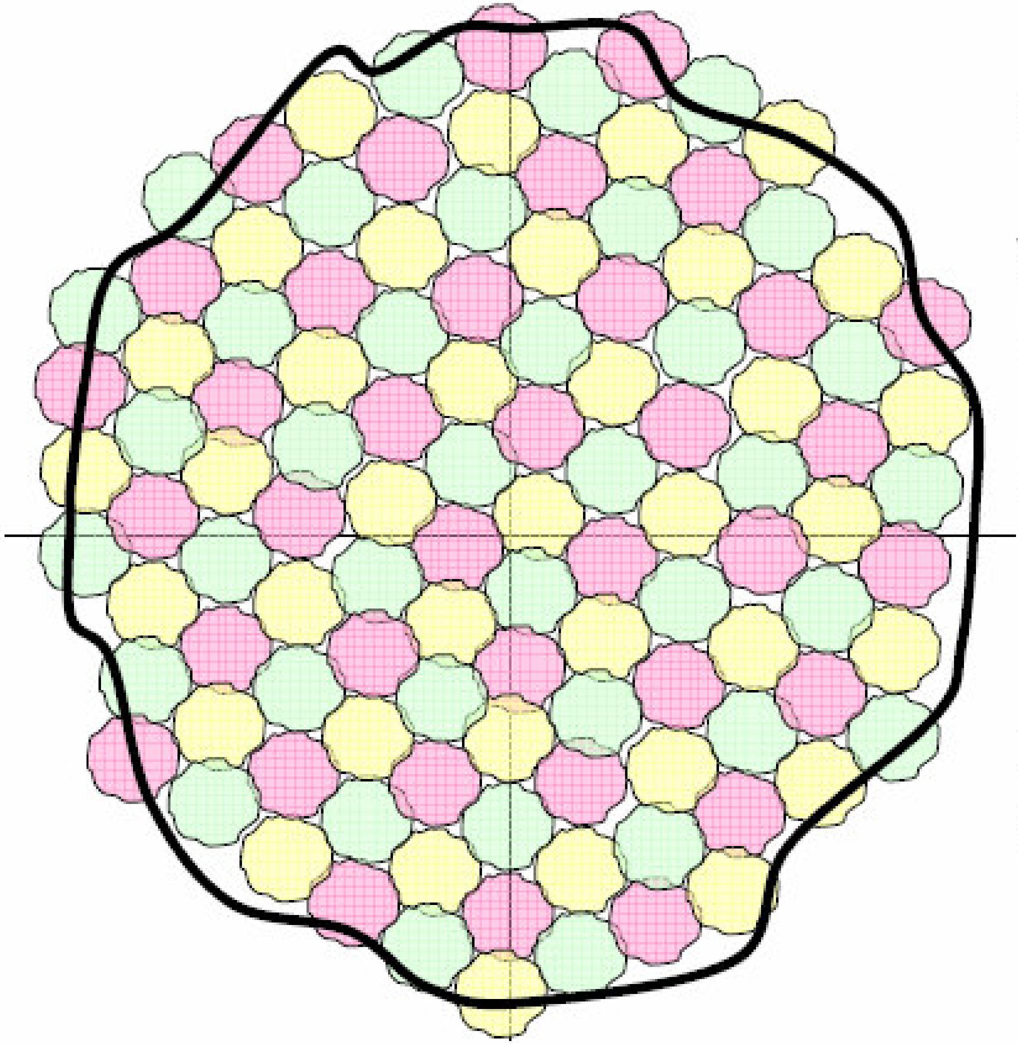
19 Base Station
12 frequencies
4 frequencies/cell

Worst case:
4 calls (all users in same cell)
Best case:
76 calls (4 users per cell)
Average case >> 12
Low transmit power

Key advantages:

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

Cellular coverage (microcells)



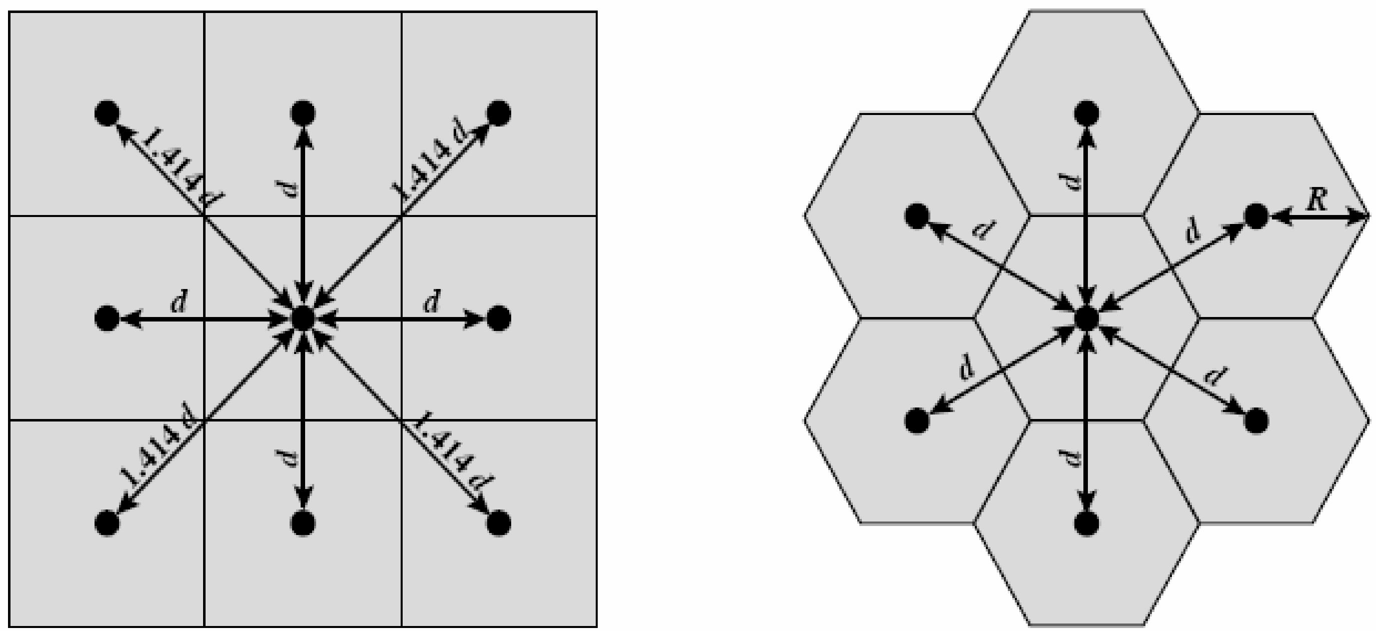
many BS

Very low power!!
Unlimited capacity!!

Usage of same spectrum
(12 frequencies)
(4 freq/cell)

Disadvantage:
mobility management

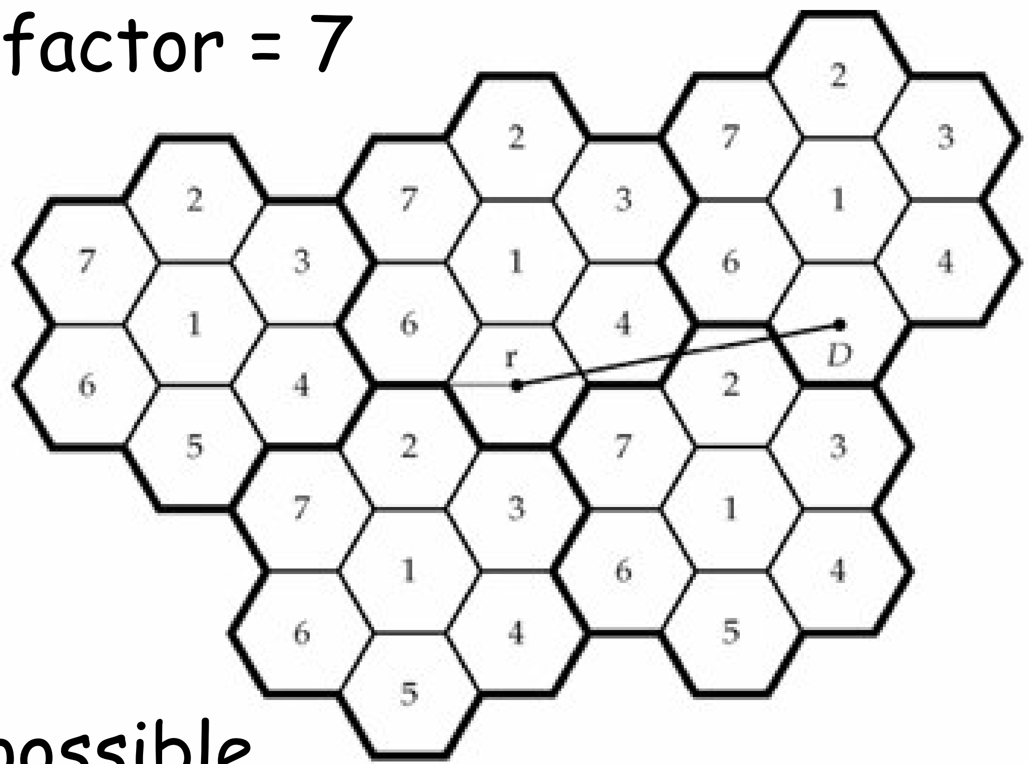
Cellular Geometries



(a) Square pattern (b) Hexagonal pattern

A frequency reuse example

- Example
  - Frequency reuse factor = 7
  - Cluster size =7



- Question
  - What are other possible frequency reuse patterns?

Cluster

- The hexagon is an ideal choice for macrocellular coverage areas, because it closely approximates a circle and offers a wide range of tessellating reuse cluster sizes.
- A cluster of size N can be constructed if,
  - $N = i^2 + ij + j^2$.
  - i,j are positive integer
- Allowable cluster sizes are
  - N = 1,3,4,7,9,12,...

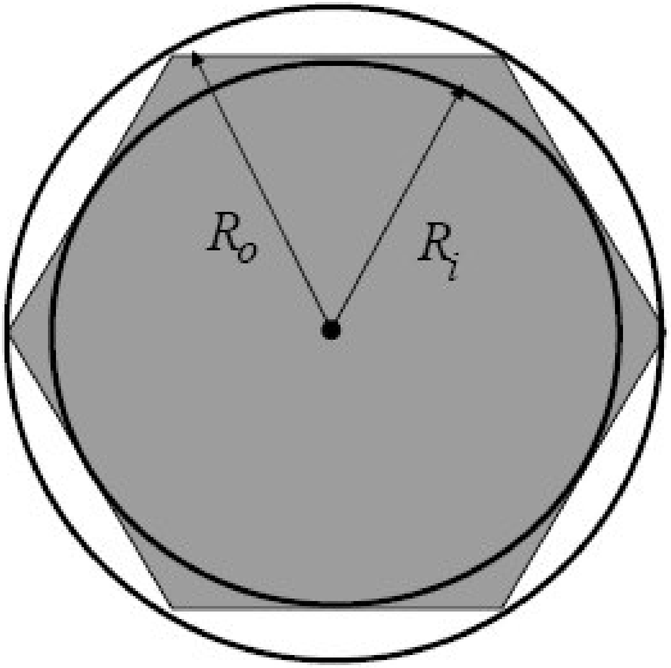
Determine frequency reuse pattern

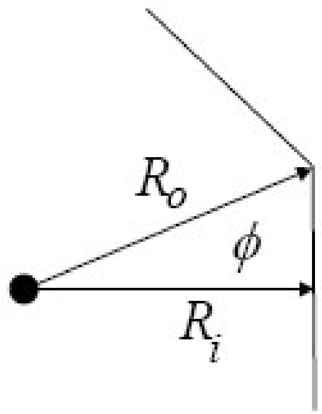
- Co-channel interference [CCI]
  - one of the major factors that limits cellular system capacity
  - CCI arises when the same carrier frequency is used in different cells.
- Determine frequency reuse factor
  - Propagation model
  - Sensitivity to CCI

Reuse distance

- Notations
  - D :Reuse distance
    - Distance to cell using the same frequency
  - r : Cell radius
  - N : Frequency reuse factor
- Relationship between D and r
  - D/r=(3N)^0.5
  - $N = i^2 + ij + j^2$

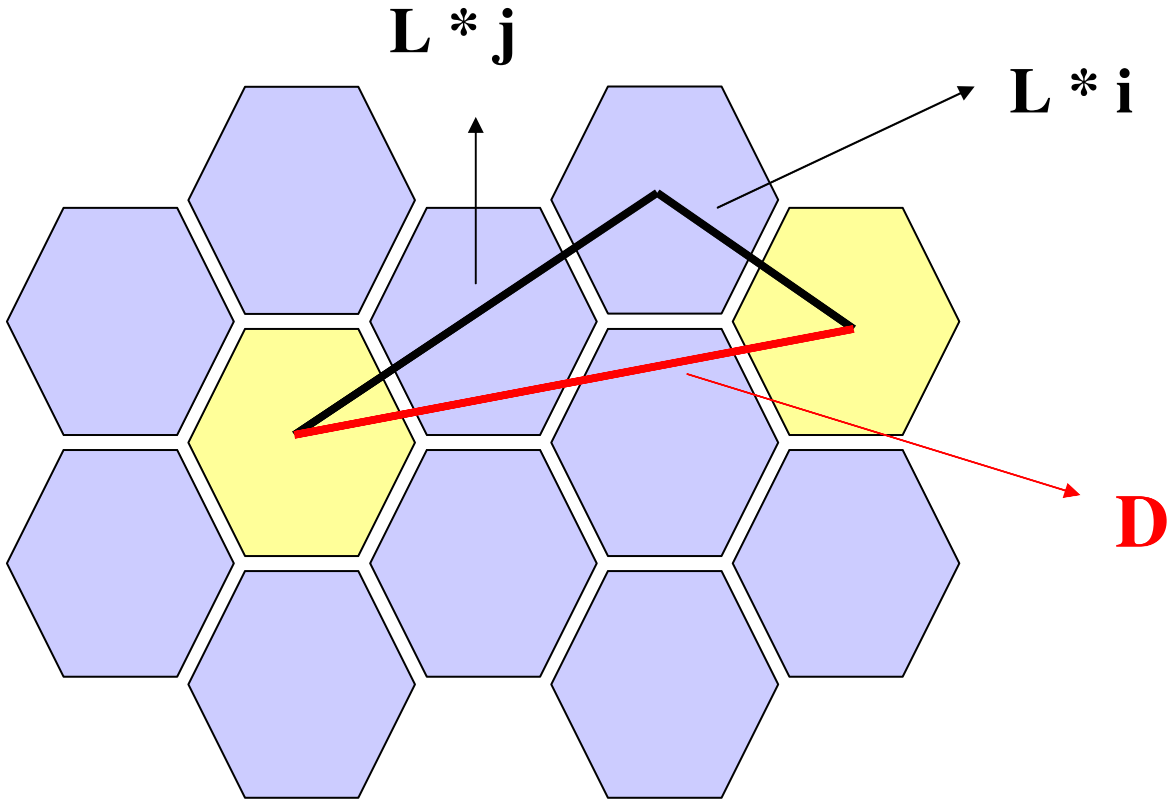
For a hexagon we can define both an inner radius and an outer radius. Both are useful.



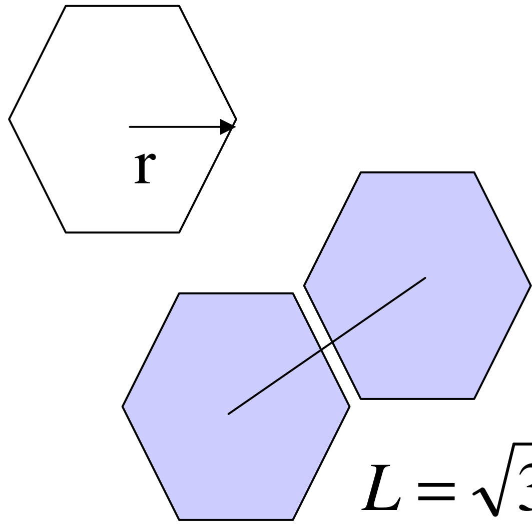


$$R_i = R_o \cos\phi = R_o \cos\frac{2\pi}{12} = R_o \frac{\sqrt{3}}{2}$$

Note that a hexagon has 6 faces or, equivalently, 12 "half-faces."



In this case: j=2, i=1



$L = \sqrt{3} r$

$$D^2 = (L \cdot i)^2 + (L \cdot j)^2 - 2(L \cdot i)(L \cdot j)\cos(2\pi / 3)$$

$$D^2 = L^2 \cdot i^2 + L^2 \cdot j^2 - 2L^2 \cdot i \cdot j \cdot (-0.5)$$

$$D^2 = L^2 (i^2 + j^2 + ij)$$

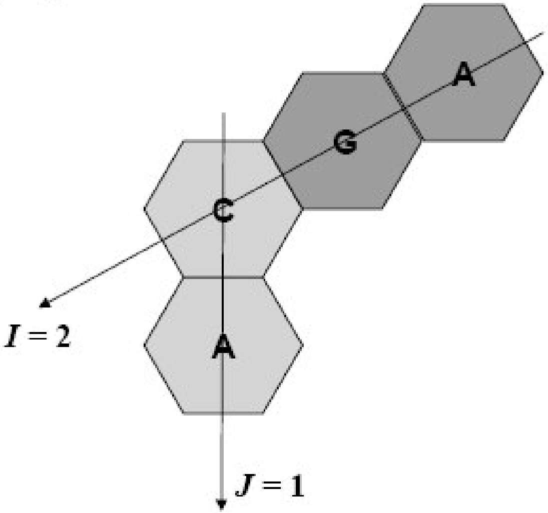
$$D / r = \sqrt{3(i^2 + j^2 + ij)} = \sqrt{3N}$$

Compute D based on "law of cosine"

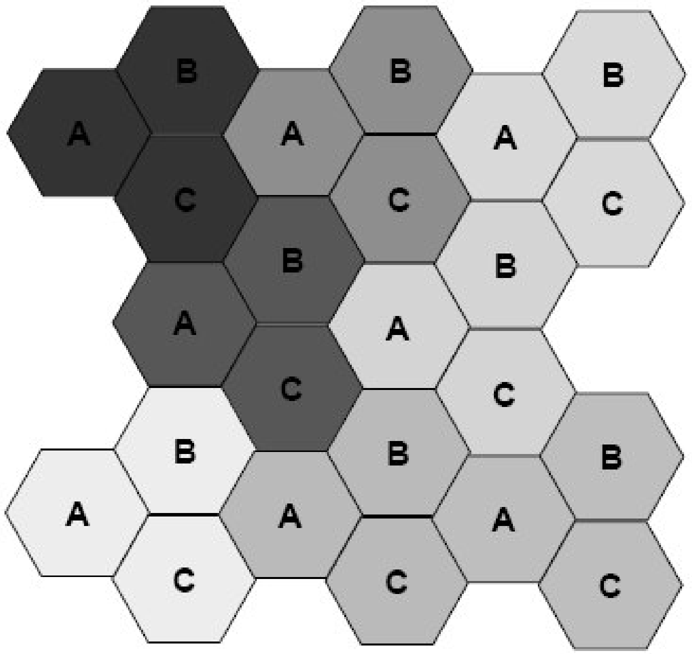
Cell size & FRF

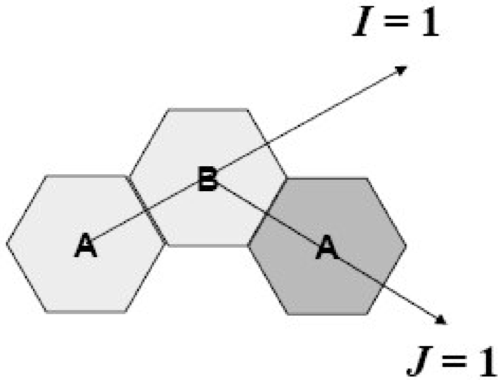
- Cell size should be proportional to 1/(subscriber density)
- Co-channel interference is proportional to
  - 1/D
  - r
  - $1/N^{0.5}$
  - Path-loss model
- Total system capacity is proportional to
  - 1/N
    - N : Frequency reuse factor

$$N = I^2 + IJ + J^2$$
$$N = (2)^2 + (2)(1) + (1)^2 = 7$$



For N = 3 we have:

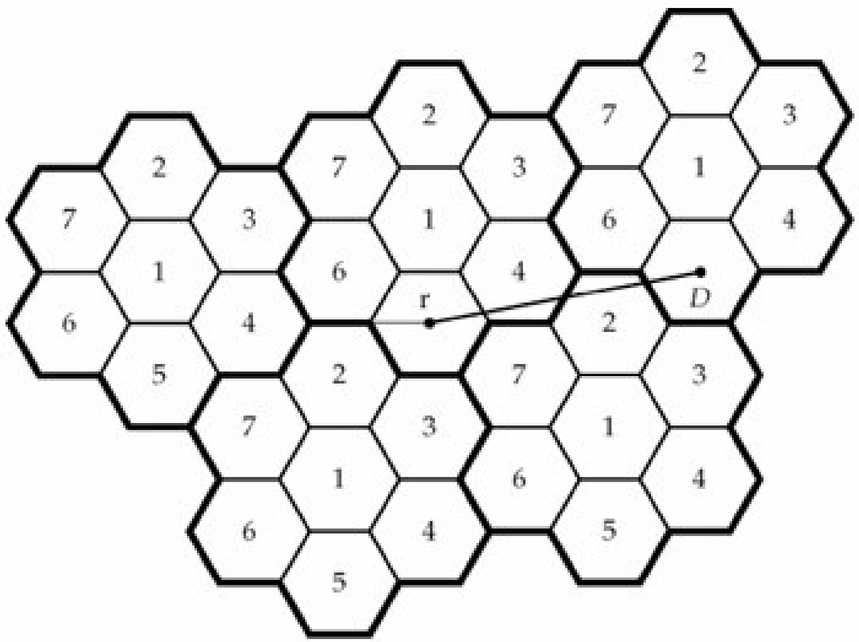




$$N = I^2 + IJ + J^2$$
$$N = (1)^2 + (1)(1) + (1)^2 = 3$$

Example: N=7

- Frequency reuse factor N=7
  - $N = i^2 + ij + j^2$
  - (i,j)=(1,2) or (2,1)
- Other commonly used patterns
  - N=3
    - (1,1)
  - N=4
    - (2,0); (0,2)
- N=1 is possible
  - CDMA



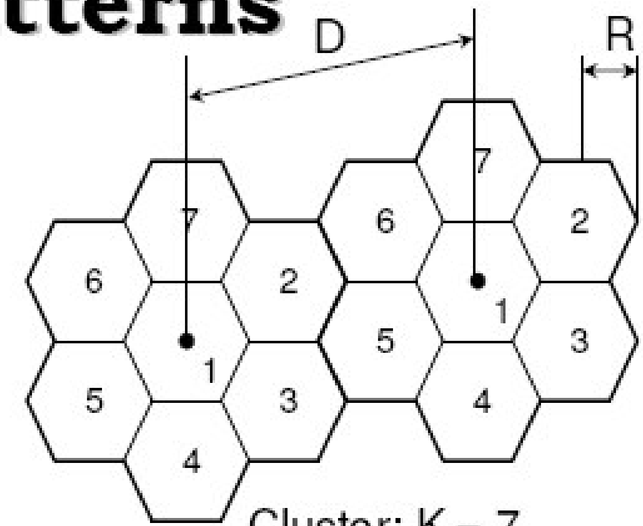
Reuse patterns

➔ Reuse distance:

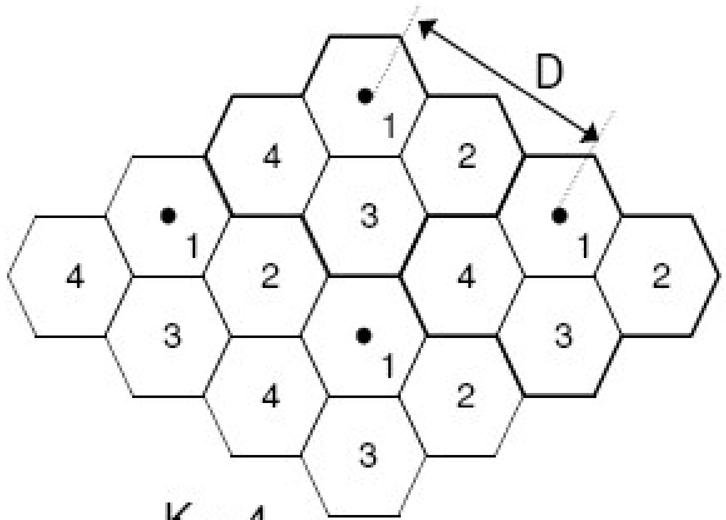
- ⇨ Key concept
- ⇨ In the real world depends on
  - → Territorial patterns (hills, etc)
  - → Transmitted power
    - » and other propagation issues such as antenna directivity, height of transmission antenna, etc

➔ Simplified hexagonal cells model:

- ⇨ reuse distance depends on reuse pattern (cluster size)
- ⇨ Possible clusters:
  - → 3,4,7,9,12,13,16,19,…



Cluster: K = 7



K = 4

Reuse distance

- ➔ General formula $D = R\sqrt{3K}$
- ➔ Valid for hexagonal geometry
- ➔ D = reuse distance
- ➔ R = cell radius
- ➔ 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

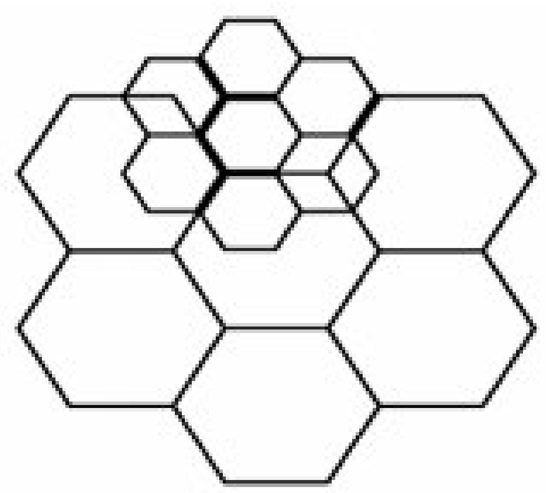
Possible clusters

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

Cell splitting

- Smaller cells have greater system capacity
  - Better spatial reuse
- As traffic load grows, larger cells could split into smaller cells



Cell splitting is the technique of splitting a congested cell into smaller cells.

- ➔ New (smaller cells) have their own base stations with reduced antenna height and reduced power.
- ➔ Cell splitting increases capacity since frequency reuse can be increased.
- ➔ Cell splitting preserves the geometry of the architecture and therefore simply scales the geometry of the architecture.
- ➔ In the following figure the cell radius has been reduced by half.

In the previous class we adopted the simple propagation model

$$P_R = P_o \left(\frac{d}{d_o} \right)^{-n}$$

At the cell boundary the distance *d* is *R*, the unsplit cell radius. Consider both an unsplit and a split scenario. For the unsplit case

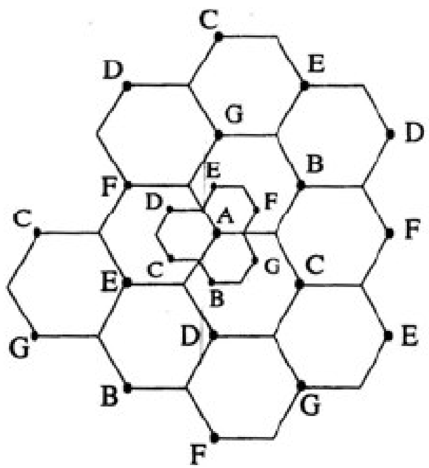
$$P_{r(unsplit)} = P_{t,unsplit} R^{-n}$$

For the split case

$$P_{r(split)} = P_{t,split} \left(\frac{R}{2} \right)^{-n}$$

or

$$P_{r,split} = P_{t,split} R^{-n} 2^{n}$$



For the received signal powers to be equal we must have

$$P_{t,unsplit} R^{-n} = P_{t,split} R^{-n} 2^{n}$$

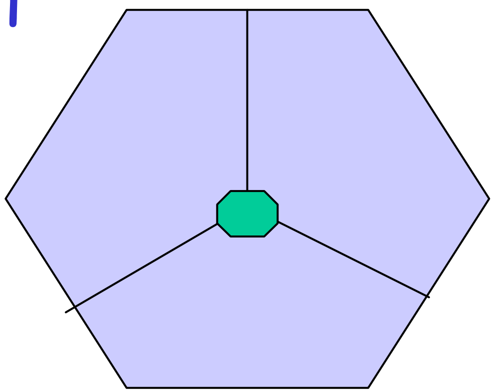
The ratio of transmitted powers is important. Consider the following:

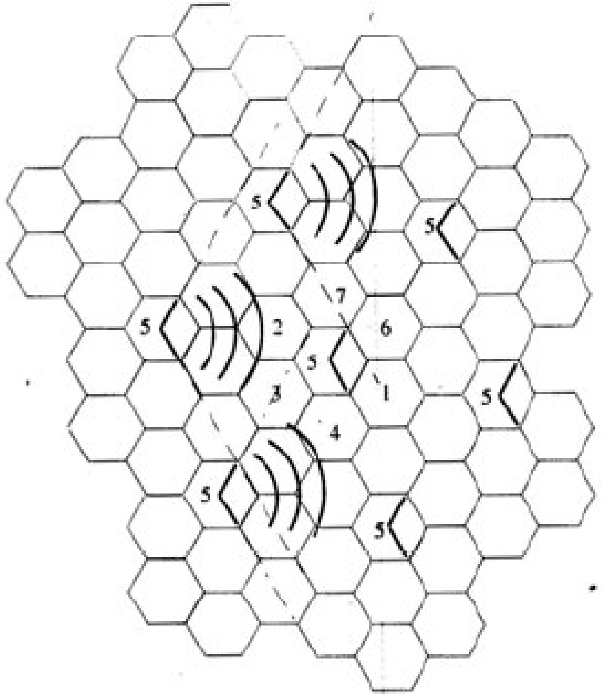
$$\frac{P_{t,split}}{P_{t,unsplit}} = 2^{-n}$$

Note the role of the path loss exponent. For $n = 4$, the transmitted can be reduced by a factor of 16 and still provide equal received signal powers.

Sectors

- Use directional antenna reduces CCI
  - Why?
- 1 base station could apply several directional antennas to form several sectors
- 3-sector cell



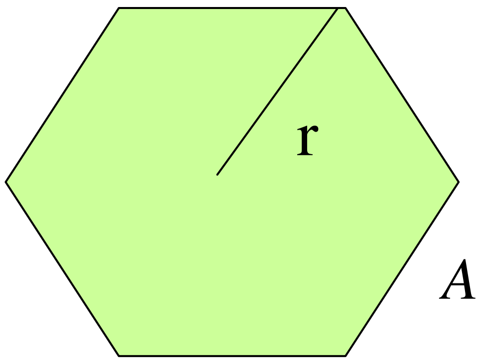


Forward link and reverse link

- Forward link
  - Also called downlink
  - BS→MS
- Reverse link
  - Also called uplink
  - MS→BS
- How forward link and reverse link are separated?
  - FDD (more often)
    - Frequency Division Duplex
  - TDD
    - Time Division Duplex
    - Why is it more difficult to engineer a TDD system?

Compute total system capacity

- Example
  - Total coverage area = 100 mile^2 = 262.4 km^2
  - Total 1000 duplex channels
  - Cell radius = 1km
  - N=4 or N=7
- What's the total system capacity for N=4 and N=7?



$$A = \frac{3\sqrt{3}}{2} r^2 = 2.6 r^2$$

Compute total system capacity

- # of cells = 262.4/2.6=100 cells
- # of usable duplex channels/cell
  - S=(# of channels)/(reuse factor)
  - S_4=1000/4=250
  - S_7=1000/7=142
- Total system capacity (# of users could be accommodated simultaneously)
  - C=S*(# of cells)
  - C_4=250*100=25000
  - C_7=142*100=14200

Cellular concepts

- W – total available spectrum, B – bandwidth per user, N is the frequency reuse factor, m – number of cells, number of simultaneous users is given by **n = (m/B)*(W/N)**
- # of users can be increased by
  - Increasing m (cells)
  - Decreasing cluster size (N)
- *A small cell size*
  - Results in longer battery life
  - Reduces handset size
  - Increases handoffs
  - Increases signaling load
  - Increases the complexity of design and network deployment

Practical deployment issues

- Location to setup antenna
  - Antenna towers are expensive
  - Local people do not like BSs
    - Antenna/BS does not look like antenna/BS
- Antenna
  - Omni-directional
  - Directional antenna

Wireless QoS

- Quality of Service (QoS)
  - Achieving satisfactory wireless QoS is an important design objective
- Quality measures
  - Channel availability (wireless network is available when users need it)
    - Blocking probability
    - Dropping probability
  - Coverage: probability of receiving adequate signal level at different locations
  - Transmission quality: fidelity/quality of received signals
    - BER
    - FER
- Application-dependent
  - Voice
  - Data
  - Multimedia

Wireless QoS

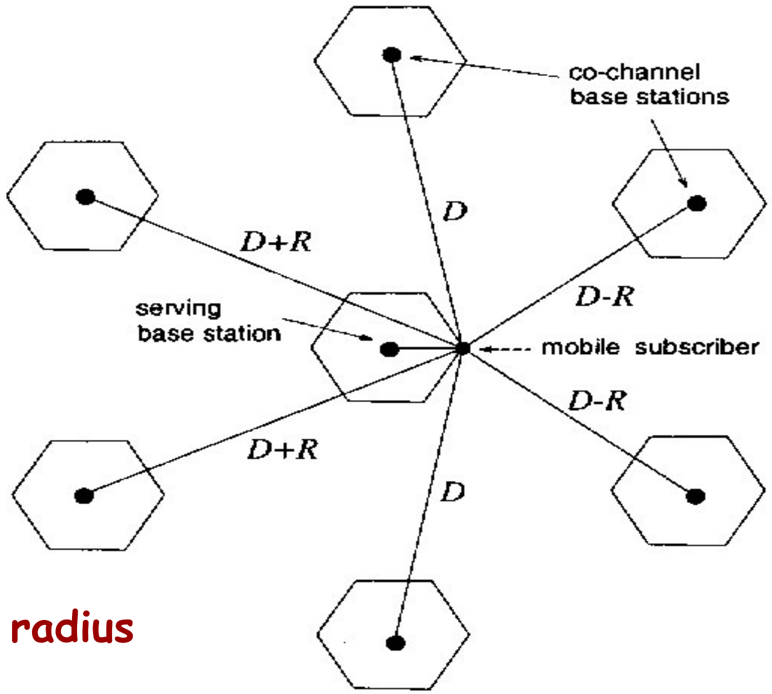
- Admission control
  - Blocking
  - Poor reception quality
- Co-channels
  - Frequency reuse factor
  - Cell planning
    - Frequency planning

Worst-Case CCI on the Forward Channel

- Co channel interference [CCI] is one of the prime limitations on system capacity. We use the propagation model to calculate CCI.
- There are six first-tier, co-channel BSs, two each at (approximate) distances of D-R, D, and R+D and the worst case (average) Carrier-to-(Co-Channel) Interference [CCI] is

$$\Lambda = \frac{1}{2}\frac{R^{-\beta}}{(D-R)^{-\beta} + D^{-\beta} + (D+R)^{-\beta}}$$

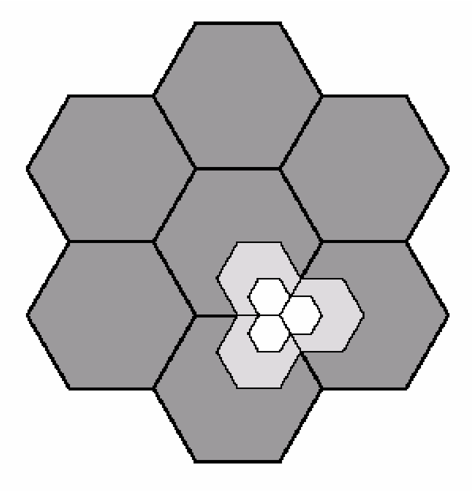
Worst case CCI
on the forward channel



R= cell radius

Approaches to Increase Capacity

- *Adding new channel* – any available channels can be added
- *Frequency borrowing* – frequencies are borrowed from adjacent cells by congested cells (or assign frequencies to cells dynamically)
- *Cell splitting* – cells in areas of high usage are split into smaller ones
- *Cell sectoring* – cells are divided into a number of wedge-shaped sectors, each with their own set of channels
- *Microcells* – decrease the cell size by moving antennas lower places (e.g. lamp posts)
  - useful in congested streets, inside public buildings, etc.



	Macrocell	**Microcell**
Cell radius	1 to 20 km	0.1 to 1 km
Transmission power	1 to 10 W	0.1 to 1 W
Average delay spread	0.1 to 10 μs	10 to 100 ns
Maximum bit rate	0.3 Mbps	1 Mbps