ECS 455 Chapter 2

Cellular Systems

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Pre-Cellular System

Area over which **reliable** radio comunication can occur btw a BS and MSs.

- Achieve a **large coverage area** by using a single, **high powered** transmitter.
  - Put BS on top of mountains or tall towers
- Next BS was so **far away** that interference was not an issue.
- Severely limit the number of users that could communicate simultaneously.
- Noise-limited system with few users.
- Bell mobile system in New York City in the 1970s could only support a maximum of twelve simultaneous calls over a thousand square miles.

Examples

- Using a typical analog system, each channel needs to have a bandwidth of around **25 kHz** to enable sufficient audio quality to be carried, as well as allowing for a guard band between adjacent signals to ensure there are no undue levels of interference.
- Can accommodate only **40 users** in a frequency “chunk” of 1-MHz wide.
- Even if **100 MHz** were allocated to the system, this would enable only **4000 users** to have access to the system.
- Today cellular systems have millions of subscribers, and therefore a far more efficient method of using the available spectrum is needed.

Pre-Cellular System (2)

- All regions use the **same group of frequencies**.
- Non-overlapping coverage of the regions is NOT enough

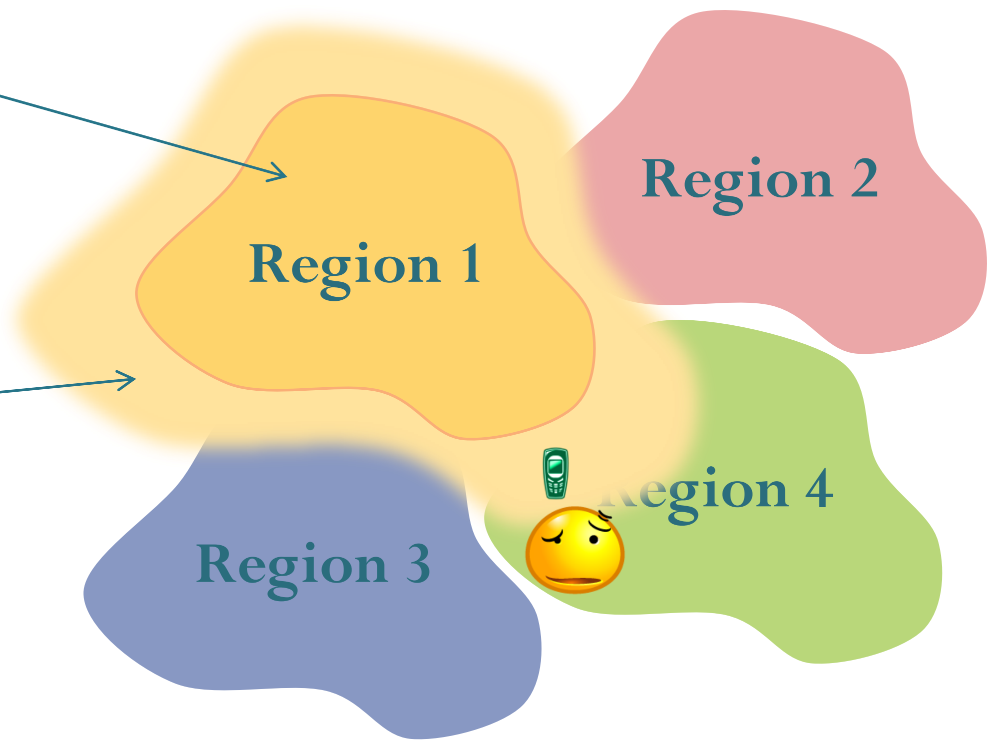
Colored area indicates the coverage area of the central transmitter in the corresponding region

Pre-Cellular System (2)

- All regions use the same group of frequencies.
- Non-overlapping coverage of the regions is NOT enough

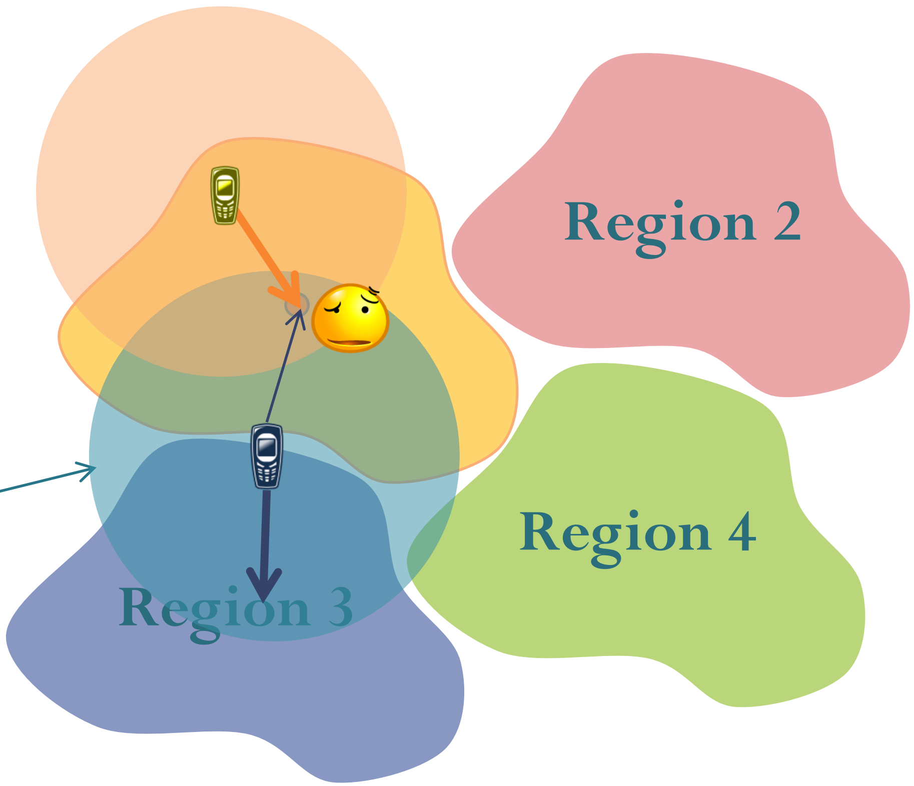
Downlink signal in this region is strong enough for communication

The signal in this region is ***not*** strong enough for communication but still impose significant ***interference*** on users in other regions



Pre-Cellular System (2)

- All regions use the same group of frequencies.
- Non-overlapping coverage of the regions is NOT enough



Uplink signals from user of a cell can reach the BS of a different region.

Pre-Cellular System (3)

- Regions need to be well-separated!

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Cellular Systems

2.1 Frequency Reuse

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Cellular systems

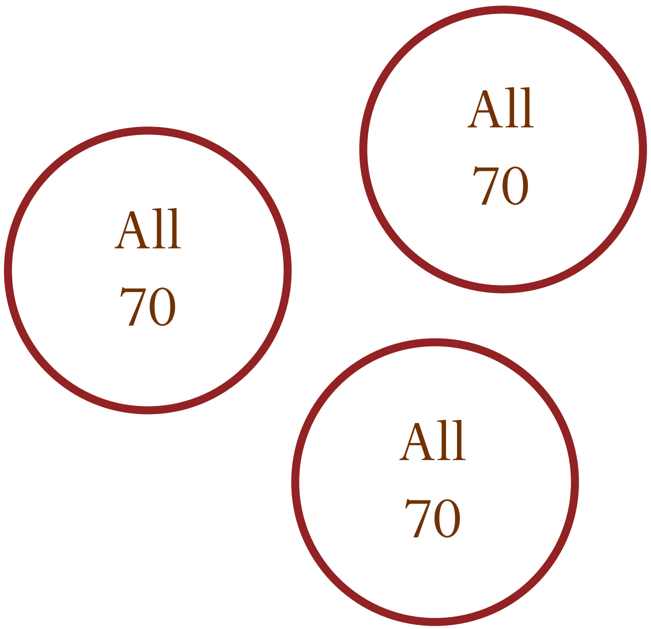
- The coverage area is divided into many small areas (**cells**).
- Replace
  - a single, high power transmitter

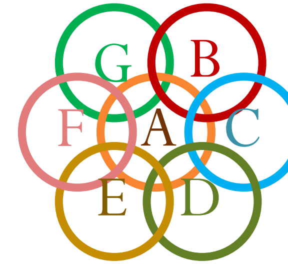
  with
  - **many low-power** transmitters each providing **coverage** to only one cell area (a small portion of the service area).

    Area over which **reliable** radio comunication can occur btw a BS and MSs.
    - Power is lowered from hundreds of watts to a few watts, or even less than one watt per channel. [Klemens, 2010]
- **Frequency**/channel **Reuse**: Divide the available channels (frequency bands) into groups/sets. Different channel sets are assigned to different cells. The same channel sets may be **reused** at **spatially separated** locations.
- **Co-channel** cells = Cells that are assigned the same channel set

Idea (1)

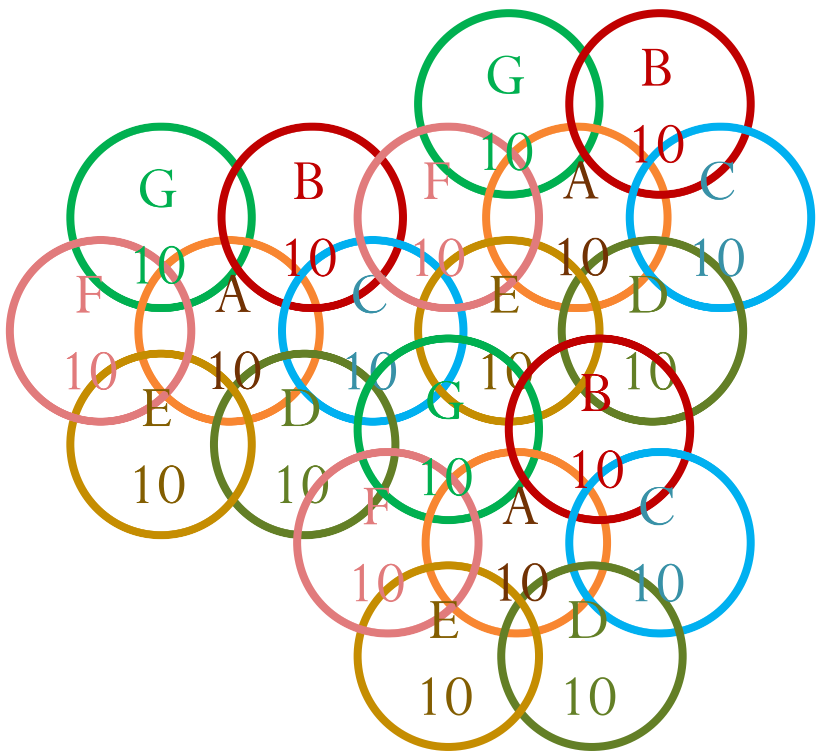
- Suppose the whole system has S = 70 frequency channels
- Pre-cellular:





Idea (2)

- Cellular:
  - Split 70 channels into 7 groups (A,B,C,D,E,F,G).
  - Each group has 10 channels. Cells using the same groups are far apart.

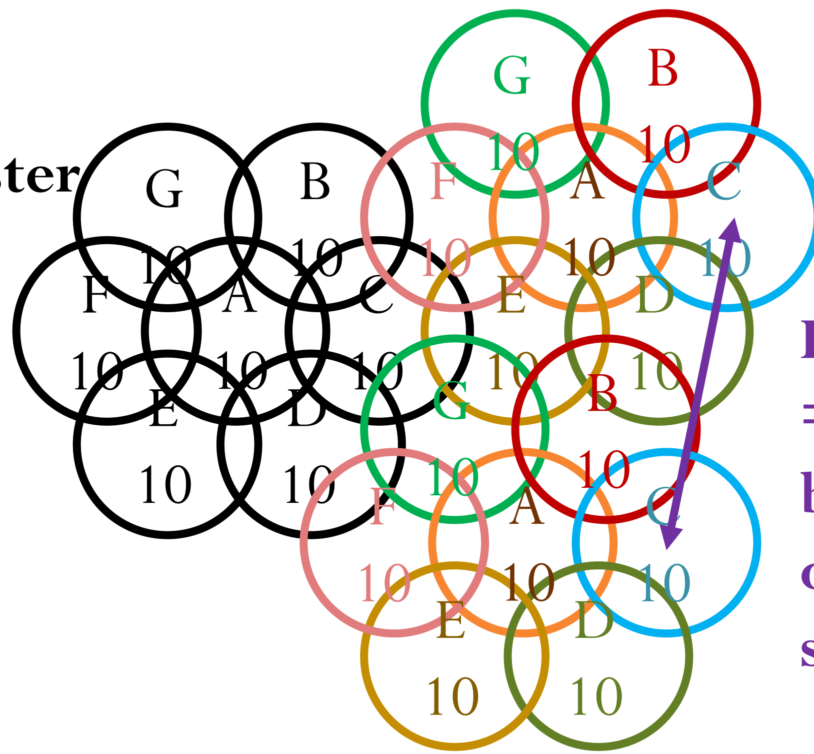


Note:
Cells can overlap.

Idea (3)

- Some Terminology:

Cluster

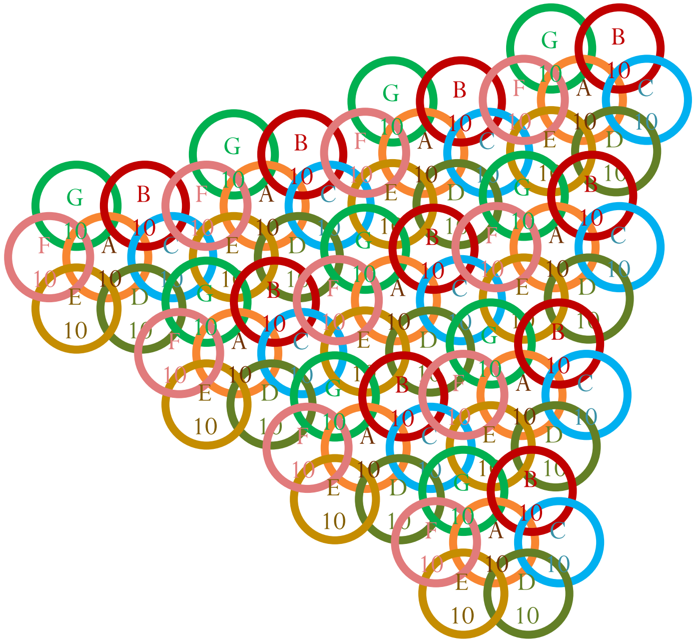


Reuse Distance (D) = minimum distance between the centers of cells that use the same channels

Cluster size
N = 7

Idea (4)

- To support more users (increase capacity), simply use smaller cell size (area).



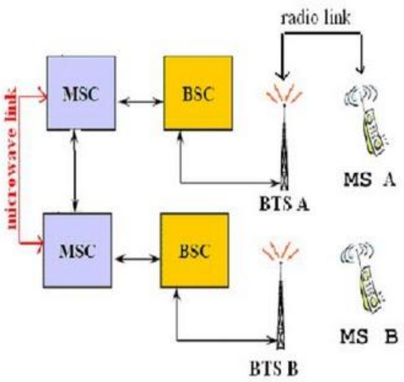
Cellular systems: Handoff

- Sophisticated **switching** technique
- Enable a call to proceed **uninterrupted** when the user moves from **one cell to another**.
- The system can switch moving users between towers to find the **strongest signal**.

Cellular systems: History

- The concept of cells was first proposed (in an unpublished work) as early as **1947** by Douglas H. Ring at **Bell Lab**oratories in the US
- Detailed proposal for a "High-Capacity Mobile Telephone System" incorporating the cellular concept submitted by Bell Laboratories to the FCC in 1971.
- The first **AMPS** system was deployed in Chicago in **1983**.

Basic cellular system



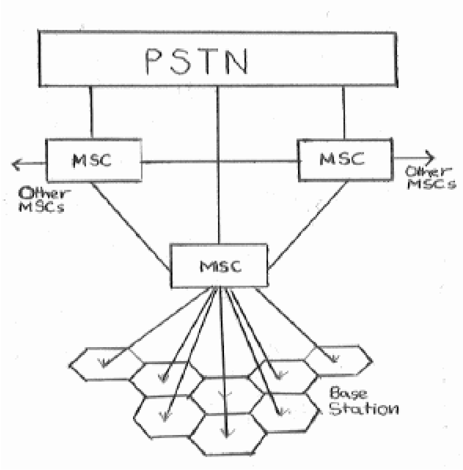
1. **Mobile stations (MS)**
2. **Base stations (BS)**
   - Serve as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephone lines or microwave links to the MSC.
   - Generally have towers which support several transmitting and receiving antennas.
     - Simultaneously handle full duplex communications.

- Each mobile communicates via radio with one of the base stations and may be handed-off to any number of base stations throughout the duration of a call.

Basic cellular system (2)

3. **Mobile switching center** (**MSC**)

- Sometimes called a **mobile telephone switching office (MTSO)**
- **Coordinates** the activities of all of the base stations
  - Coordinating which BS will **handle** a call to or from a user and when to **handoff** a user from one base-station to another.
- **Connect** the entire cellular system to the **PSTN** (public switched telephone network).

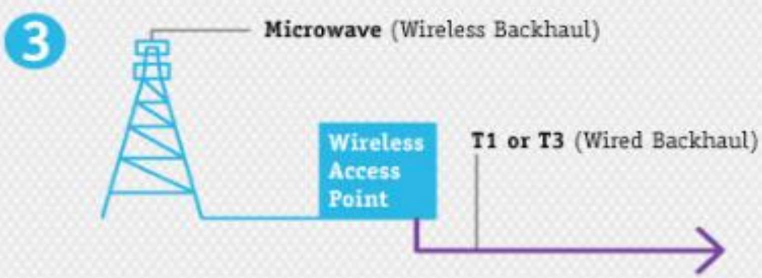


How a Cell Phone Call Works

Cell phones are radio devices — they communicate by transmitting and receiving voice over an area.

First a cell phone radios the nearest cell tower (or *site*). When you make a call or turn your phone on, your phone sends a message via radio that's picked up by the tower's antennas.

Next, a wire or fiberoptic line carries the call down to the wireless access point, connected to a multi-port switch.



The call (along with many others) gets routed to a backhaul — usually down to an underground wired T1 or T3 line, but sometimes back up the mast to a powerful line-of-sight wireless microwave antenna (typically only used either when there isn't a ground connection, or when the ground connection is poor).

The incoming call or data comes back from the backhaul and up through the switch to the antenna, where it then hits your phone (presuming your phone is still communicating with the same site). If you are moving, then there's a handoff—a new but more or less identical cell site transmits the data to your phone, once your phone checks in.

[http://cellphones.org/blog/how-cell-phone-calls-work/]

Common Air Interface (CAI)

- Standard for communication between BS and MSs

1. **Voice channels**
   - **Forward voice channels** (**FVC**) : voice transmission from BS to MSs
   - **Reverse voice channels** (**RVC**): voice transmission from MSs to BS
2. **Control channels**
   - Often called **setup channels**
   - **Forward control channels** (**FCC**) and **reverse control channels** (**RCC**)
   - Involve in setting up a call and moving it to an unused voice channel.
   - Transmit and receive data messages that carry call initiation and service requests
   - Monitored by mobiles when they do not have a call in progress.

- Typically, 5% control channels and 95% voice channels.

Frequency Reuse (Review)

Definition

"The use of radio channels on the **same carrier frequency** to cover **different areas** which are separated from one another by sufficient distances so that **co-channel interference** is not objectionable."

[Mac Donald, 1979, p 16]

- Employed not only in mobile-telephone service but also in entertainment broadcasting and many other radio services.

Frequency Reuse (Review)

- Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region
- Each cellular BS is allocated a **group** of radio channels to be used within the corresponding cell.
- BSs in **adjacent** cells are assigned channel groups which contain completely **different** channels than neighboring cells.
- By limiting the coverage area to within the boundaries of a cell, the same group of channel may be used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits.
- The distance between two cells that use the same frequency channels is called the **reuse distance**.

[Rappaport, 2002]

Cell Shape

- The actual radio coverage of a cell is known as the **footprint**.
  - Determined from field measurements or propagation prediction models.
- In reality, it is **not possible to define exactly the edge of a cell**.
  - Signal strength gradually reduces, and towards the edge of the cell performance falls.
  - MSs have different levels of sensitivity, this adds a further greying of the edge of the cell.
  - Impossible to have a sharp cut-off between cells.
- In some areas they may overlap, whereas in others there will be a hole in coverage.
- Although the real footprint is amorphous in nature, a **regular** cell shape is needed for systematic system design and adaptation for future growth.

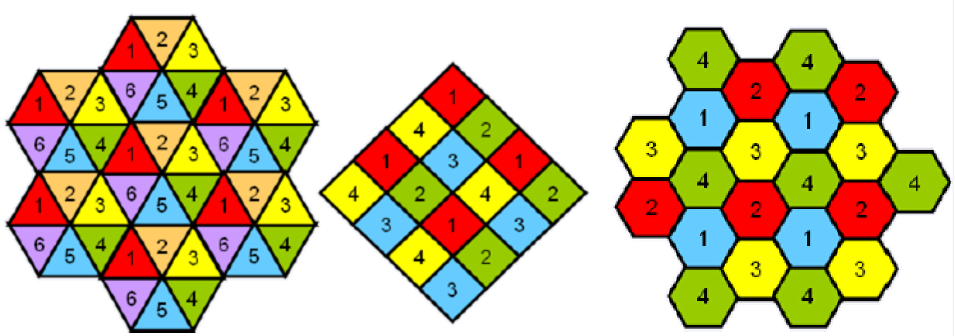
[Rappaport, 2002]

Hexagonal cell shape

- Simplistic model of the radio coverage for each BS.
- Universally adopted
- Permit easy and manageable analysis

Why hexagon?

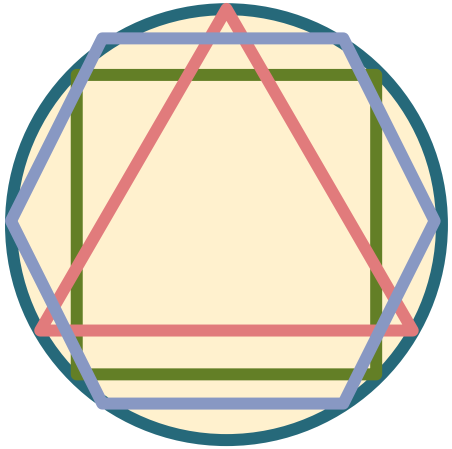
- Omnidirectional BS antenna and free space propagation → Circular radiation pattern.
  - Adjacent **circles** cannot be overlaid upon a map without leaving gaps or creating overlapping regions.
- **Tessellating Cell Shapes**: When considering geometric shapes which **cover** an entire region **without overlap** and with equal area, there are three sensible choices: a square, an equilateral triangle, and a hexagon.



Diamond and rectangles are also tessellating shapes.

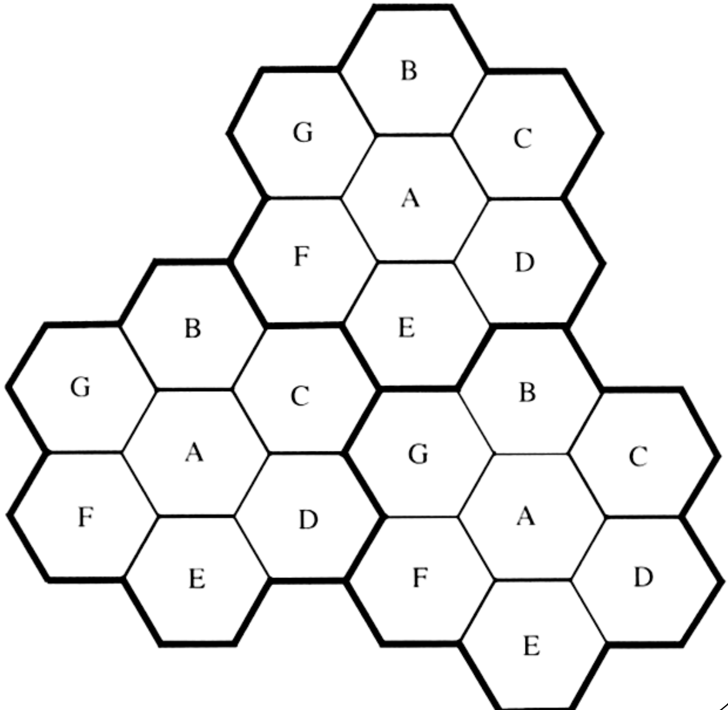
Why hexagon? (2)

- A cell must be designed to **serve** the **weakest** mobiles within the footprint, and these are typically located at the **edge** of the cell.
  - For a given distance between the center of a polygon and its farthest perimeter points, the hexagon has the **largest area** of the three.
  - By using the hexagon geometry, the **fewest** number of cells can cover a geographic region



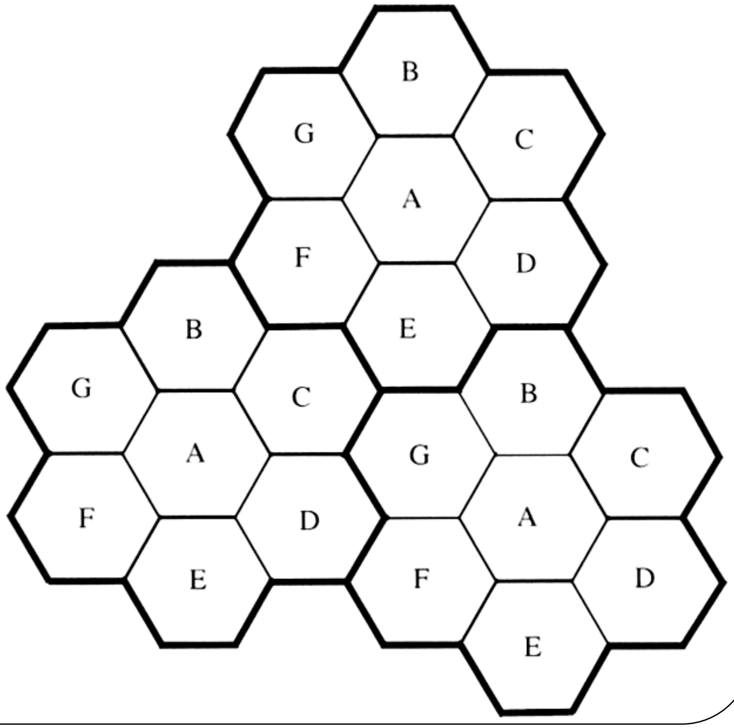
Frequency Reuse Plan

- The **frequency reuse plan** is overlaid upon a map to indicate where different frequency channels are used.
- Cells labeled with the same letter use the same group of channels.
  - Create **co-channel interference**

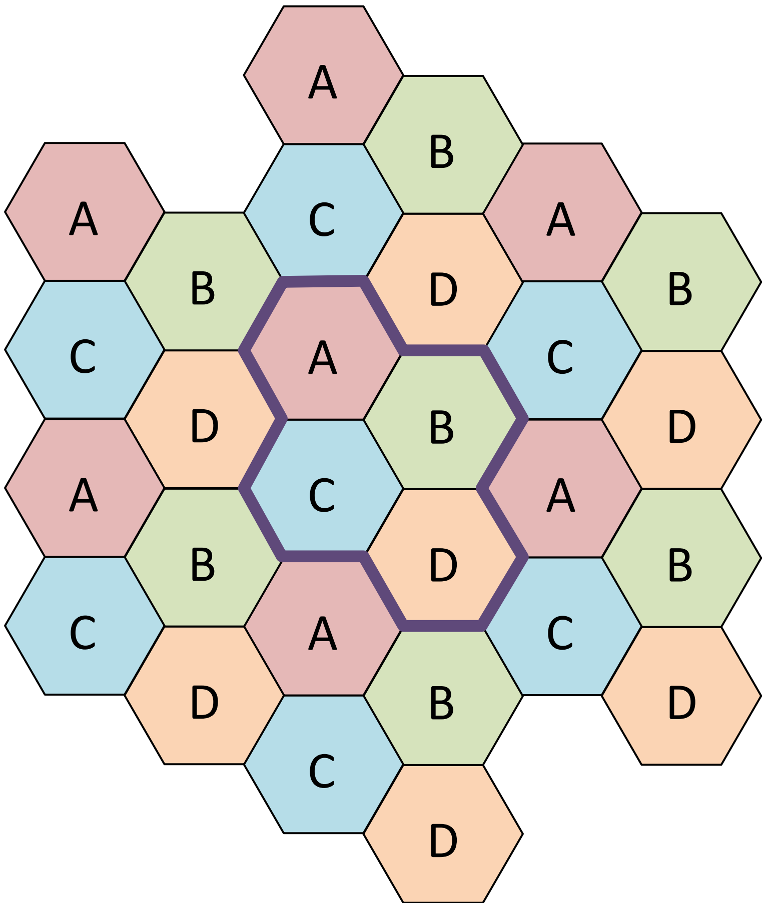


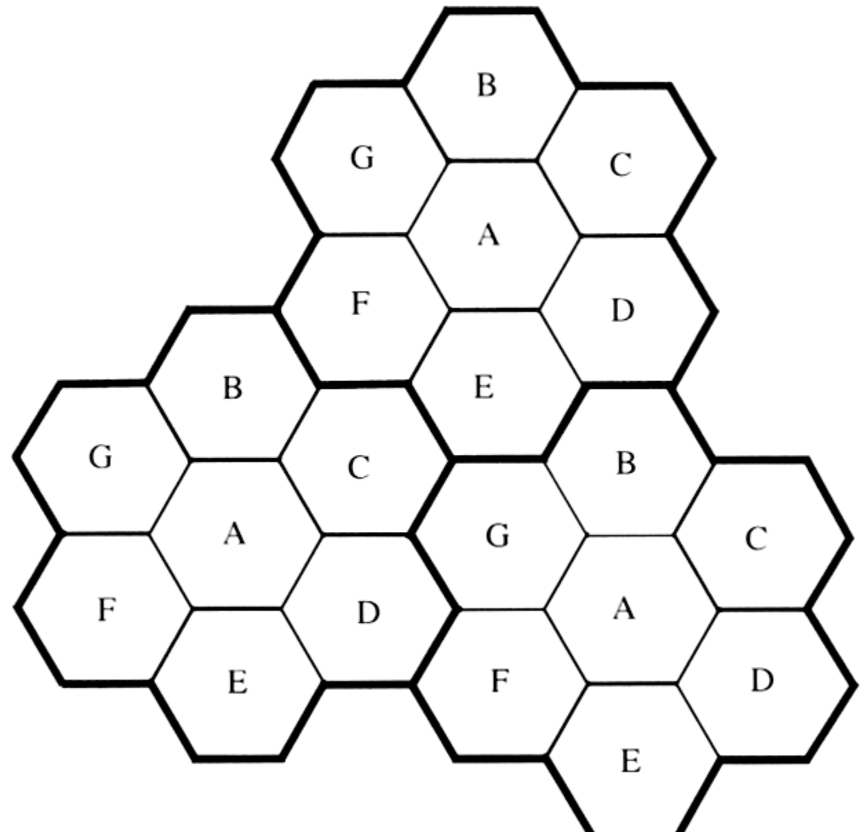
Clusters

- The total coverage area is divided into **clusters.**
- The number of cells (***N***) in a cluster is called the **cluster size**.
- Cells in a cluster collectively use the **complete set** of available frequencies.
- *No* co-channel interference *within* a cluster.
- **Replicated** over the coverage area.
- Example: The picture shows clusters of size $N = 7$, outlined in bold.



Frequency Reuse (N = 4, N = 7)





Frequency reuse factor = 1/N

(Each cell within a cluster is only assigned 1/N of the total available channels in the system.)

"Capacity"

total # available duplex radio channels for the system

cluster size

$$S = mN$$

(**Frequency reuse factor** = 1/N)

#channels allocated to each cell

Ability to handle simultaneous numbers of calls

"**Capacity**" $C = \dfrac{A_{\text{total}}}{A_{\text{cell}}} \times m = \dfrac{A_{\text{total}}}{A_{\text{cell}}} \times \dfrac{S}{N}$

total # cells in the system

This formula suggests that if the cluster size N is reduced, more capacity is achieved.*

*Tradeoff: Small value of N may lead to large interference.

Cluster: Summary

A **cluster** is a grouping of cells in which each cell uses different frequencies. A cell's frequencies may be reused by other cells in the system, but those cells will be in other clusters and therefore sufficiently far away not to cause interference.

[Klemens, 2010, p 59]

Cluster size (*N*)

- There are only certain cluster sizes and cell layouts which are possible [Mac Donald,1979].
- N can only have values which satisfy

$$N = i^2 + i \times j + j^2$$

where i and j are *non-negative* integers.

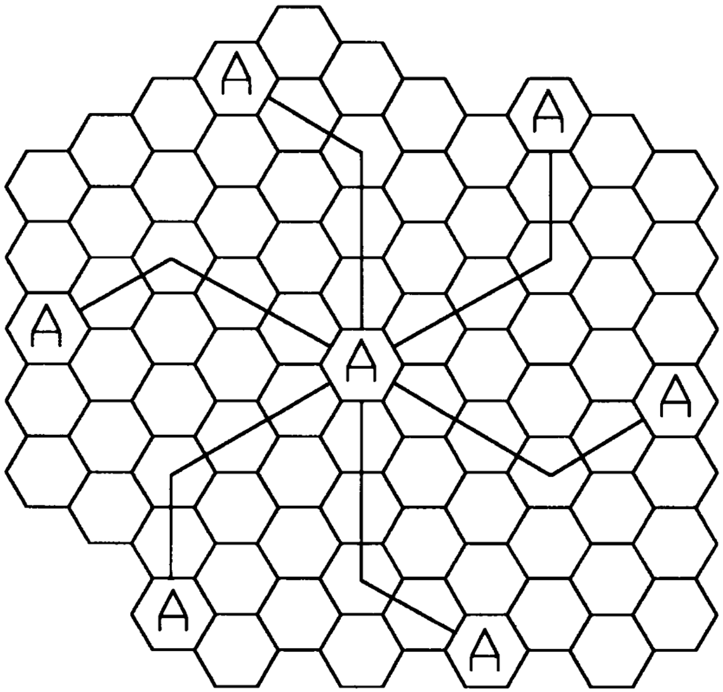
	Cluster Size (*N*)
$i = 1,\ j = 1$	3
$i = 1,\ j = 2$	7

- **Exercise**: For $N = 4$, what are the values of i and j?

Locating co-channel cells

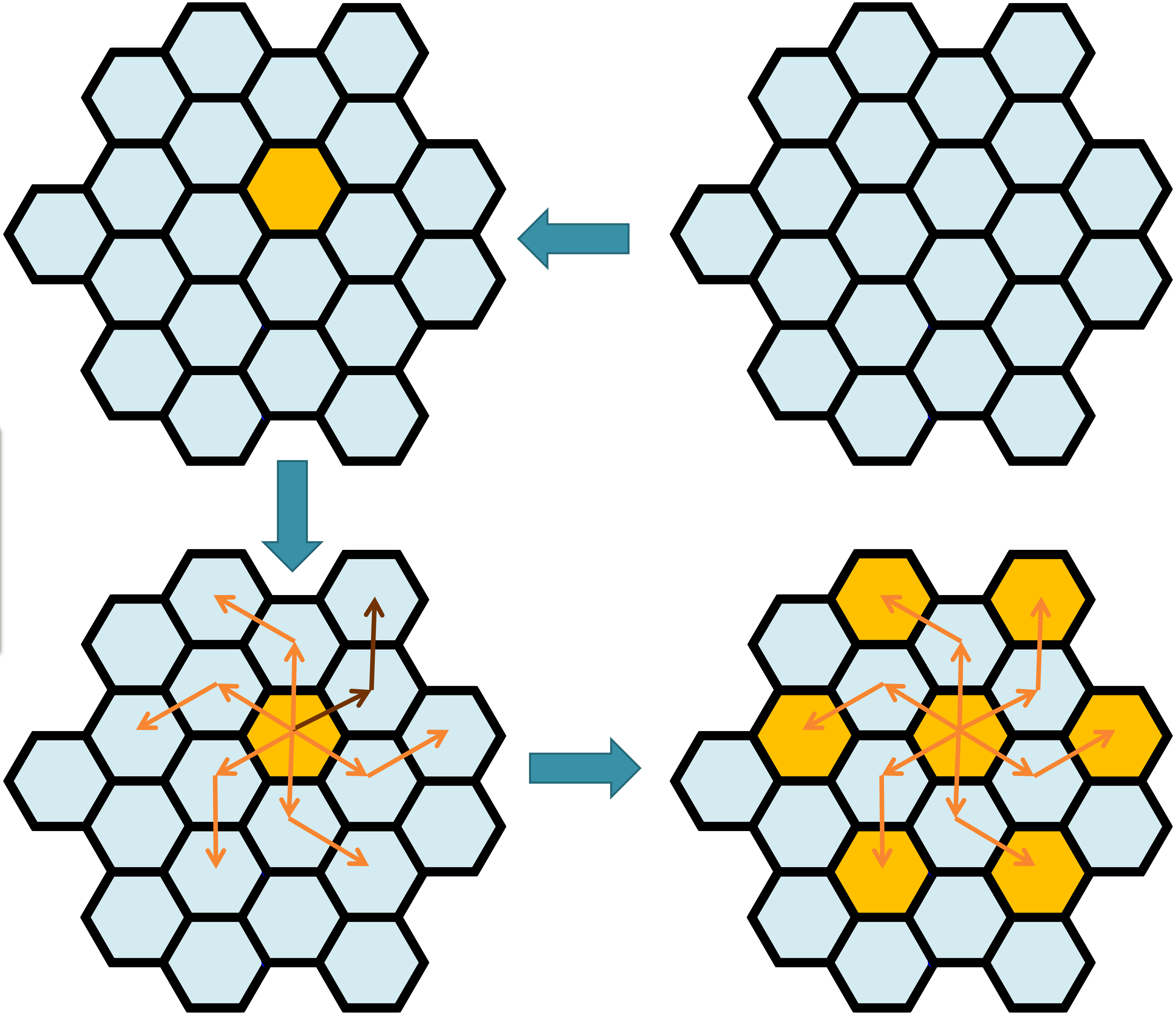
[Rappaport, 2002, p 60]
[Goldsmith, 2005, p 476]

- To locate the **nearest co-channel neighbors** of a particular cell,
  - move i cells along any chain of hexagons and then
  - turn 60 degrees **counter-clockwise** and move j cells.
- Try $N = 19$
  - i = 3
  - j = 2



[Rappaport, 2002, Fig. 3.2]
[Goldsmith, 2005, Fig 15.6]

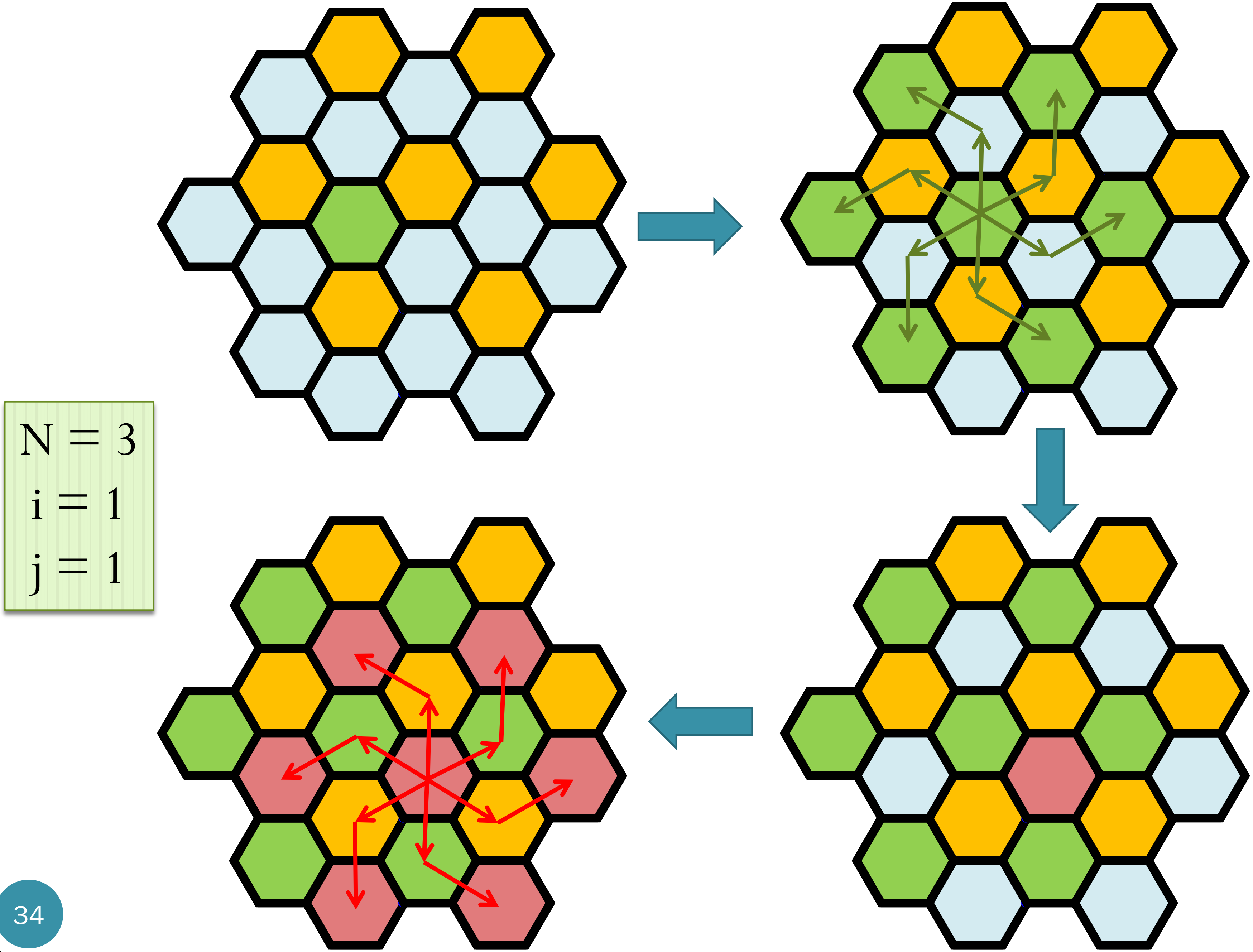
$$3^2 + 2 \cdot 3 + 2^2 = 9 + 6 + 4 = 19$$



$N = 3$

$i = 1$

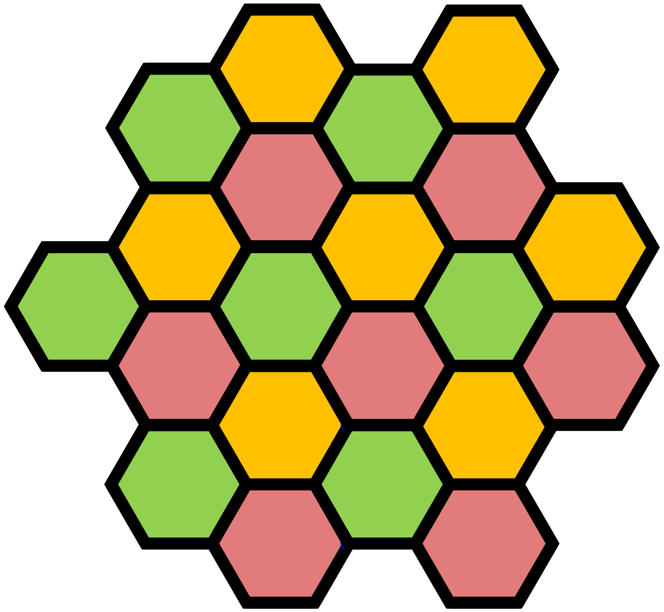
$j = 1$



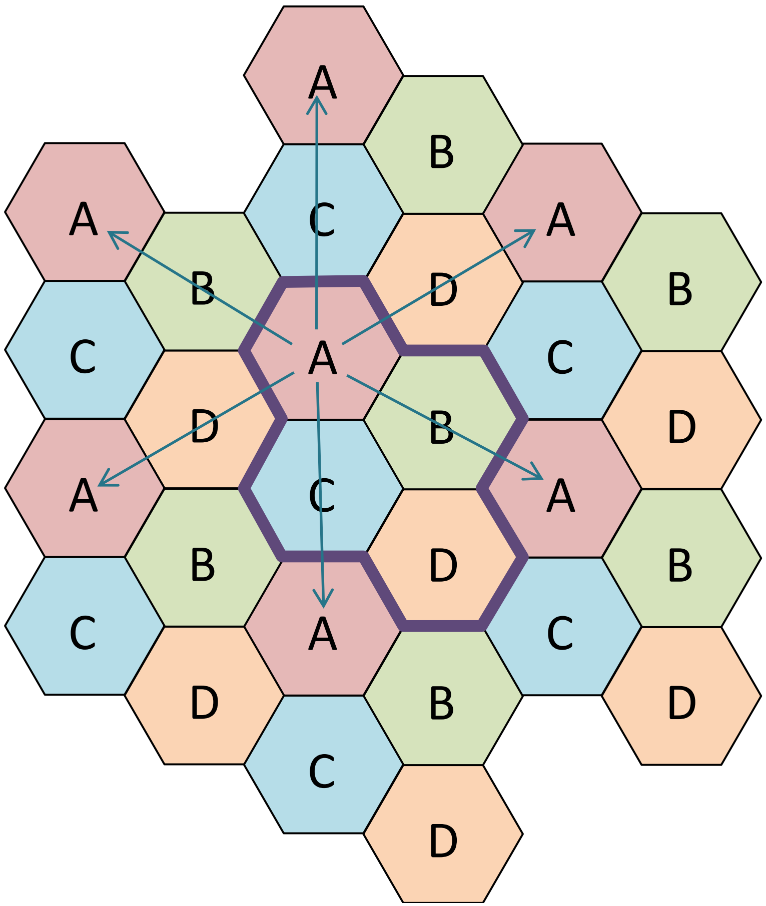
N = 3
i = 1
j = 1

Locating co-channel cells (N = 3)

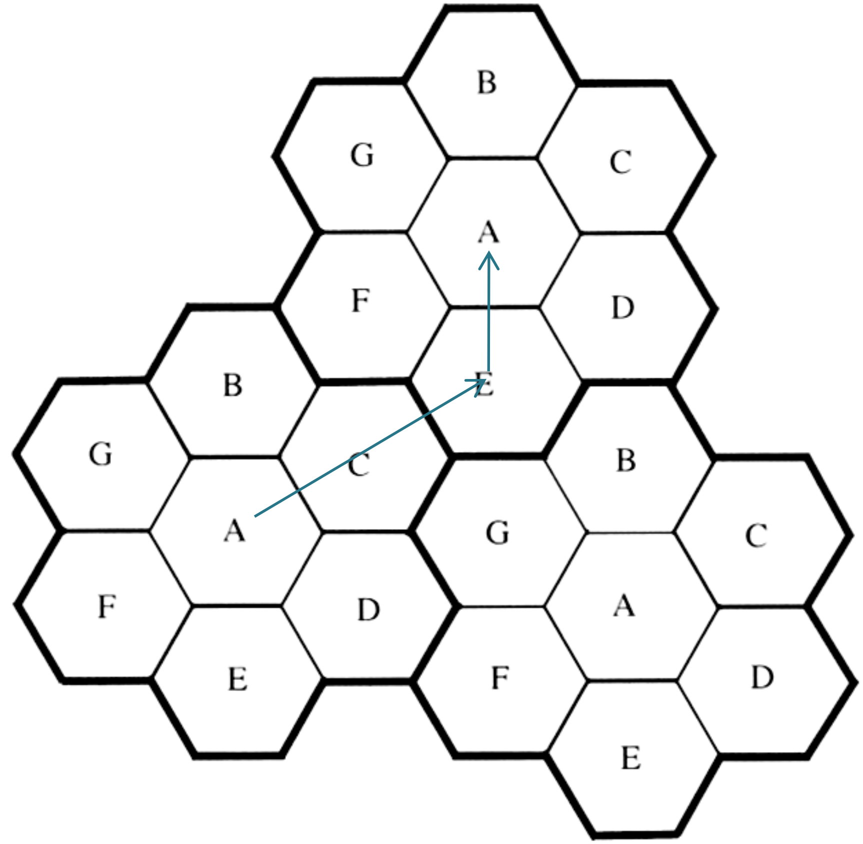
- To locate the nearest co-channel neighbors of a particular cell,
  - move *i* cells along any chain of hexagons and then
  - turn 60 degrees counter-clockwise and move *j* cells.



Locating co-channel cells (N = 4, N = 7)

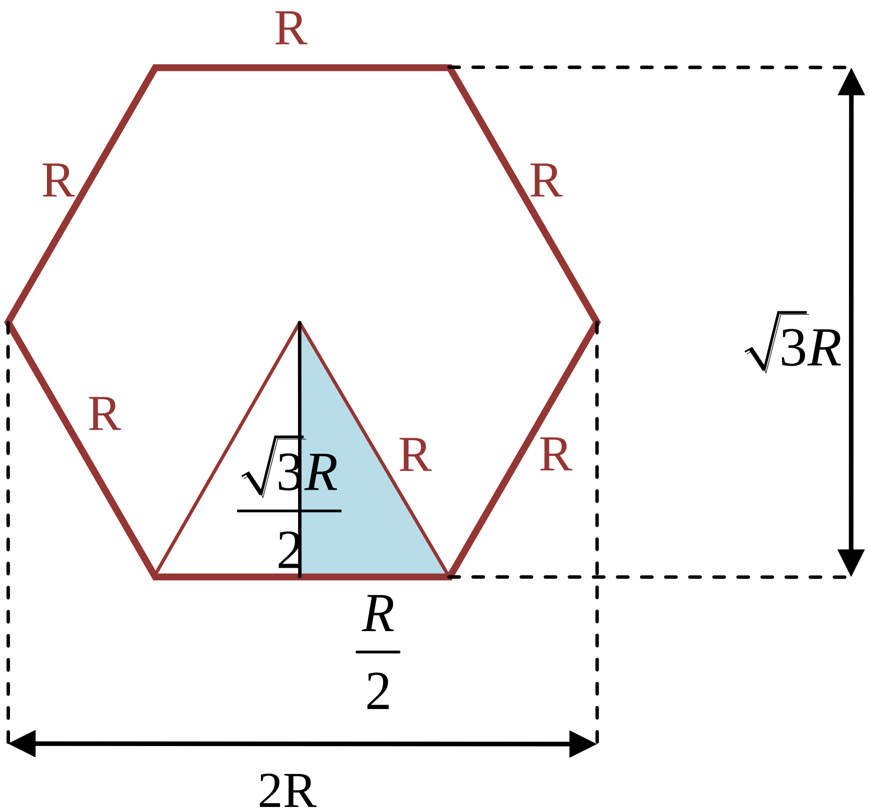


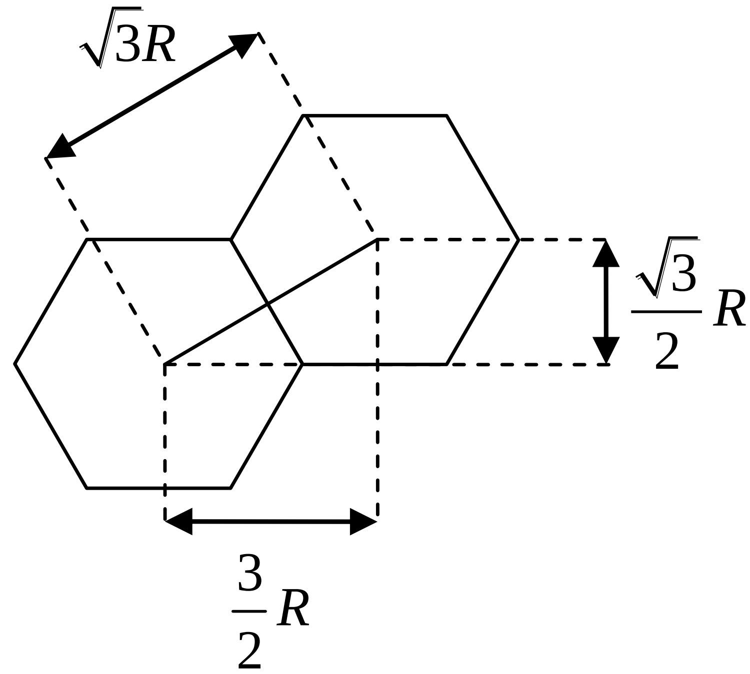
(i = 2, j =0)



(i = 2, j =1)

Hexagon





$$\text{Area} = 6 \times 2 \times \left(\frac{1}{2} \times \frac{\sqrt{3}}{2} R \times \frac{1}{2} R \right) = \frac{3\sqrt{3}}{2} R^2 \approx 2.598 R^2$$

ECS455 Chapter 2

Cellular Systems

2.2 Co-Channel Interference

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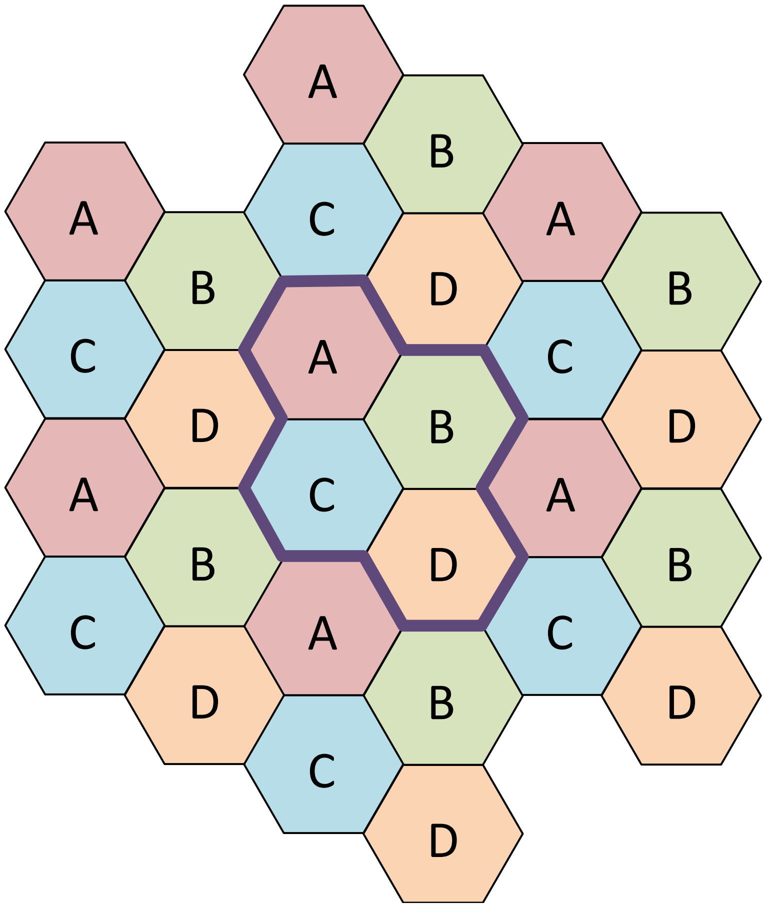
(Intercell)

Co-Channel Interference

- Frequency reuse → co-channel interference
- Consider only nearby interferers.
  - Power decreases rapidly as the distance increases.
- In a **fully equipped hexagonal-shaped** cellular system, there are always K = 6 cochannel interfering cells in the **first tier**.



Three Measures of Signal Quality

- Old (**noise-limited** systems) $\text{SNR} = \dfrac{P_r}{P_{\text{noise}}}$

- Consider both noise & interference $\text{SINR} = \dfrac{P_r}{P_{\text{interference}} + P_{\text{noise}}}$

- The best cellular system design places users that share the same channel at a separation distance (as close as possible) where the intercell interference is just below the maximum tolerable level for the required data rate and BER. Why?

- Good cellular system designs are interference-limited, meaning that the interference power is much larger than the noise power.

$$\text{SIR} = \frac{P_r}{P_{\text{interference}}}$$

"Reliable"/"tolerable"?

(Why not as far as possible?)

Co-channel cells, must be spaced **far enough** apart so that interference between users in co-channel cells does not degrade **signal quality** below tolerable levels.

Subjective tests found that people regard an FM signal using a 30 kHz channel bandwidth to be clear if the signal power is at least **sixty times** higher than the noise/interference power.

[Klemens, 2010, p 54]

$$10\log_{10} 60 = 17.78 \approx 18 \text{ dB}$$

We will soon revisit and use these numbers for some more specific calculations

Review: Simplified Path Loss Model

$$\frac{P_r}{P_t} = K\left(\frac{d_0}{d}\right)^{\gamma} \quad \Rightarrow \quad P_r = \frac{P_t K d_0^{\gamma}}{d^{\gamma}} \propto \frac{1}{d^{\gamma}}$$

Captures the essence of signal propagation without resorting to complicated path loss models, which are only approximations to the real channel anyway!

- *K* is a unitless constant which depends on the antenna characteristics and the average channel attenuation
- d_0 is a reference distance for the antenna far-field
  - Typically 1-10 m indoors and 10-100 m outdoors.
- γ is the **path loss exponent**.
  - 2 in free-space model
  - 4 in two-ray model [Goldsmith, 2005, eq. 2.17]

Environment	γ range
Urban macrocells	3.7-6.5
Urban microcells	2.7-3.5
Office Building (same floor)	1.6-3.5
Office Building (multiple floors)	2-6
Store	1.8-2.2
Factory	1.6-3.3
Home	3

[Goldsmith, 2005, Table 2.2]

SIR (S/I): Definition/Calculation

Not the same as the K shown on the previous slide

- K = # co-channel interfering cells
- The **signal-to-interference ratio** (S/I or SIR) for a mobile receiver which monitors a ***forward channel*** can be expressed as

$$\mathrm{SIR} = \frac{P_r}{P_{\text{interference}}} = \frac{P_r}{\sum_{i=1}^{K} P_{\text{of the } i^{th} \text{ interferer}}}$$

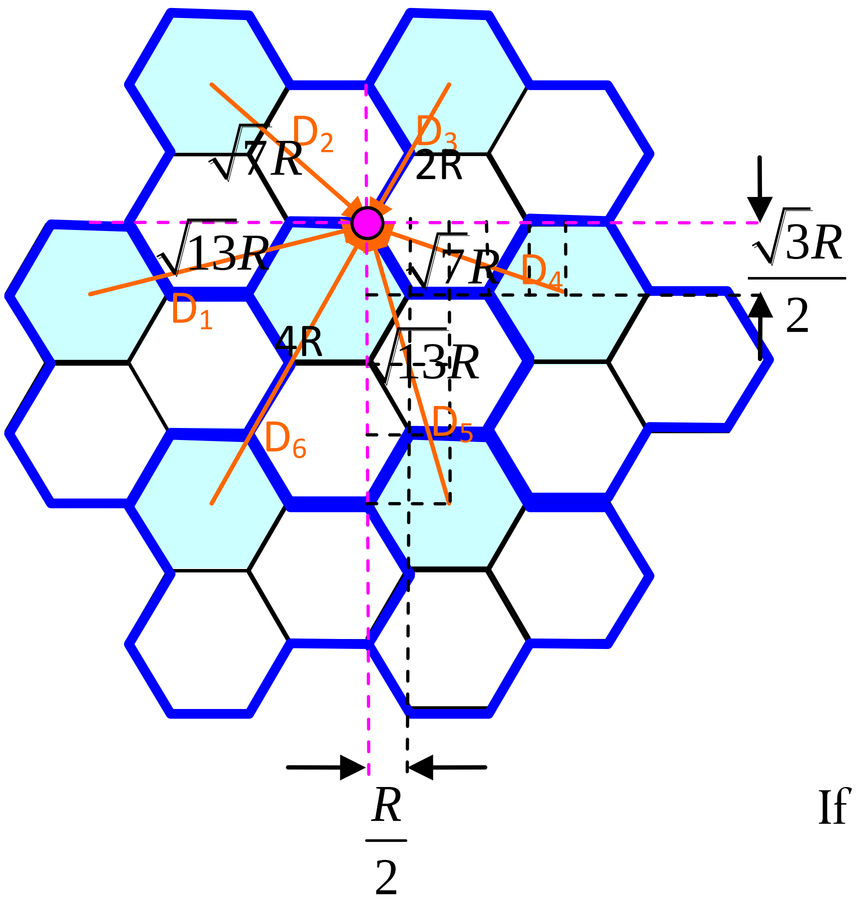
- S = the desired signal **power** from the desired base station
- I_i = the interference **power** caused by the *i*th interfering co-channel cell base station.
- Often called the **carrier-to-interference ratio**: CIR.

SIR Threshold

[Schwartz, 2005, p 64]

- The SIR should be greater than a specified threshold for proper signal operation.
- In the 1G **AMPS** system, designed for **voice** calls, the threshold for acceptable voice quality is SIR equal to **18 dB**.
- For the 2G digital AMPS system (D-AMPS or IS-54/136), a threshold of 14 dB is deemed suitable.
- For the **GSM** system, a range of **7–12 dB**, depending on the study done, is suggested as the appropriate threshold.
- The probability of error in a digital system depends on the choice of this threshold as well.

SIR: N = 3



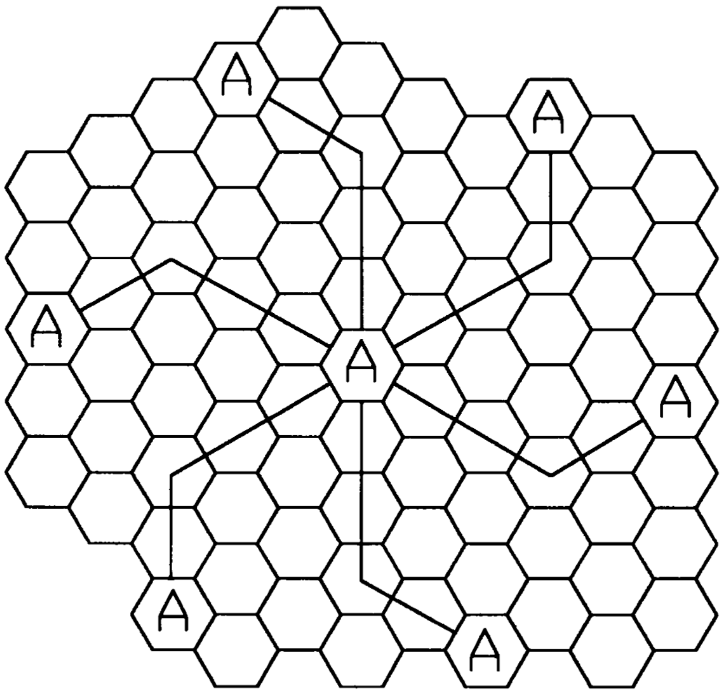
- Consider only first tier.
- Worse-case distance

$$\mathrm{SIR} \approx \frac{k/R^\gamma}{\sum_i k/D_i^\gamma} = \frac{1}{\sum_i 1/\left(\frac{D_i}{R}\right)^\gamma} = \frac{1}{\sum_i \left(\frac{D_i}{R}\right)^{-\gamma}}$$

$$= \frac{1}{2\left(\sqrt{7}\right)^{-\gamma} + 2\left(\sqrt{13}\right)^{-\gamma} + 2^{-\gamma} + 4^{-\gamma}}$$

If N = 19, will the SIR be better or worse?

Approximation

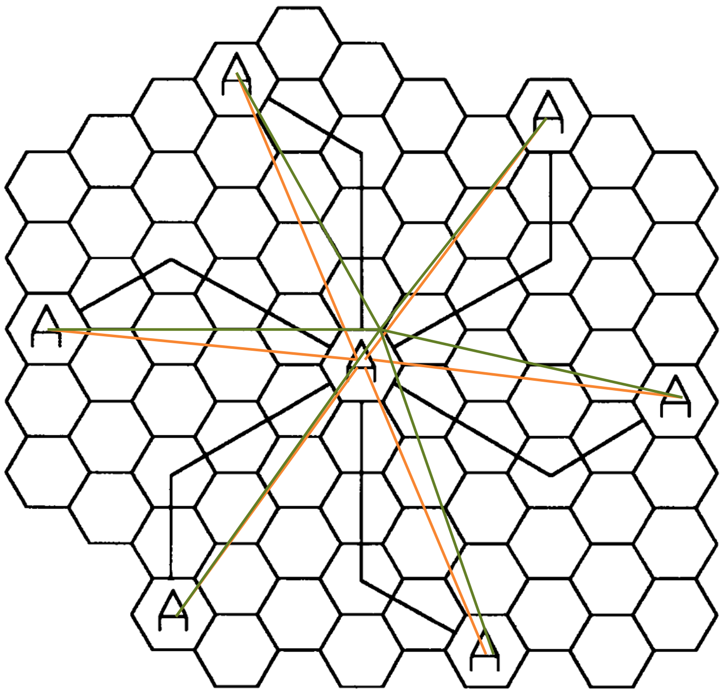


- Consider only first tier.
- Worse-case distance

$$\mathrm{SIR} \approx \frac{1}{\sum_i \left(\frac{D_i}{R}\right)^{-\gamma}}$$

- Use the same D for D_i

Approximation



- Consider only first tier.
- Worse-case distance

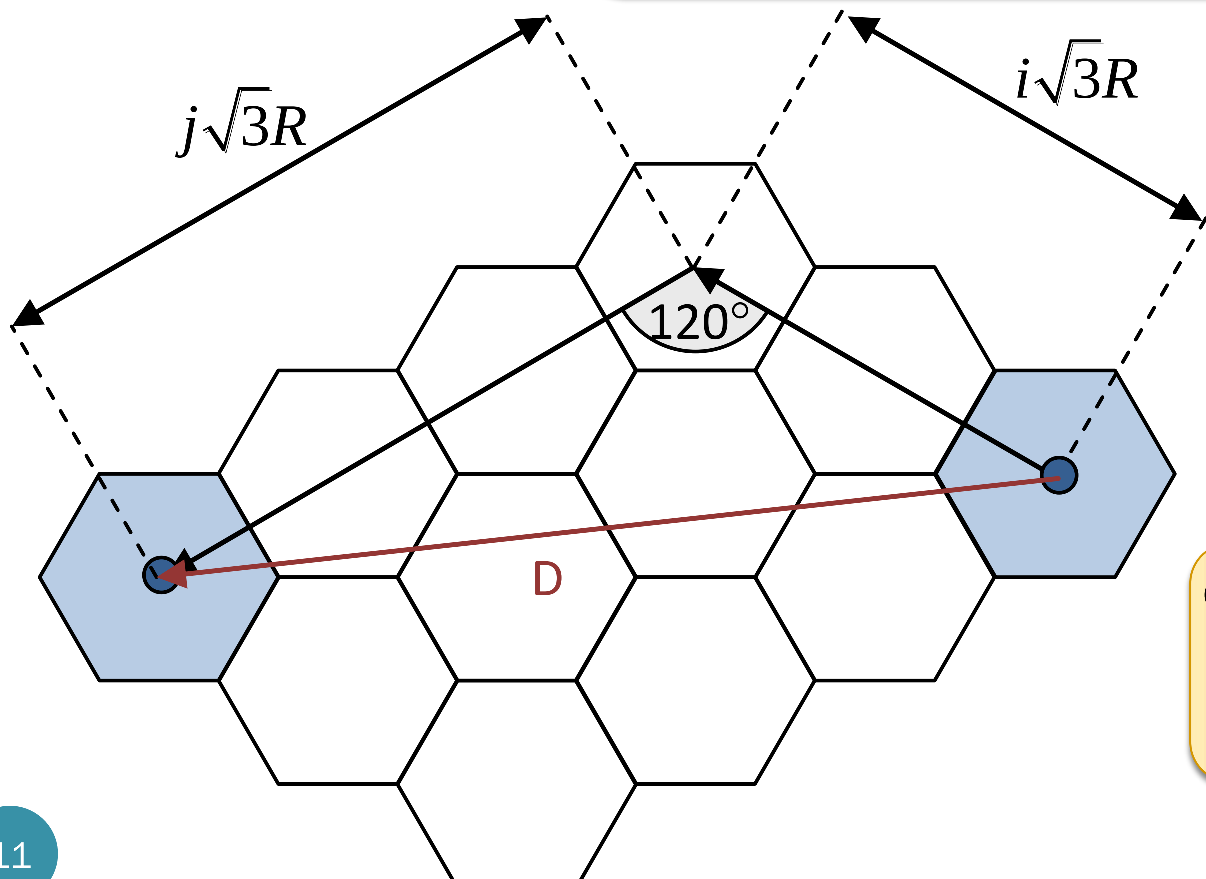
$$\mathrm{SIR} \approx \frac{1}{\sum_i \left(\frac{D_i}{R}\right)^{-\gamma}}$$

- Use the same D for D_i

$$\mathrm{SIR} \approx \frac{1}{\sum_i \left(\frac{D}{R}\right)^{-\gamma}} \approx \frac{1}{K\left(\frac{D}{R}\right)^{-\gamma}} = \frac{1}{K}\left(\frac{D}{R}\right)^{\gamma}$$

Center-to-center distance (D)

$$D = \sqrt{\left(i\sqrt{3}R\right)^2 + \left(j\sqrt{3}R\right)^2 - 2\left(i\sqrt{3}R\right)\left(j\sqrt{3}R\right)\cos\left(120^\circ\right)}$$
$$= R\sqrt{3\left(i^2 + j^2 + ij\right)} = R\sqrt{3N}$$



This distance, D, is called **reuse distance**.

Co-channel reuse ratio

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

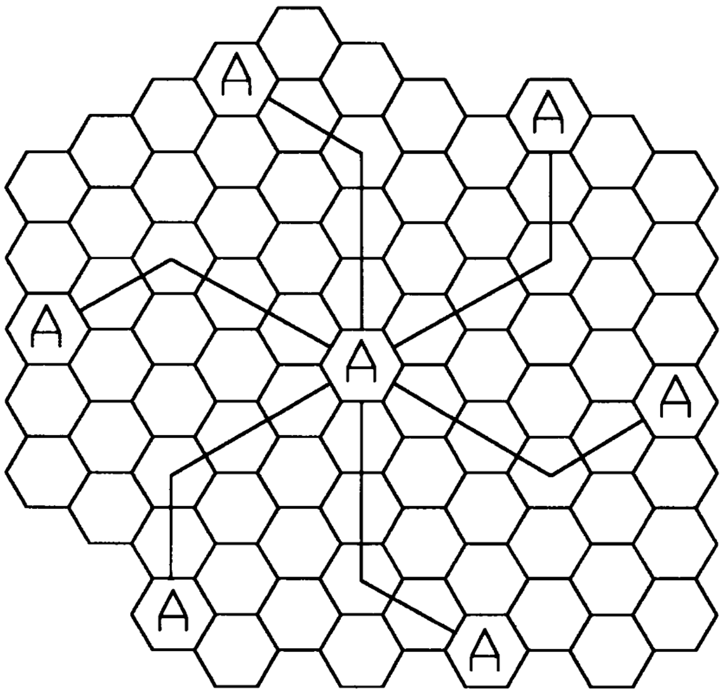
Q and N

Co-channel reuse ratio

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

	Cluster Size (*N*)	Co-channel Reuse Ratio (*Q*)
$i = 1,\ j = 1$	3	3
$i = 1,\ j = 2$	7	4.58
$i = 0,\ j = 3$	9	5.20
$i = 2,\ j = 2$	12	6

Approximation: Crude formula



$$\mathrm{SIR} = \frac{P_r}{P_{\text{interference}}} = \frac{P_r}{\sum_{i=1}^{K} P_{\text{of the } i^{th} \text{ interferer}}}$$

$$\approx \frac{1}{\sum_i \left(\frac{D_i}{R}\right)^{-\gamma}} \approx \frac{1}{K\left(\frac{D}{R}\right)^{-\gamma}} = \frac{1}{K}\left(\frac{D}{R}\right)^{\gamma}$$

$$= \frac{1}{K}\left(\sqrt{3N}\right)^{\gamma}$$

As the cell cluster size (N) increases, the spacing (D) between interfering cells increases, reducing the interference.

Summary: Quantity vs Quality

S = total # available duplex radio channels for the system

Path loss exponent

"Capacity" $C = \frac{A_{total}}{A_{cell}} \times \frac{S}{N}$

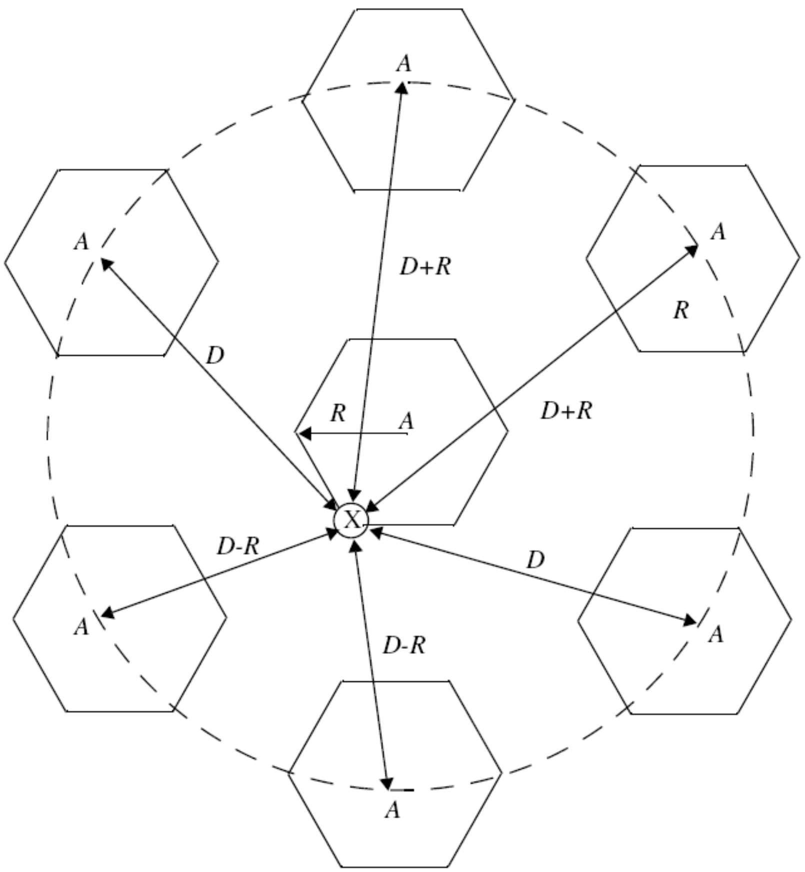
Tradeoff

$\text{SIR} \approx \frac{1}{K}\left(\sqrt{3N}\right)^{\gamma}$

m = # channels allocated to each cell.

Frequency reuse with **cluster size *N***

SIR: N = 7



More accurate calculation…

$$\frac{S}{I} \approx \frac{R^{-4}}{2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}}$$

$$\frac{S}{I} \approx \frac{1}{2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}}$$