Cellular Fundamentals 2: Frequency Planning

- Frequency Reuse
- Co-channel Interference
- Adjacent Channel Interference

Review of Previous Lectures

- **Cellular Concept Architecture**
  - **Frequency Reuse**
- **Functionality of architectural components**
  - **MSC, HLR, VLR, BS and MS, Channels**
- **AMPS spectrum allocation – 30KHz**

Frequency Planning

- The allocation of frequency channels depends on several factors:
  - Cellular geometry
  - Signal propagation characteristics
  - Interference
- In the Cellular Concept (AMPS)
  - The channel allocation was fixed
    - A set of frequency channels was statically allocated to a cell

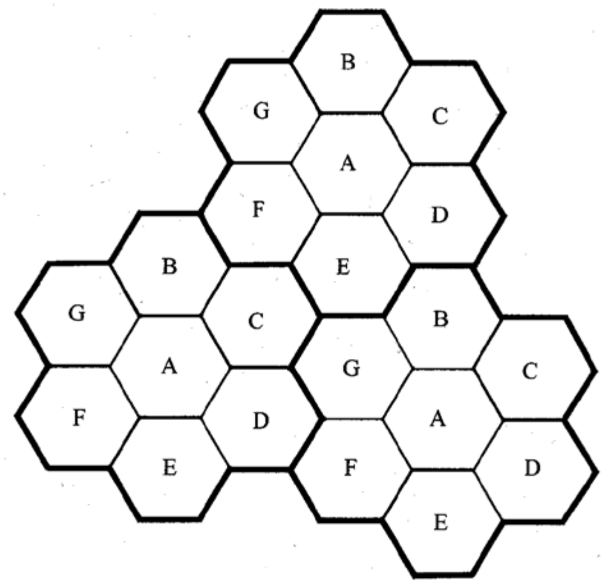
Frequency Reuse

- Each cellular base station is allocated a group of radio channels within a small geographic area called a *cell*.
- Neighboring cells are assigned different channel groups.
- By limiting the coverage area to within the boundary of the cell, the channel groups may be reused to cover different cells.
- Keep interference levels within tolerable limits.
- Frequency reuse or frequency planning

  •seven groups of channel from A to G

  •footprint of a cell - actual radio coverage

  •omni-directional antenna v.s. directional antenna



Why hexagonal cells?
It is proved that hexagons are the most efficient cells fill up an area without gaps.

Frequency Reuse Factor

- Consider a cellular system which has a total of *S* duplex channels.
- Each cell is allocated a group of *k* channels, $k < S$
- The *S* channels are divided among *N* cells.
- The total number of available radio channels

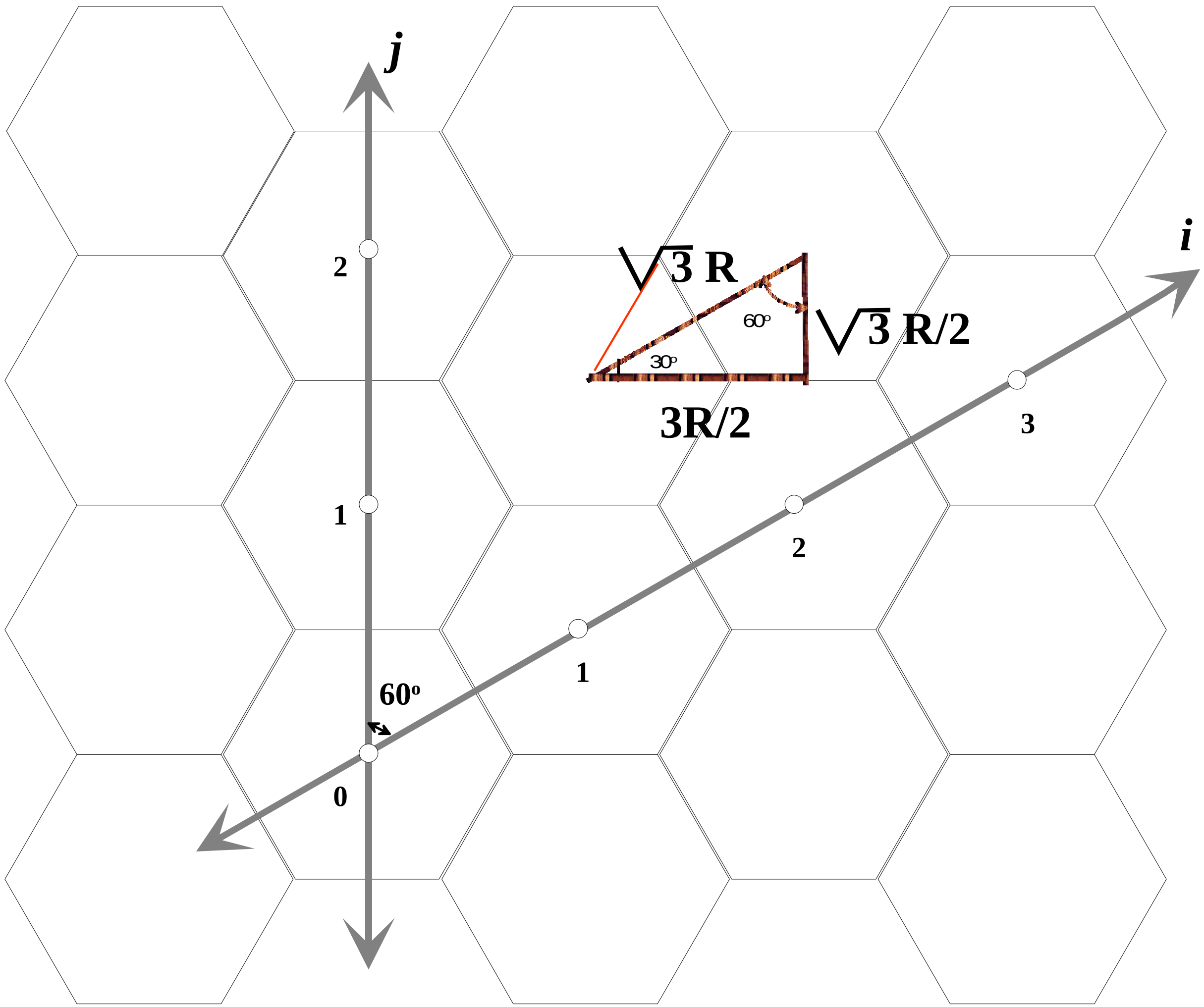
$$S = kN$$

- The *N* cells which use the complete set of channels is called *cluster*.
- The cluster can be repeated *M* times within the system. The total number of channels, *C*, is used as a measure of capacity

$$C = MkN = MS$$

- The capacity is directly proportional to the number of replication *M*.
- The cluster size, *N*, is typically equal to 3, 4, 7, 9 or 12.
- Small *N* is desirable to maximize capacity as *k = S/N*.
- The frequency reuse factor is given: $1/N$

Hexagonal Geometry



Assuming cell radius: R

The distance between two adjacent cell centres d is:

$$d = 2 \times R \times \cos 30^o$$

$$= 2 \times R \times \frac{\sqrt{3}}{2} = \sqrt{3}R (1.1)$$

Cell area:

$$area = 6 \times (\frac{1}{2} R \times \frac{\sqrt{3}}{2} R)$$

$$= \frac{3R^2\sqrt{3}}{2} (1.2)$$

Hexagonal Geometry

- The positive halves of the coordinates ***i*** and ***j*** intersect at a 60^o angle
- The unit distance along either axis is $\sqrt{3}$ times the cell radius (***R***)
- The cell radius is defined as the distance from the centre of the hexagon to any of its vertices
- The vectors from the centre of any arbitrary cell and the six adjacent cells are separated from each other by 60^o angle, the same observation is valid for the vectors to the co-channel cells

Hexagonal Coordinates

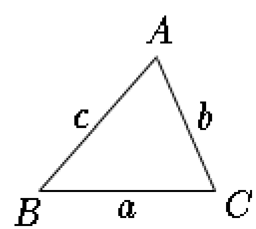
- Distance between two points in the Orthogonal Coordinates

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

- Distance between two points in the Hexagonal Coordinates

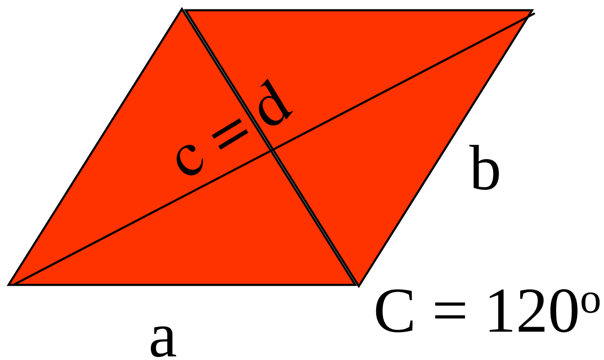
$$d = \sqrt{(i_2 - i_1)^2 + (i_2 - i_1)(j_2 - j_1) + (j_2 - j_1)^2}$$

- Why?
  - Trigonometry
    - *The Law of cosines*



$$a^2 = b^2 + c^2 - 2bc\cos A$$
$$b^2 = c^2 + a^2 - 2ca\cos B$$
$$c^2 = a^2 + b^2 - 2ab\cos C$$

Hexagonal Coordinates



$$c^2 = a^2 + b^2 - 2ab\cos C$$

$$c^2 = a^2 + b^2 - 2ab\cos 120^o$$

$$c^2 = a^2 + b^2 - 2ab\left(-\frac{1}{2}\right)$$

$$c^2 = a^2 + b^2 + ab$$

$$c = \sqrt{a^2 + ab + b^2}$$

The distance between the origin to any cell centre, **in hexagonal coordinate system**, is given by:

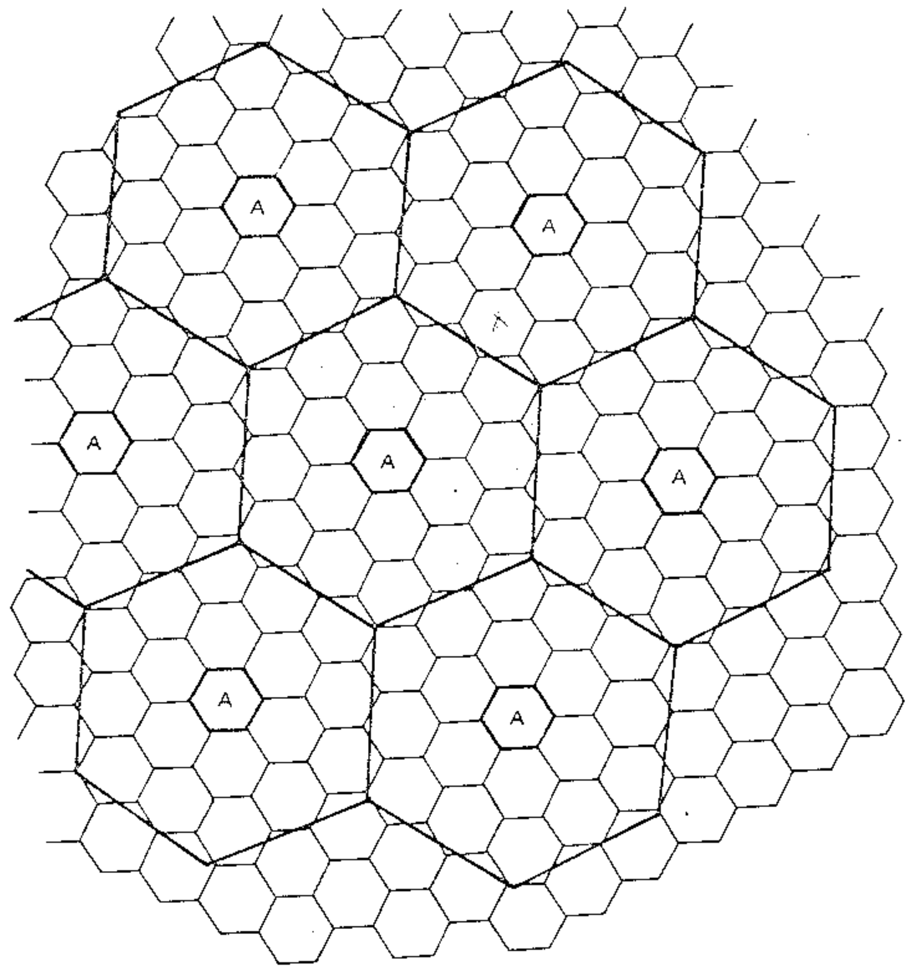
$$\boldsymbol{d = (i^2 + ij + j^2)^{1/2}} \qquad \textbf{(1.3)}$$

Construction of the large hexagons [Mac 79]

- A cluster of contiguous cells can be visualized as a large hexagon (actually a large hexagon can have the same area of a cell cluster) and the distance between centres of large hexagons is

  $$(i^2 + ij + j^2)^{1/2}$$

- D is the frequency reuse distance – between the centre of two co-channel cells



Construction of the large hexagons

- The pattern of the large hexagons can be seen as an enlargement of the original cell size using an enlargement scale of ***$(i^2 + ij + j^2)^{1/2}$***
- The number of cell areas contained inside the large hexagon is:

  $N = i^2 + ij + j^2$ (1.4)
- Therefore, the area of the larger hexagon is N times greater than the smaller hexagon, only if N complies with the values given by 1.7
- Valid number of cells per cluster are: 3, 4, 7, 9, 12, 13, 19, etc.

Proof:

$$small\_ha = \frac{3R_{sh}^{\ 2}\sqrt{3}}{2}$$

$$R_{bh} = R_{sh}\sqrt{i^2 + ij + j^2}$$

$$big\_ha = \frac{3\left(R_{sh}\sqrt{i^2 + ij + j^2}\right)^2\sqrt{3}}{2}$$
$$= small\_ha\left(i^2 + ij + j^2\right)$$
$$= small\_ha \times N$$

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

Finding the number of cells per cluster

- The relation between the ***co-channel reuse ratio:*** D/R and the ***number of cells per cluster*** can be found by combining the equations 1.1 and 1.3 :

$$\frac{D}{R} = \sqrt{3N} \,(1.5)$$

Proof: owing to (1.1)

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

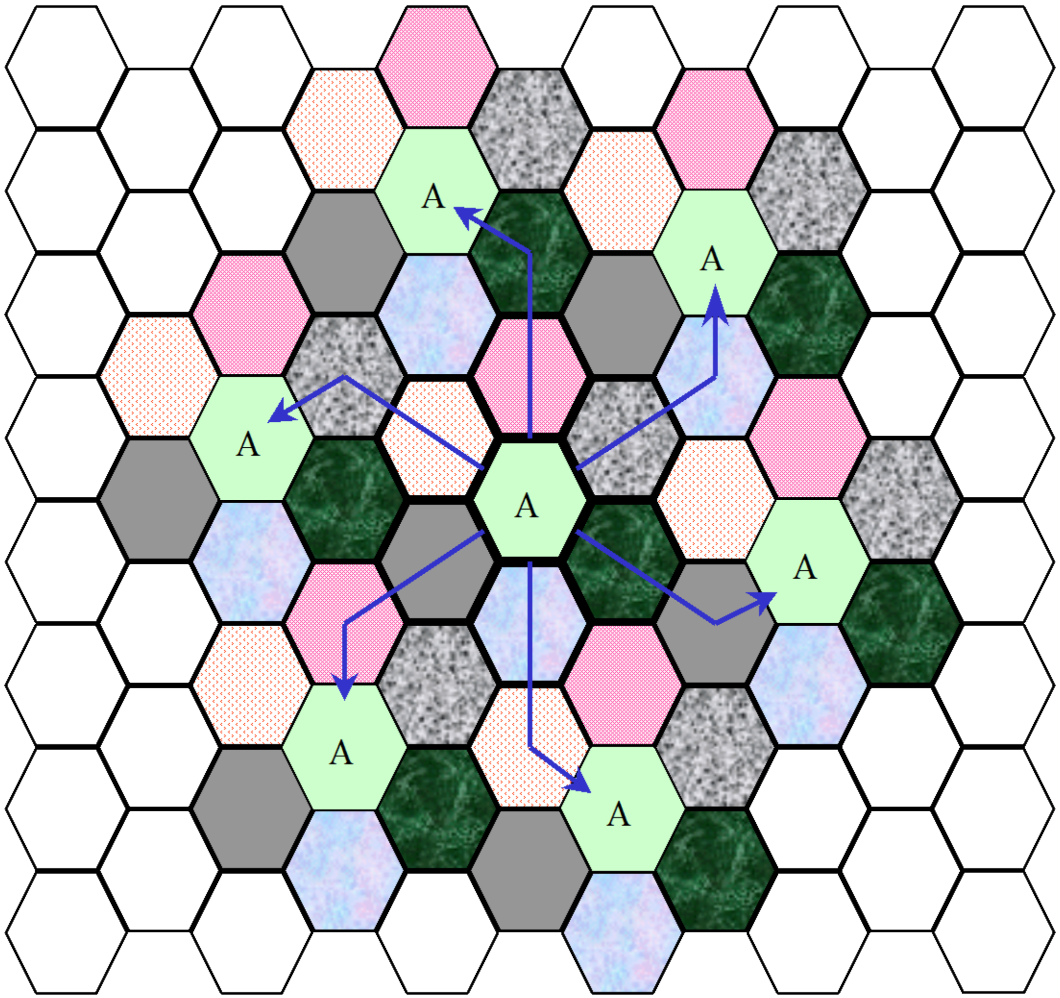
$$= R\sqrt{3} \times \sqrt{N}$$

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

Finding co-channel cells

- The frequency reuse layout of the cellular system is easily assembled following a scheme that finds the nearest co-channel cells of any cell of the network
- In the scheme, *i* and *j* are called *shift parameters, d*epending on their values different patterns are formed
- The chosen cell and its N-1 surrounding cells form a pattern known as a *compact pattern*
- The steps of the scheme are as follow:
  - Choose any cell as reference;
  - For each side of the hexagon: move ***i*** cells along that side, turn anti-clockwise 60 degrees and then move j cells on this new direction
  - Repeat the scheme to the surrounding cells of the initial reference cell which are not found co-channel cells
- Next slide shows seven compact patterns in a 7-cell cluster cellular network (where *i*=2 and *j*=1)

Finding co-channel cells



Frequency Planning - Summary

- This same set of channels is used in other distant cells (c*o-channel cells*)
- The distance between co-channel cells, called ***co-channel reuse distance D***, is such that users can utilise the same channels and have a good quality connection with acceptable levels of interference
- A group of cells using different sets of frequency channels is called a *cell cluster (*there is no frequency reuse inside a cluster*)*
- *The cluster* is repeated inside the cellular network

* More details about signal propagation, cellular geometry and channel interference are needed in order to understand how the channels are allocated to cells

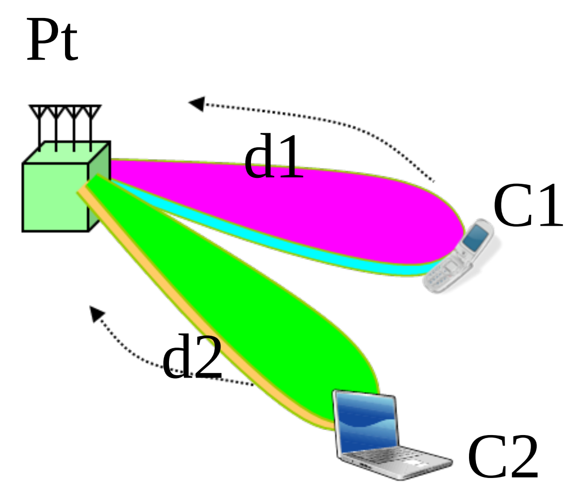
Propagation Path Loss

- The propagation path loss is a function of several factors: environment, antenna type, antenna height, antenna position
- Given a transmitted power (P_t), the received power (P_r) can be roughly calculated as [Lee95]:

$$P_r = P_t\, d^{-\gamma} \qquad (1.6)$$

- The ratio between the received power in two different locations d_1 and d_2 can be roughly estimated as:

$$\mathbf{C_2/C_1 = d_2^{-\gamma} / d_1^{-\gamma}} \qquad \mathbf{(1.7)}$$



  - C_1 is the signal level in receiver 1
  - C_2 is the signal level in receiver 2
  - d_1 is the distance between the transmitter and receiver 1
  - d_2 is the distance between the transmitter and receiver 2

Co-channel Interference

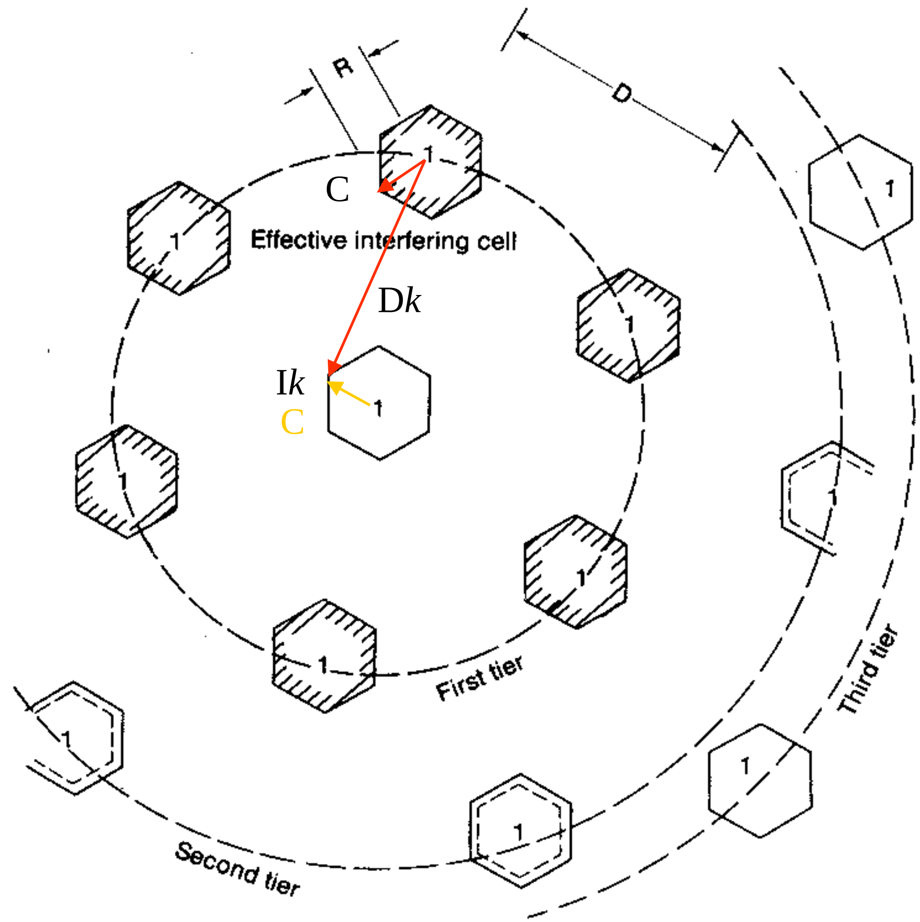
- What is the minimum reuse distance (D) a cellular system needs to leave between co-channel cells in order to have acceptable levels of co-channel interference?
  - The co-channel interference occurs as a result of the multiple use of the same frequency carrier
  - The *carrier-to-interference ratio* (***C/I***) is used to measure the amount of interference over a specific carrier
  - In an ideal situation, where all cells have the same radius and coverage area (assuming all BSs transmit with power P), the co-channel interference is independent of the transmitted power [Lee 95] therefore:

Six Effective Interfering cells of cell 1 [Lee 95]

- K_I is the number of co-channel interfering cells in the first tier (the interference caused by the second tier of interfering cells can be neglected [Lee95])

- Total co-channel interfering signal at the cell edge using Eq.(1.7), assuming all co-channel transmitting at the level C.

$$I = \sum_{k=1}^{K_I} I_k \qquad I_k = C \frac{D_k^{-\gamma}}{R^{-\gamma}}$$



Co-channel Interference

- Assuming the local noise can also be neglected in relation to the signal strength, the ***C/I*** ratio can be expressed by equation 1.8
  - **γ** is the propagation path loss factor
  - ***D*** is the distance from BS_i
  - ***R*** is the cell radius, defined as the distance from the centre of the cell to its edge
  - Assuming, omni directional antennas and D_k = D for all K_I we get expression 1.9 (in decibel) [Far 96]
  - ***D*** is the reuse distance
- D/R is the co-channel reuse ratio

$$\frac{C}{I} = \frac{C}{\sum_{k=1}^{K_I} I_k}$$

$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{K_I} \left(\frac{D_k}{R}\right)^{-\gamma}} \quad (1.8)$$

$$\frac{C}{I} = 10\log\left[\frac{1}{K_I} * \left(\frac{D}{R}\right)^{\gamma}\right] \quad (1.9)$$

Co-channel Interference

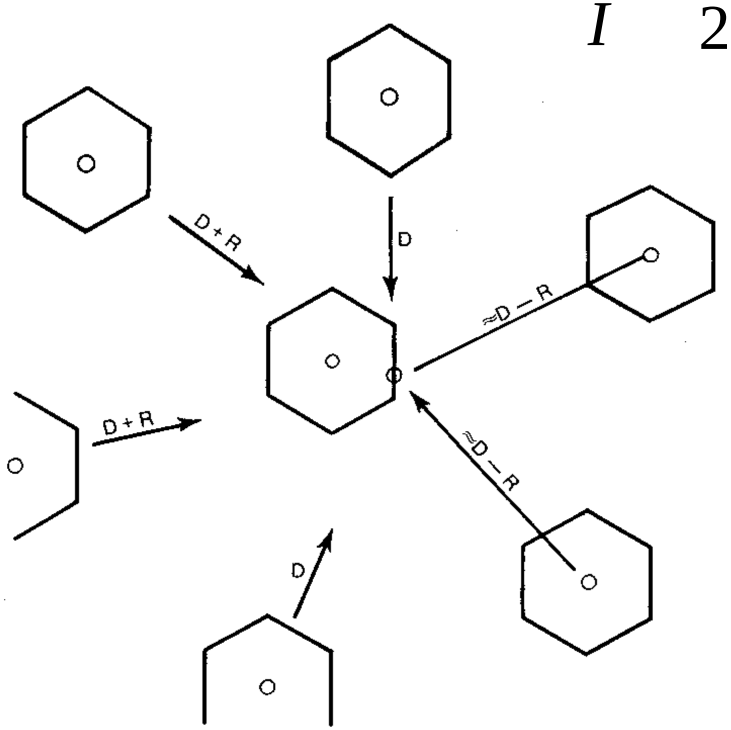
- After several field tests and consideration of other propagation loss dependent factors, the designers of AMPS conclude that a minimum C/I and *signal-to-noise ratio (*SNR) of 18 dB would be acceptable as good quality communication
- Solving 1.9 for C/I equals to 18 dB, 6 interfering cells and propagation path loss factor of 4, we have:
  - ***D/R*** = 4.41
- After practical simulations and taking into consideration the specified 75% of the mobile users saying that the voice quality is good or excellent in 90% of the coverage area, led a value of ***D/R*** of 4.6 as described in the Bell labs publication [Mac79]
- Using 1.5, we can calculate the number of cells needed to obtain a 4.6 D/R using omni-directional antennas:

$$N=7$$

Mobile Radio Propagation Effects

- However, in practical systems when omni directional antennas are used a cell cluster of 9 or 12 cells is implemented (Why???)
- Actually, a 7-cell cluster does not provide a sufficient frequency reuse distance separation even when an ideal condition of flat terrain is assumed
- To understand why, we need to study the worst case scenario for the mobile station
- the mobile station is at the boundary R, where it would receive the weakest signal from its own base station
- The distances from all six co-channel cells are: two distances of D – R, two distances of D, and two distances of D + R

Mobile Radio Propagation Effects



$$\frac{C}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2D^{-4} + 2(D+R)^{-4}} \tag{1.10}$$

$$\frac{C}{I} = \frac{1}{\frac{2(D-R)^{-4}}{R^{-4}} + \frac{2D^{-4}}{R^{-4}} + \frac{2(D+R)^{-4}}{R^{-4}}}$$

$$\frac{C}{I} = \frac{1}{2\left(\frac{D}{R}-1\right)^{-4} + 2\left(\frac{D}{R}\right)^{-4} + 2\left(\frac{D}{R}+1\right)^{-4}}$$

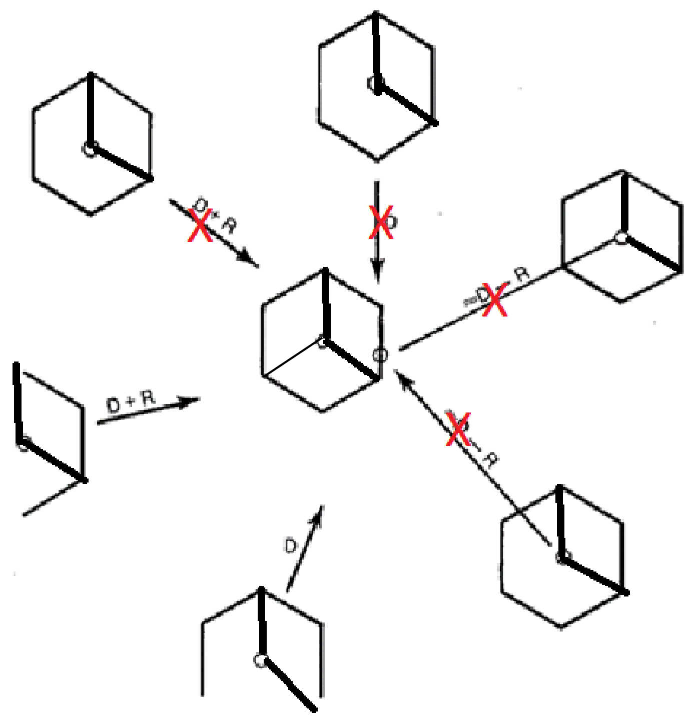
Mobile Radio Propagation Effects [Lee 95]

- For a D/R of 4.6, the value of C/I is 54 or 17 dB, which is lower than 18 dB
- In real systems as the site locations are imperfect and the terrain is not flat, the C/I received is always worse than 17 dB and could be lower than 14 dB
- Therefore, in an omni directional cell system, a cell cluster of 9 or 12 would be a correct choice, because, even considering the shortest distance of D-R for all six interferes as worst case, the values of C/I would be greater than 18 dB

N	D/R	C/I Eq(1.10)	C/I (dB)
7	4.6	54	17
9	5.2	84.5	19.25
12	6	179.33	22.54

Cell Sectoring (Capacity Expansion Technique)

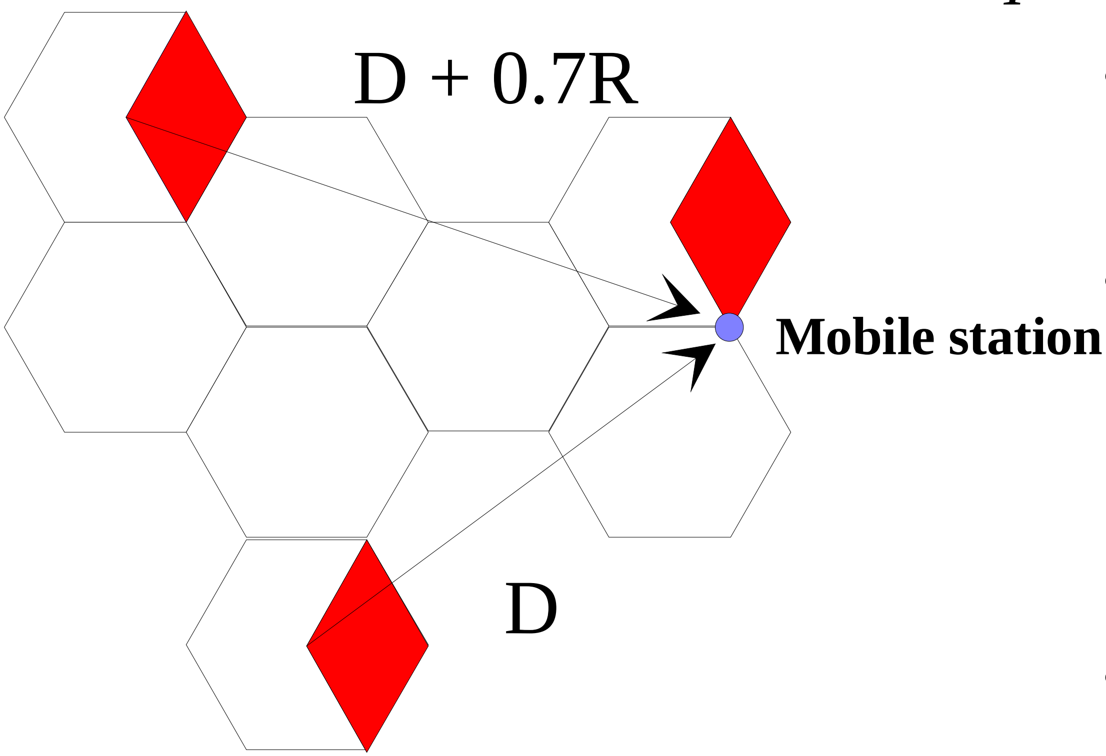
- The use of directional antennas can improve the C/I without the need to increase the number of cells in the cluster
- The left diagram illustrates the situation for a cell site with three 120-degree directional antennas
- The front-to-back ratio of a sectored antenna is at least 10 dB
  - therefore the interference can be considered in only one direction
- For the 3-sector cell, the number of interfering cells is reduced to two



Cell Sectoring (Capacity Expansion Technique)

Assuming the values of the distance of the interfering cells to the mobile station are D+0.7R and D, then:

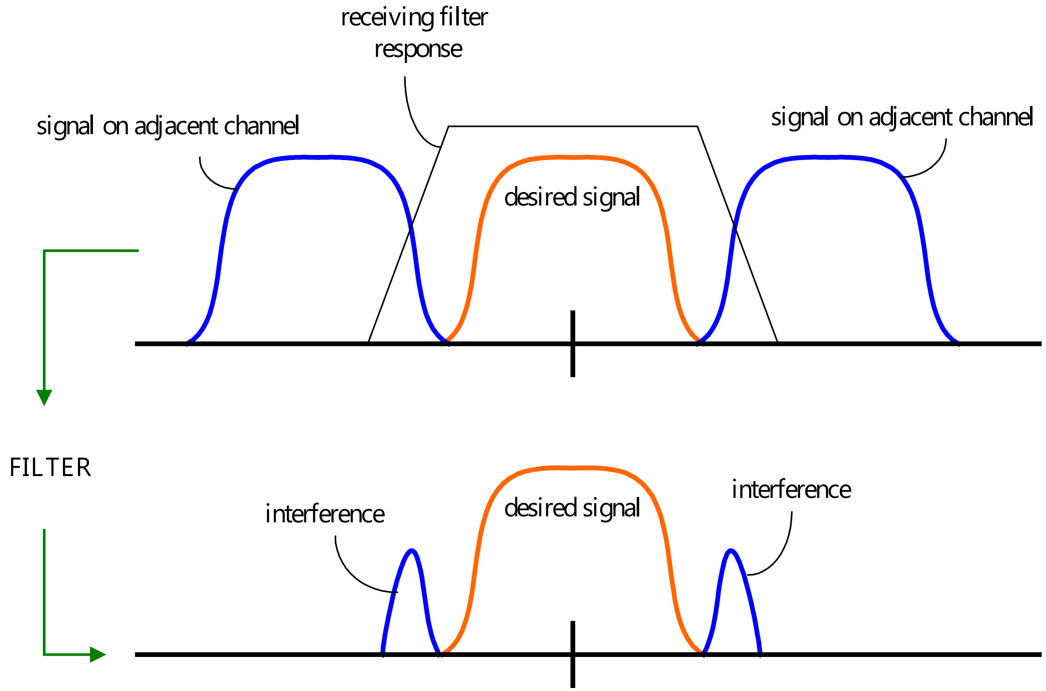
$$\frac{C}{I} = \frac{R^{-4}}{(D+0.7R)^{-4} + D^{-4}} \qquad (1.11)$$



- Applying the reuse distance of 4.6 to the equation, results in a C/I of 24.5 dB > 18 dB
- In real systems, the C/I could be 6 dB weaker in a heavy traffic area as a result of irregular terrain contour and imperfect site locations [Lee95]
- but in this case the C/I still would be adequate

Adjacent Channel Interference

- Adjacent channel interference: interference from adjacent in frequency to the desired signal.
  - Imperfect receiver filters allow nearby frequencies to leak into the passband
  - Performance degrade seriously due to *near-far* effect.



Adjacent Channel Interference

- frequency filters
  - require a substantial spectral guard band to reject adjacent frequencies adequately
  - For example, in AMPS, the spacing of 30 kHz , and peak deviation of 12 kHz in AMPS are not enough for a correct rejection

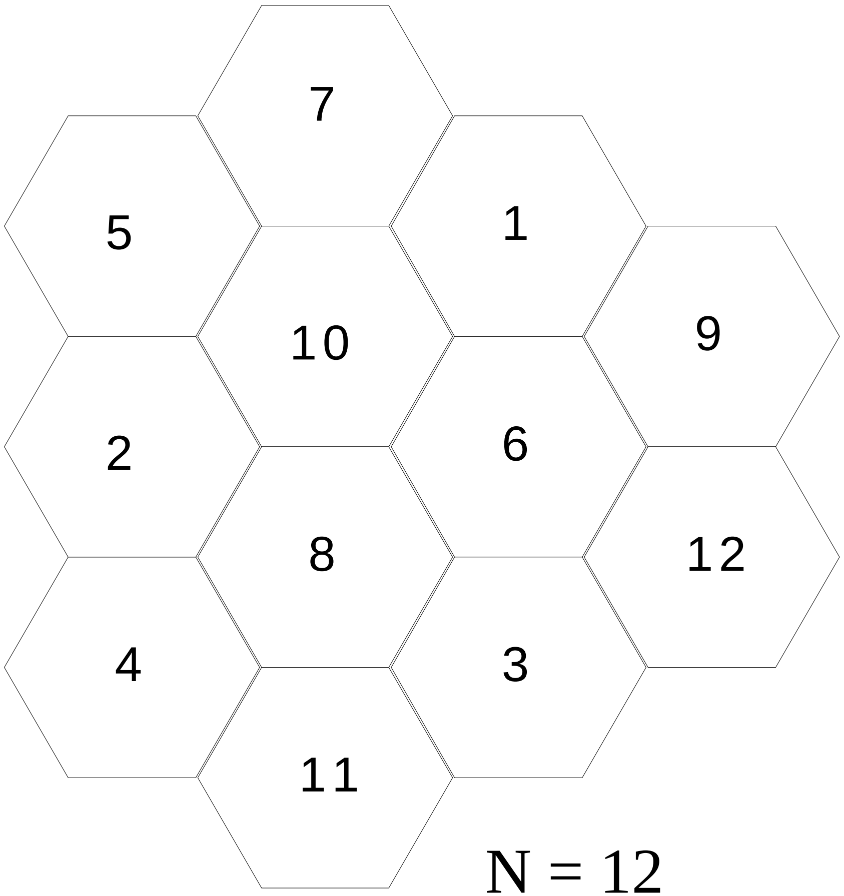
- The assignment of channels in a cell is kept as far apart as possible. Method:
  - If the number of cells per cluster is ***N,*** then ***N*** disjoint channel sets are deployed, and the *n*th set would contain channels *n*, *n* + ***N***, *n* + 2***N***, etc.
  - For example, if ***N*** = 7, the first set would contain channels 1, 8, 15, etc.

Give one example of the separation of channels table:

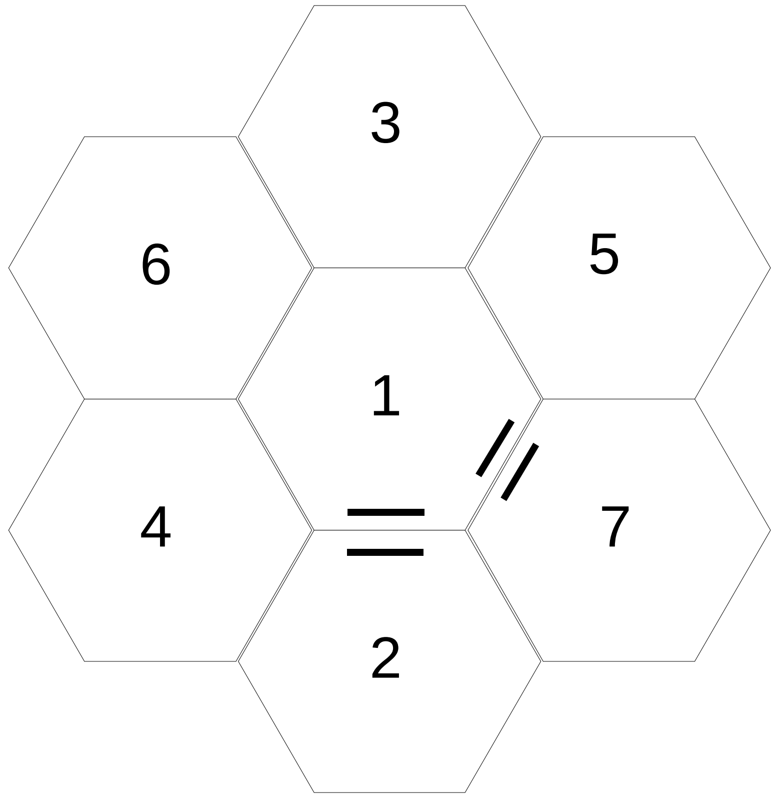
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21 …

Adjacent Channel Interference

- Second source of adjacent channel interference
  - geographically adjacent cells



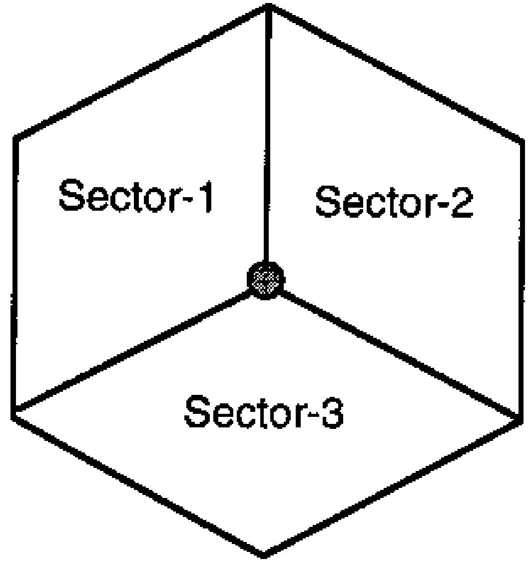
N = 12



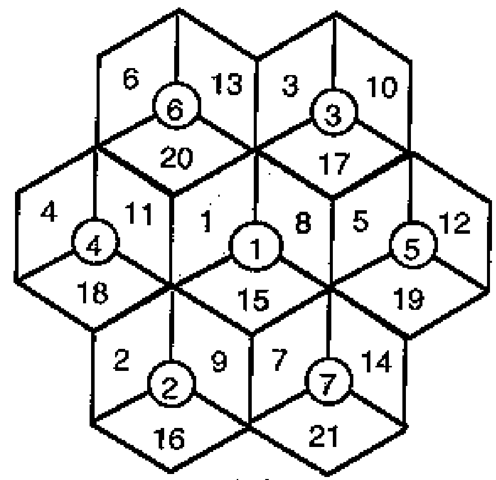
N=7 channel still not far enough

Adjacent Channel Interference

- It is impossible to avoid adjacent interference in a 7-cell cluster
- The use of directional antennas allows to overcome this problem



(a)



(b)

Class Quiz

- **What is the co-channel reuse ratio? How is the co-channel reuse ratio related to the number of cells in a cluster?**

- **What is the co-channel interference? How do we determine how many cells in a cluster? Why can cell sectoring reduce the co-channel interference?**

- **What is the adjacent channel interference? How can the adjacent channel interference be mitigated?**

References

– [Far96] Saleh Faruque. Cellular Mobile Systems Engineering. *Mobile Communication Series*. Artech House Publishers. ISBN 0-89006-518-7.1996.

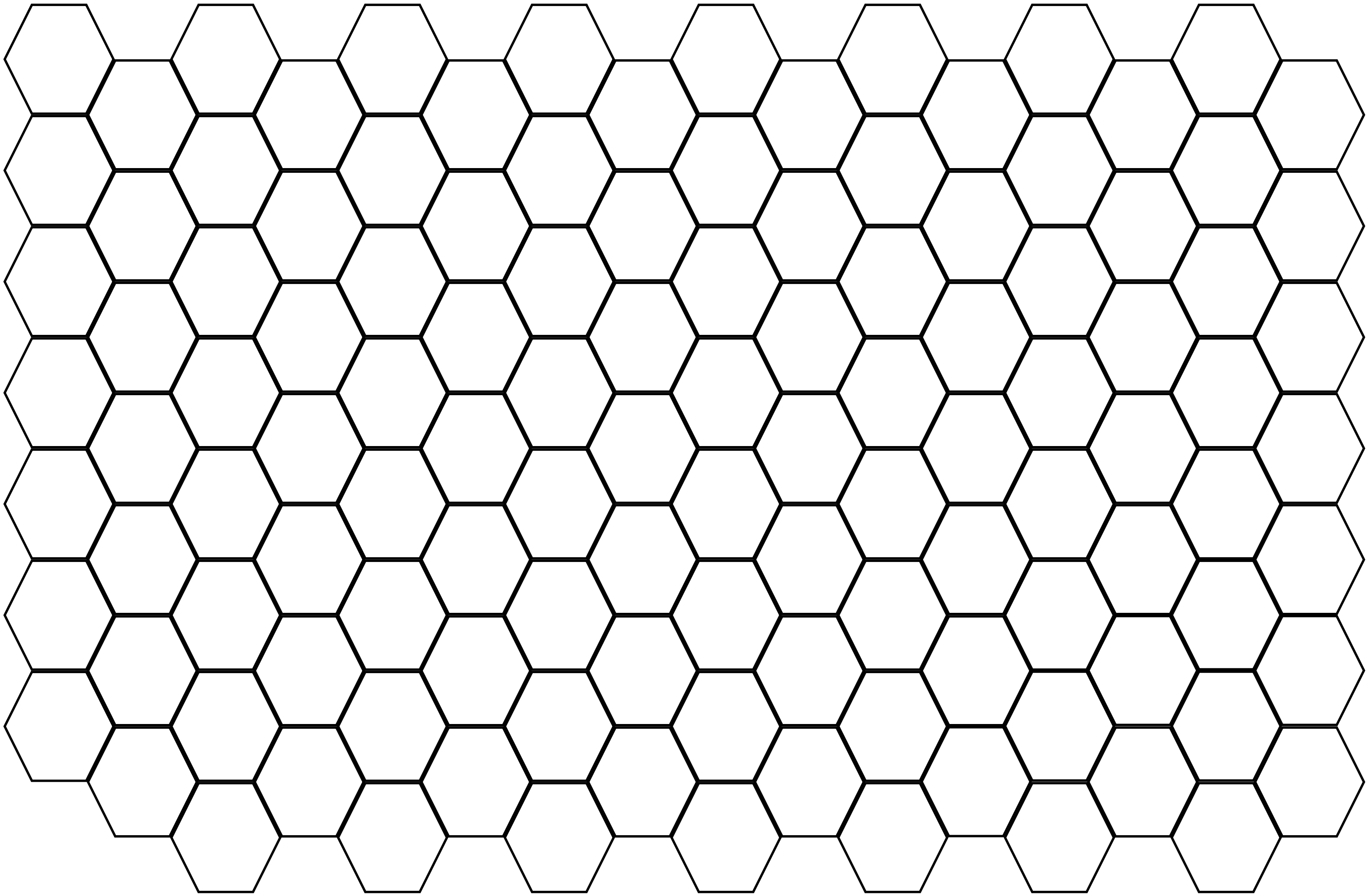
– [Lee 95] William C. Y. Lee. Mobile Cellular Telecommunications: Analog and Digital Systems. Second Edition. McGraw-Hill, Inc. ISBN 0-07-038089-9. 1995.

– [PK] Kaveh Pahlavan and Prashant Krishnamurthy. Principles of Wireless Networks. *Prentice Hall*. ISBN 0-13-093003-2, 2002.

– [Mac 79] V. H. Mac Donald. Advanced Mobile Phone Service: The Cellular Concept. *The Bell System Technical Journal*, volume 58, number 1, pages 15-41, January 1979.

– [WS] William Stallings. Wireless Communications and Networks. *Prentice Hall*. ISBN 0-13-040864-6, 2002.

Network Grid



Network Grid