ECS 455 Chapter 2
Cellular Systems

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Office Hours:
BKD 3601-7
Wednesday 15:30-16:30
Friday   9:30-10:30

Pre-Cellular System

Area over which **reliable** radio comunication can occur btw a BS and MSs.
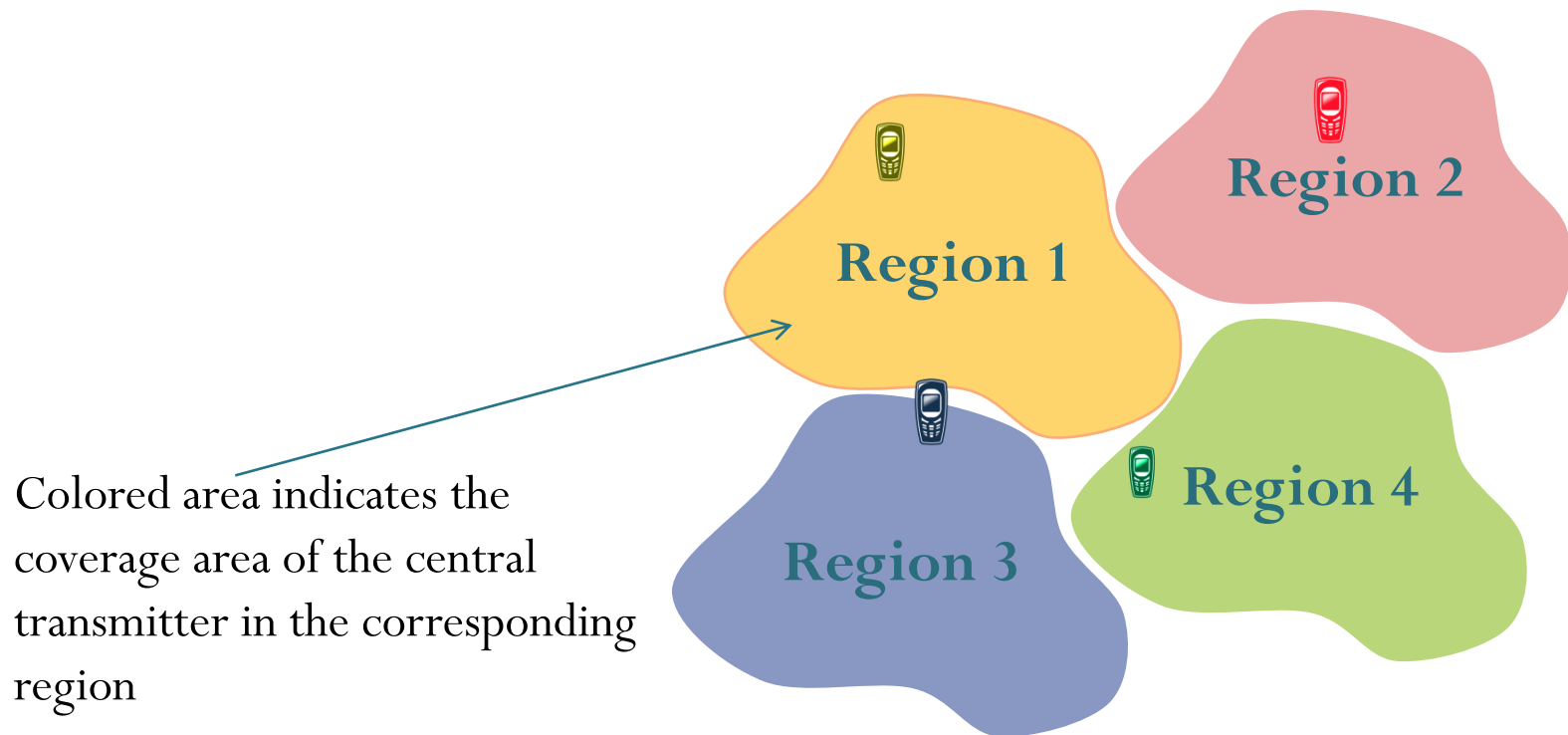
- Achieve a **large coverage area** by using a single, **high powered** transmitter.
  - Put BS on top of mountains or tall towers
- Next BS was so **far away** that interference was not an issue.
- Severely limit the number of users that could communicate simultaneously.
- Noise-limited system with 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.
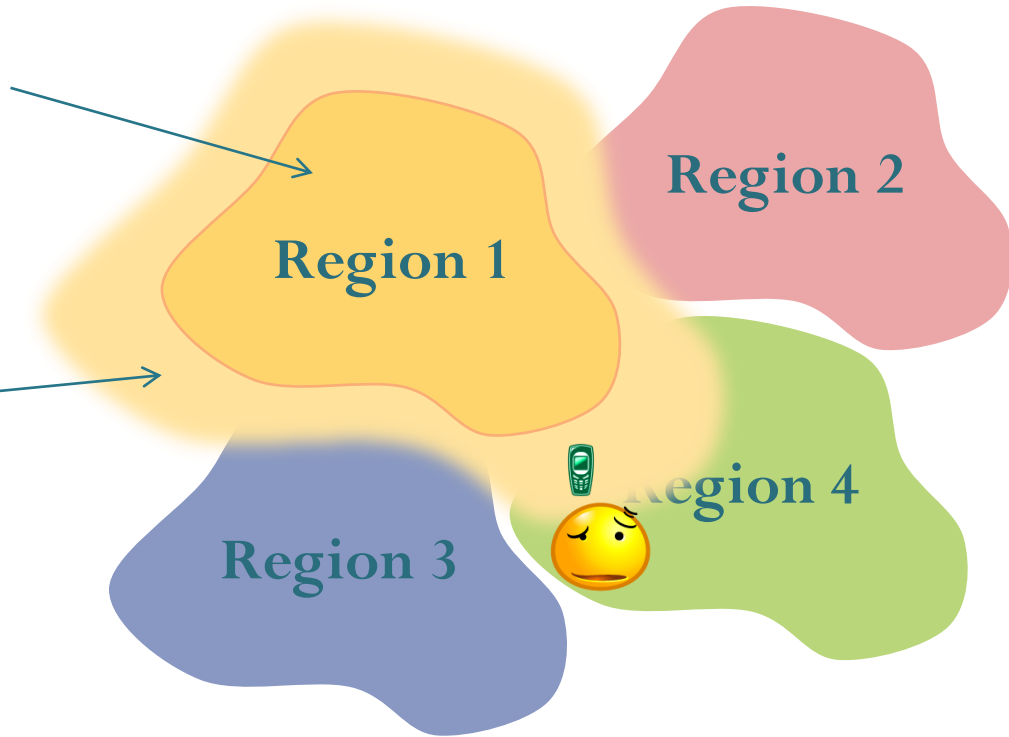
Pre-Cellular System (2)

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

Region 1

Region 2

Region 3

Region 4

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

Region 1

Region 2

Region 3

Region 4

Pre-Cellular System (2)

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

Region 2
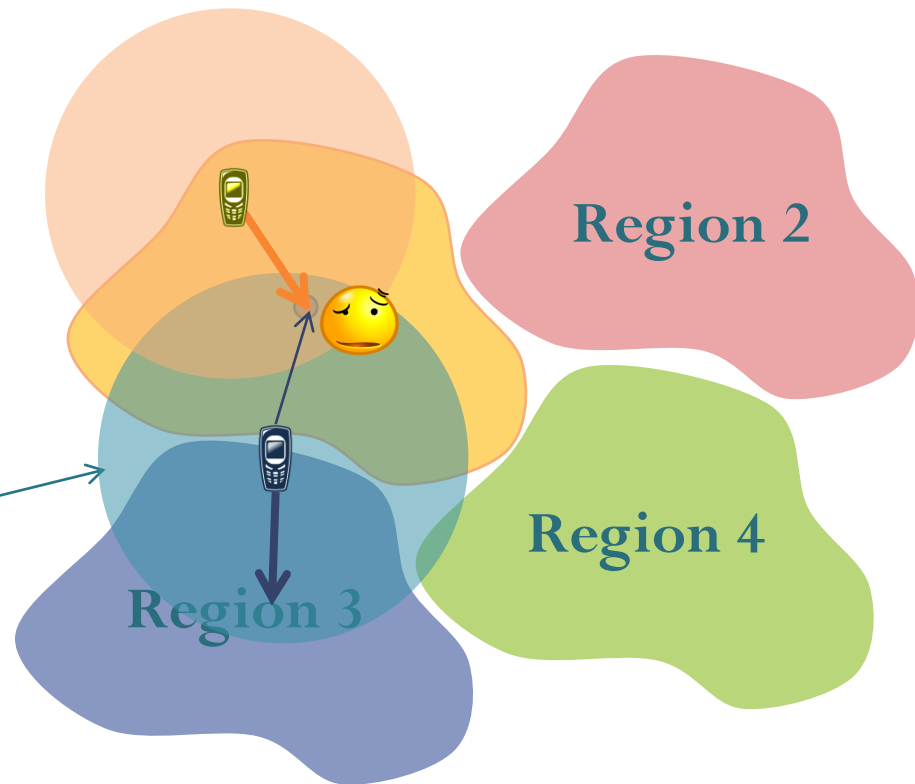
Region 4

Region 3

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!

Region 1

Region 2

Region 3

Region 4

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2.1 Frequency Reuse

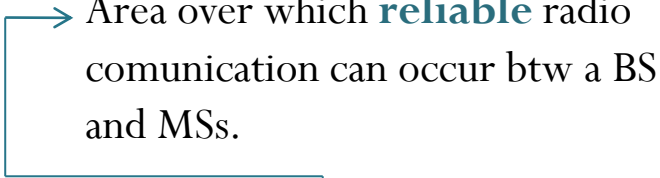Dr.Prapun Suksompong
prapun.com/ecs455

Office Hours:
BKD 3601-7
Wednesday 15:30-16:30
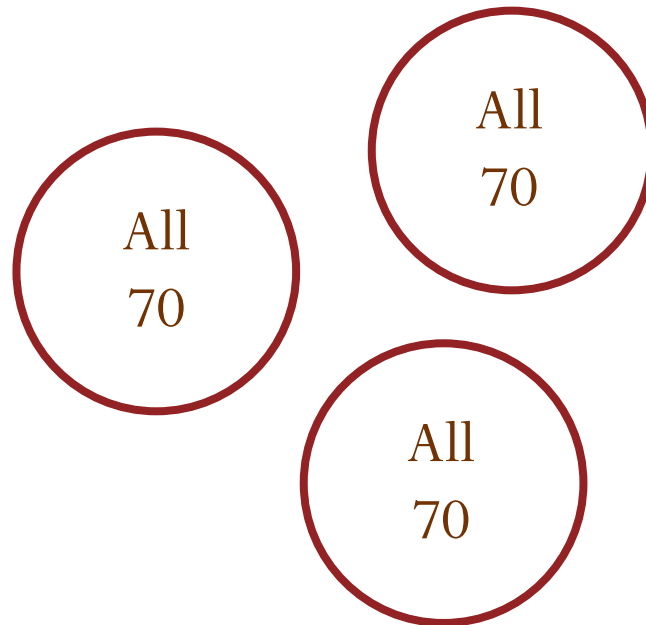**Friday   9:30-10:30**

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).
    - 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

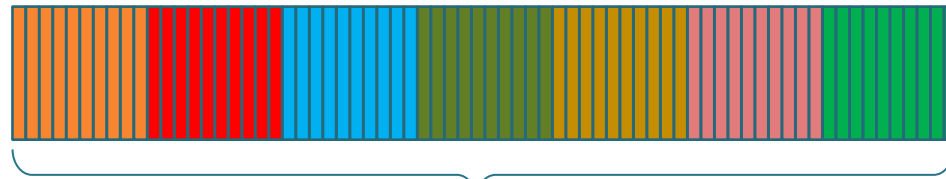→ Area over which **reliable** radio comunication can occur btw a BS and MSs.

Idea (1)
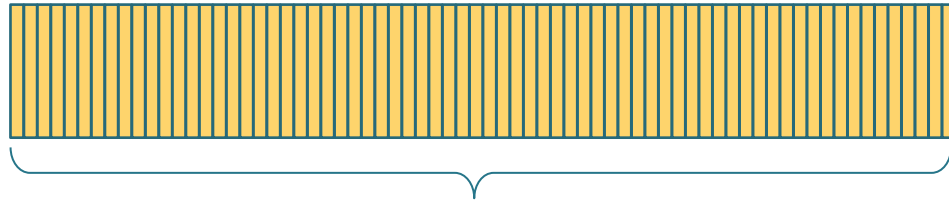
- Suppose the whole system has **S = 70 frequency channels**
- Pre-cellular:

All
70

All
70

All
70

"Capacity" of the system
= # users the system can
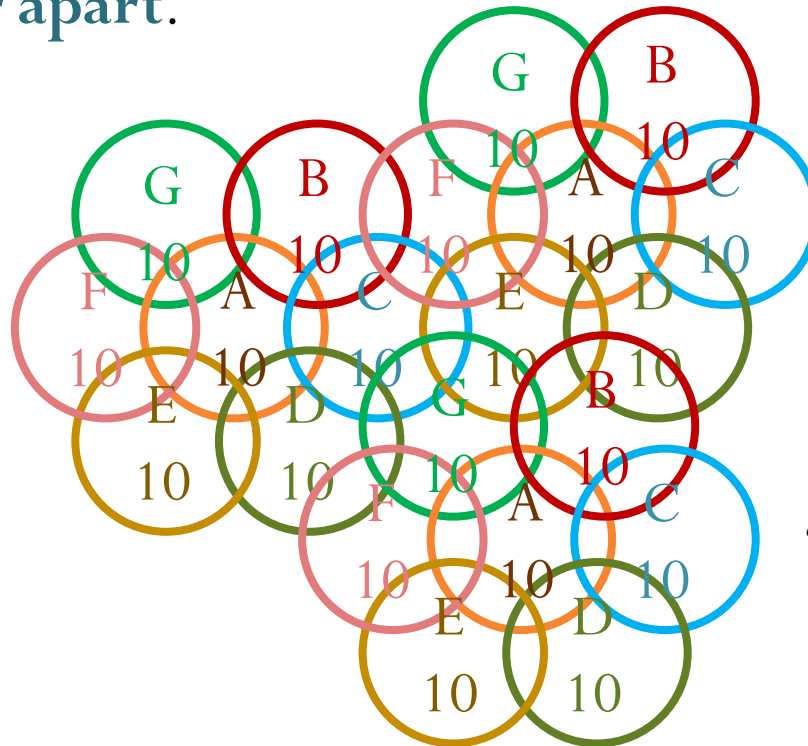support simultaneously
= 70×3 = 210

Idea (2)

S = 70 frequency channels

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

Less interference
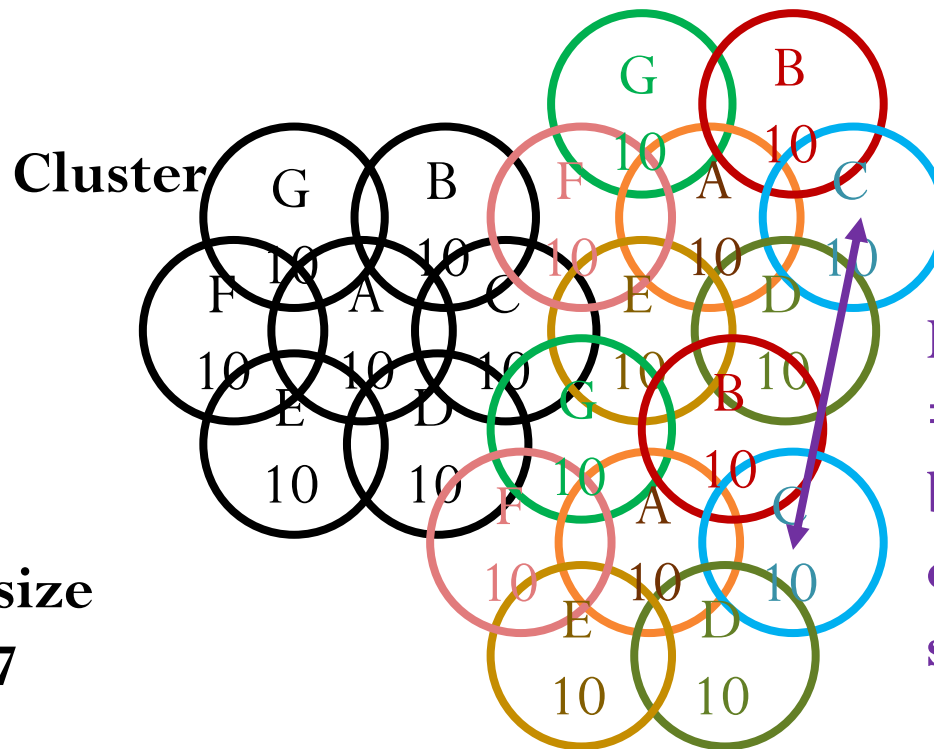(Recall that P_r is inversely proportional to d^γ.)

Note:
Cells can overlap.

"Capacity" of the system
= # users the system can
support simultaneously
= 70×3 = 210
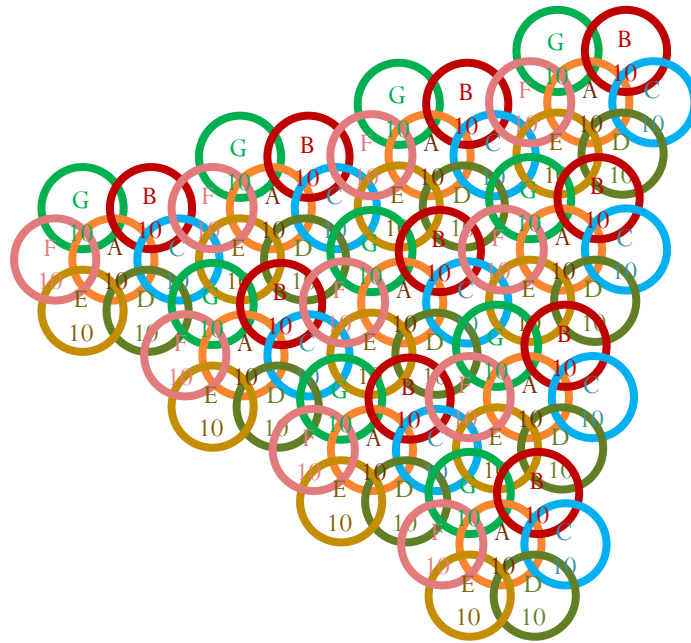
Idea (3)

- Some Terminology:

Cluster

Cluster size
N = 7

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

Idea (4)

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

"Capacity" of the system
= # users the system can
   support simultaneously
>> 210

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**.

Can we keep reducing the cell size?

- While smaller cells generally increase capacity, they also have their disadvantages.

- Smaller cell size increases the rate at which **handoffs** occur, which increases the dropping probability if the percentage of failed handoffs stays the same.

- Smaller cells increase the **load** on the backbone network.

- More cells per unit area requires more base stations, which can increase system **cost**.

- **Propagation** characteristics typically change as cell size shrinks, so the system does not scale perfectly.

[Goldsmith, 2005, p. 471]

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.
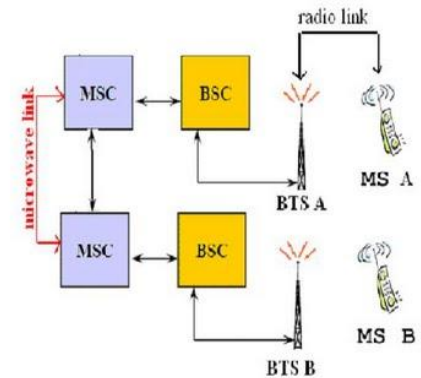
Basic cellular system (2)

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).
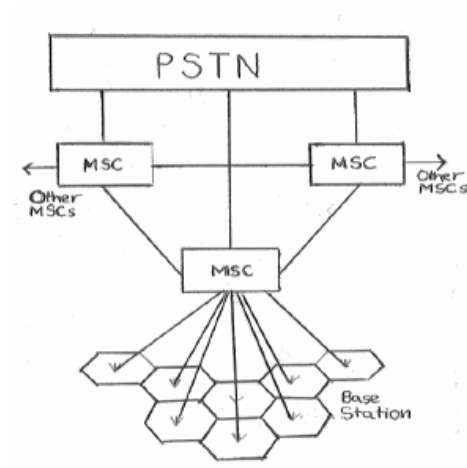
How a Cell Phone Call Works

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.

①

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

②

Wireless Access Point

③

Microwave (Wireless Backhaul)

Wireless Access Point

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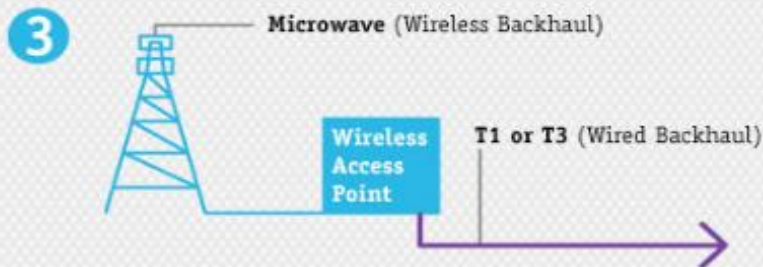
The call (along with many others) gets routed to a backhaul — usually down to an underground wired T1 or T3 line, but sometimes back up the mast to a powerful line-of-sight wireless microwave antenna (typically only used either when there isn't a ground connection, or when the ground connection is poor).

④

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.

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[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**.

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.
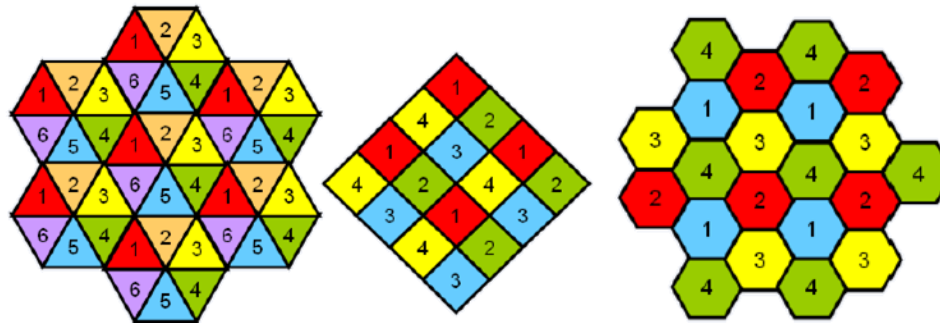
Diamond and rectangles are also tessellating shapes.

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
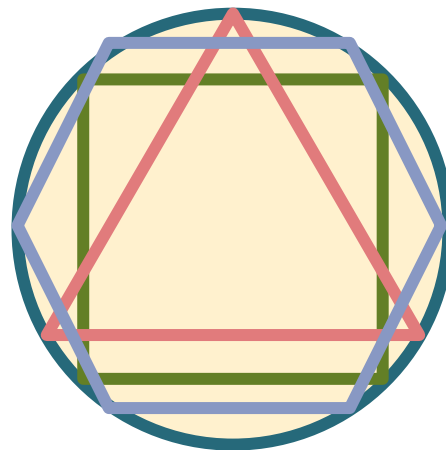
Frequency Reuse Plan

- 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**
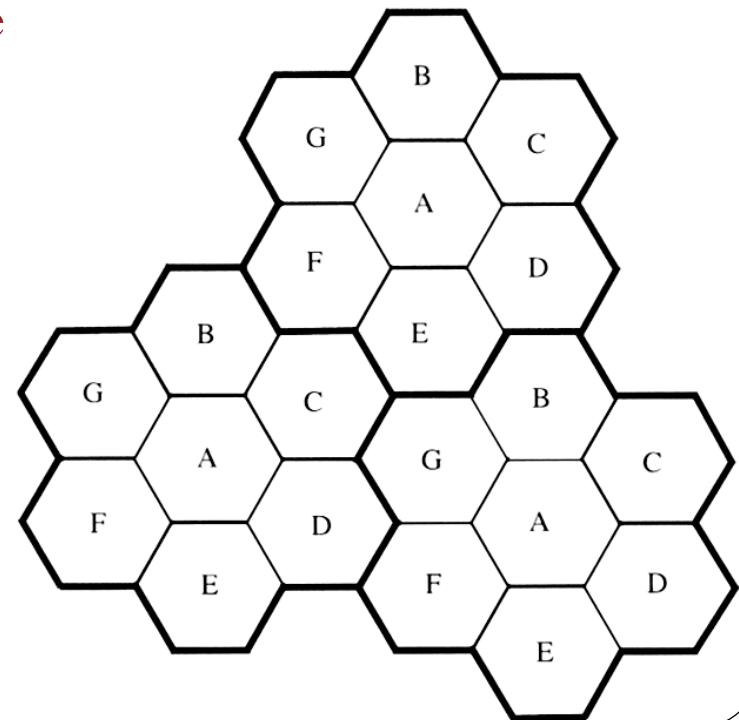
Clusters

- 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.
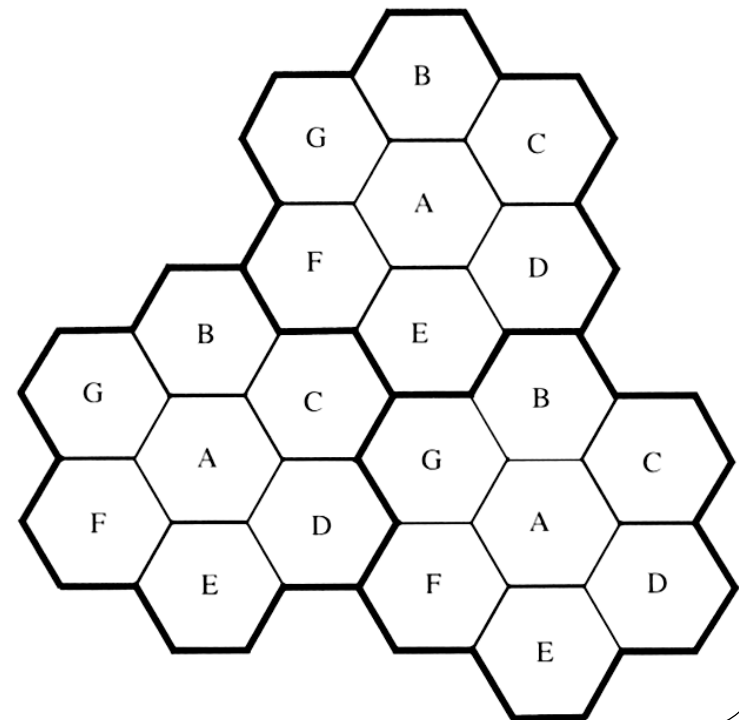
Frequency Reuse (N = 4, N = 7)
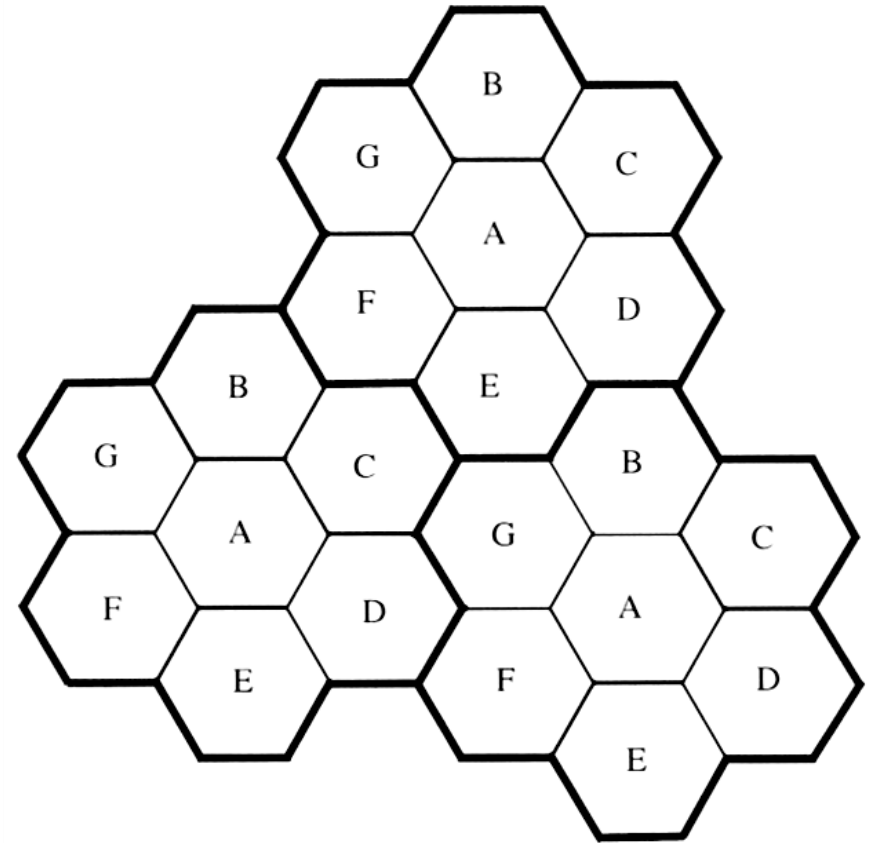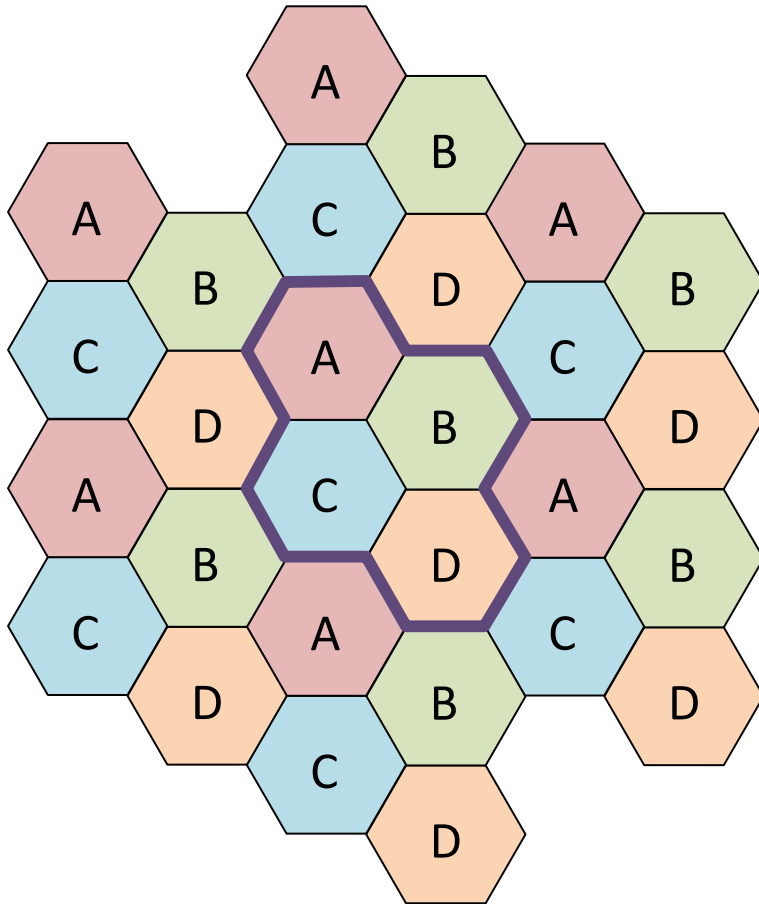
Frequency reuse factor = 1/N

(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** $= 1/N$)

Ability to handle simultaneous numbers of calls

#channels allocated to each cell

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

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

total # cells in the system
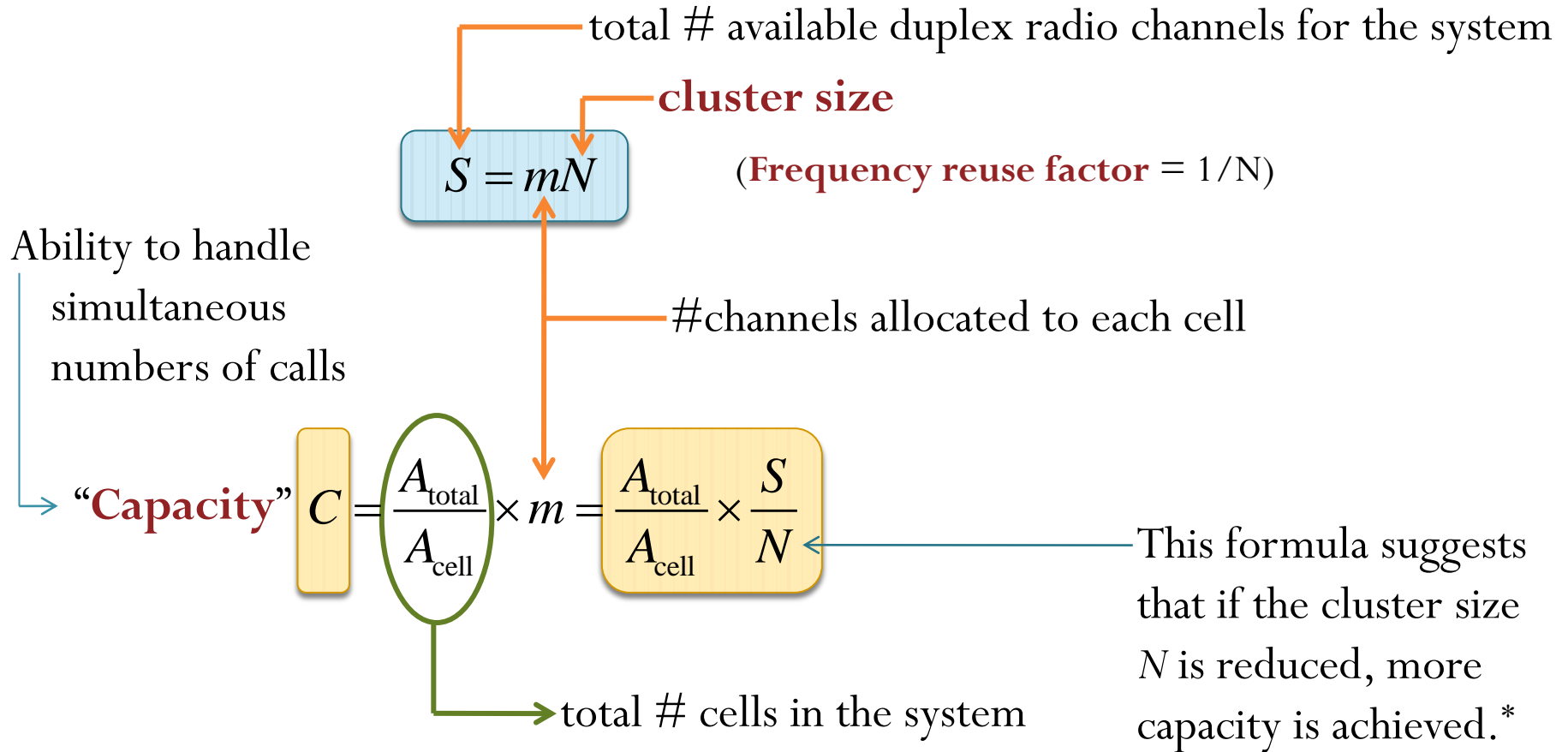
*Tradeoff: Small value of N may lead to large interference.

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

- 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.
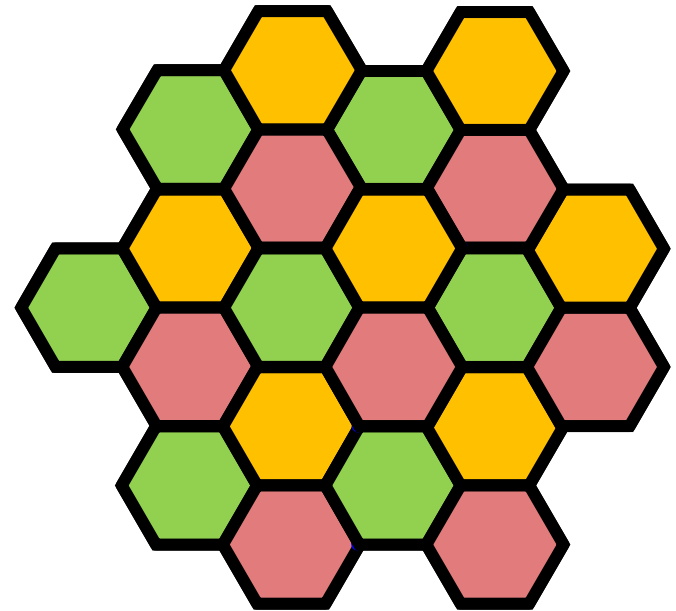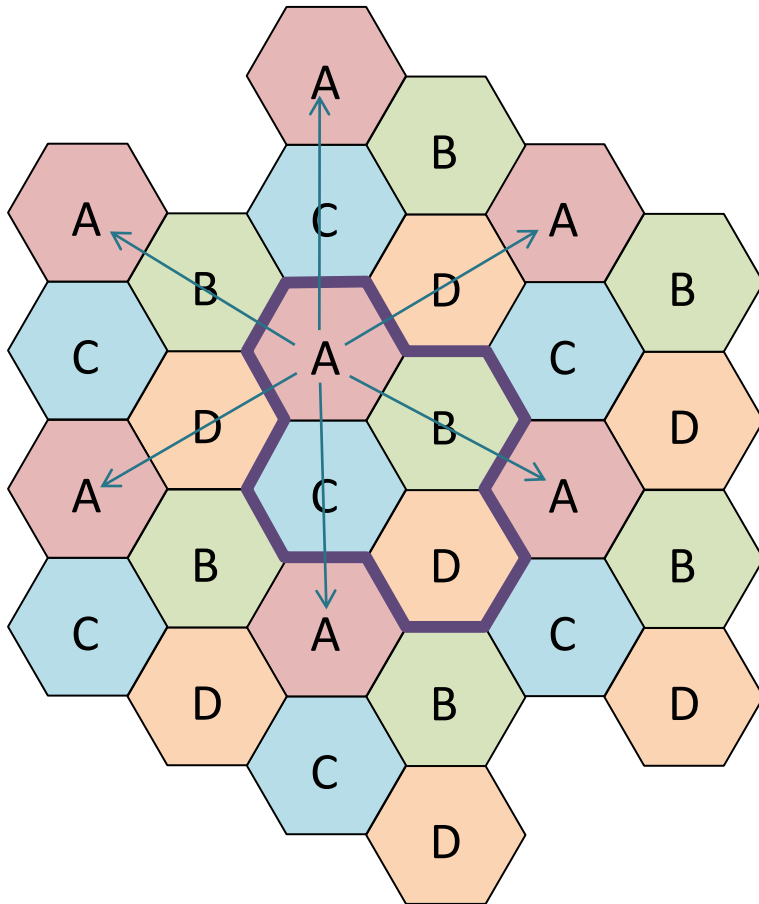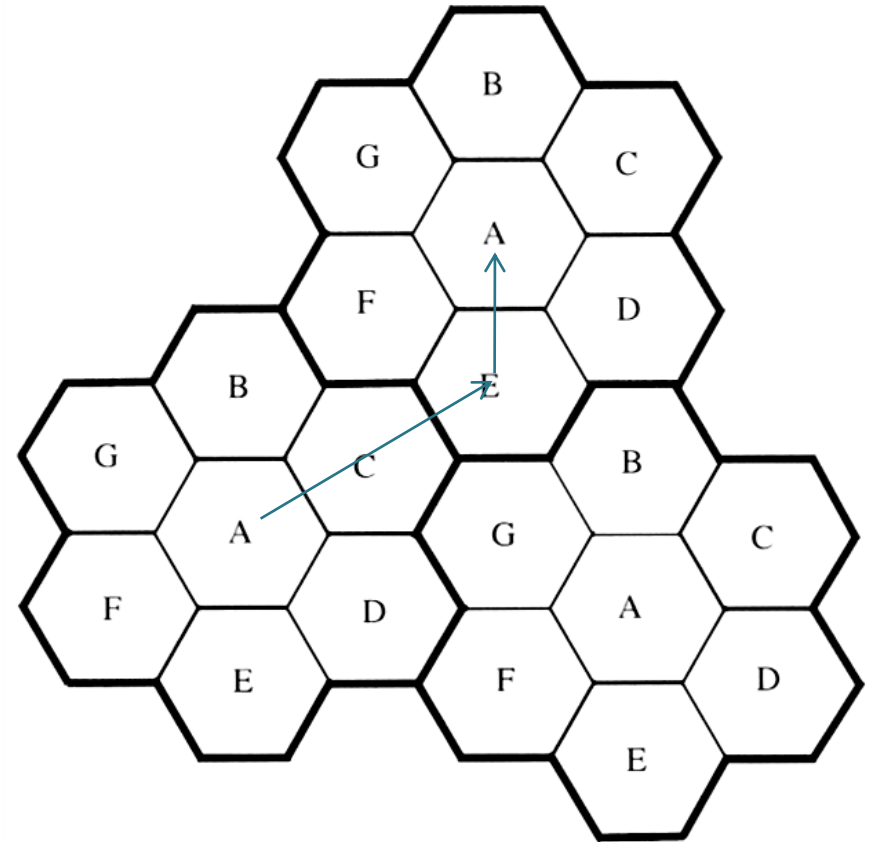- Try *N* = 19
  - i = 3
  - j = 2
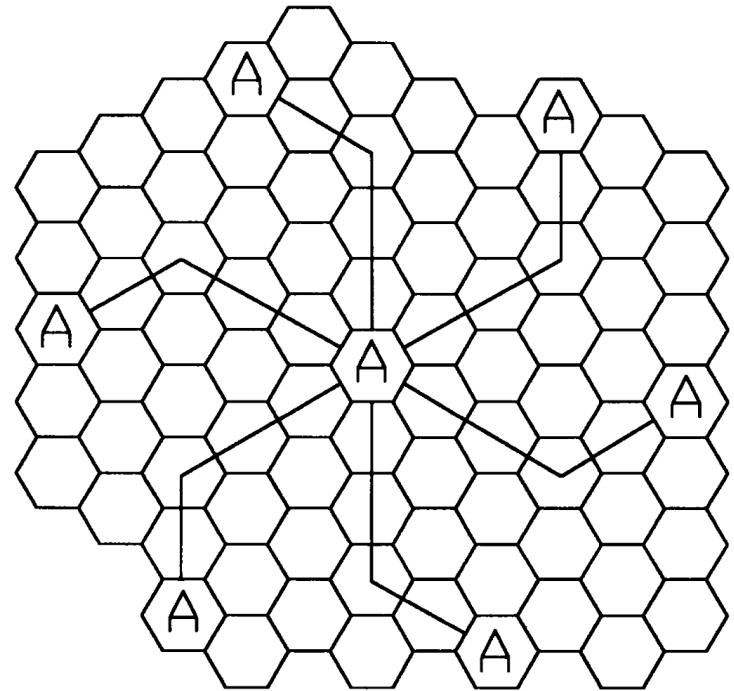
$$3^2 + 2 \cdot 3 + 2^2 = 9 + 6 + 4 = 19$$

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

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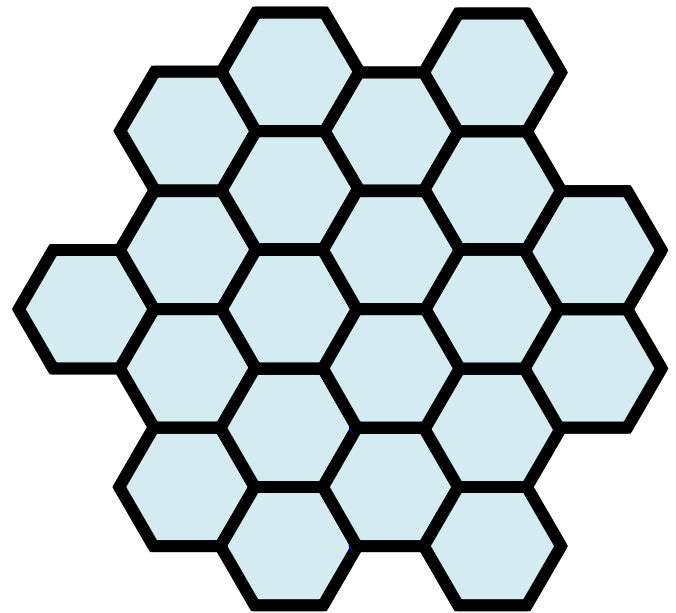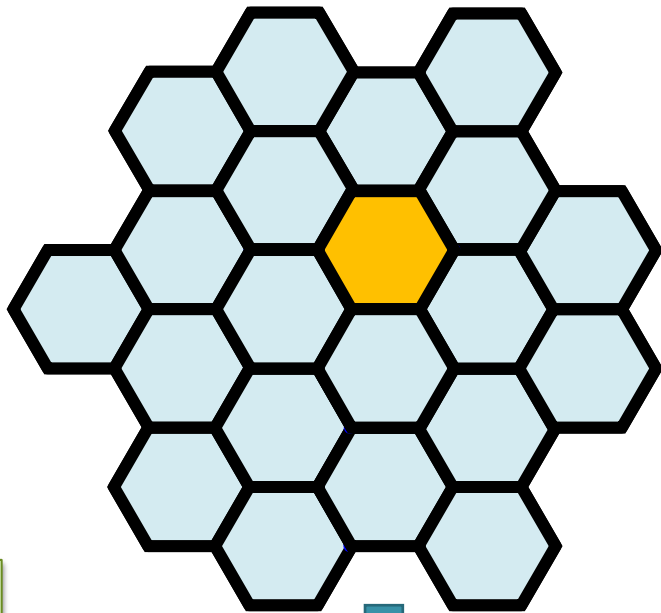
N = 3
i = 1
j = 1
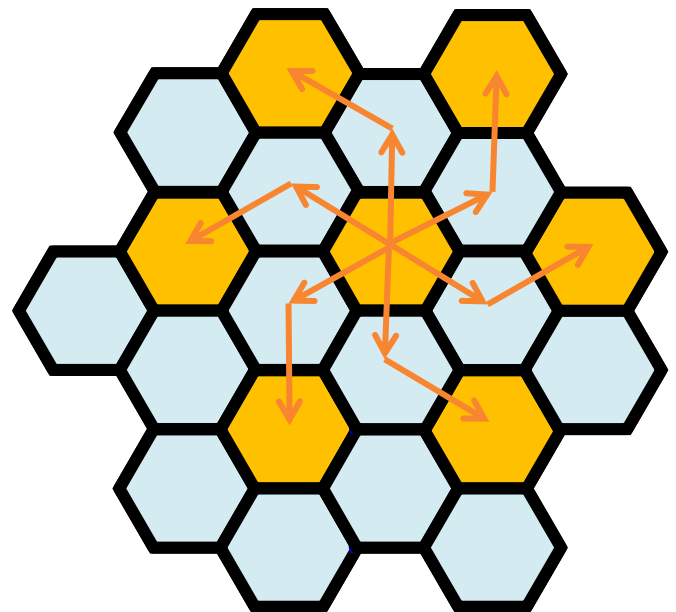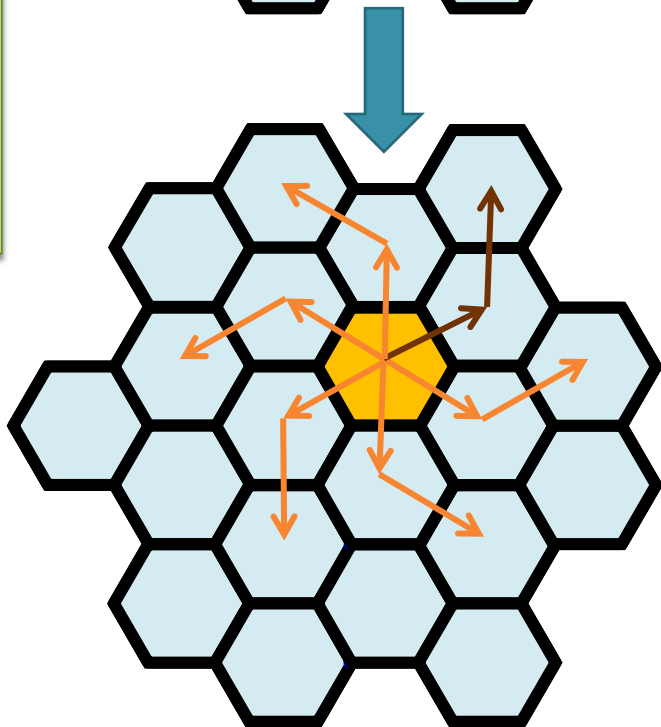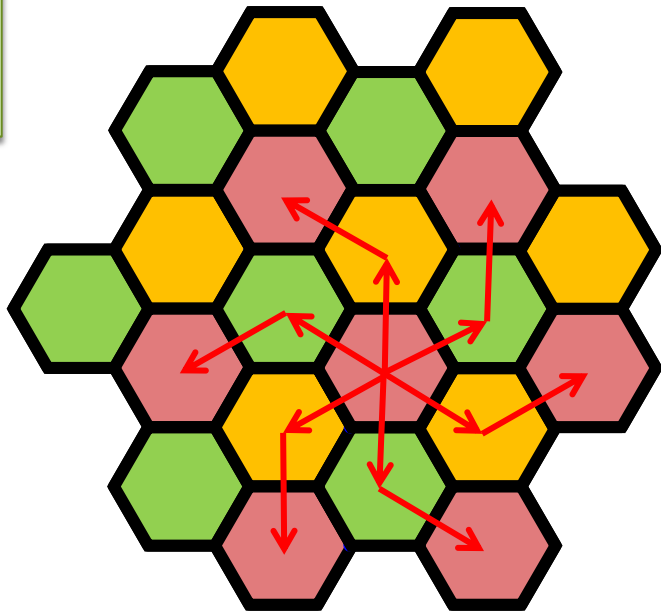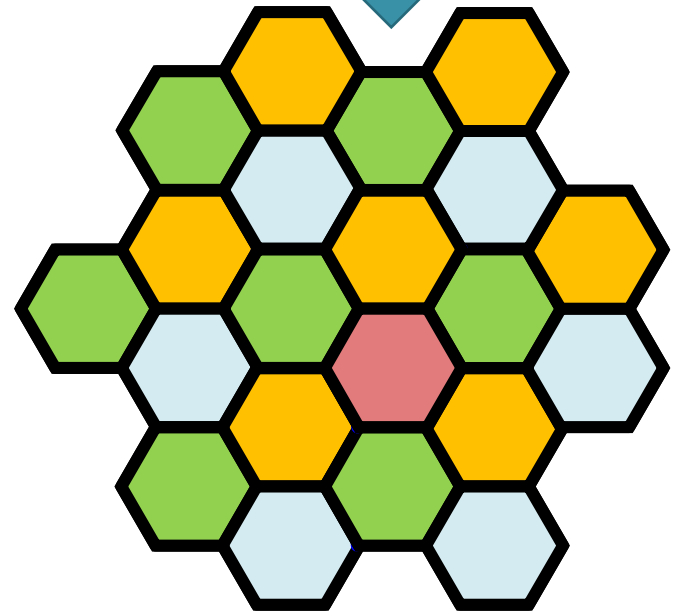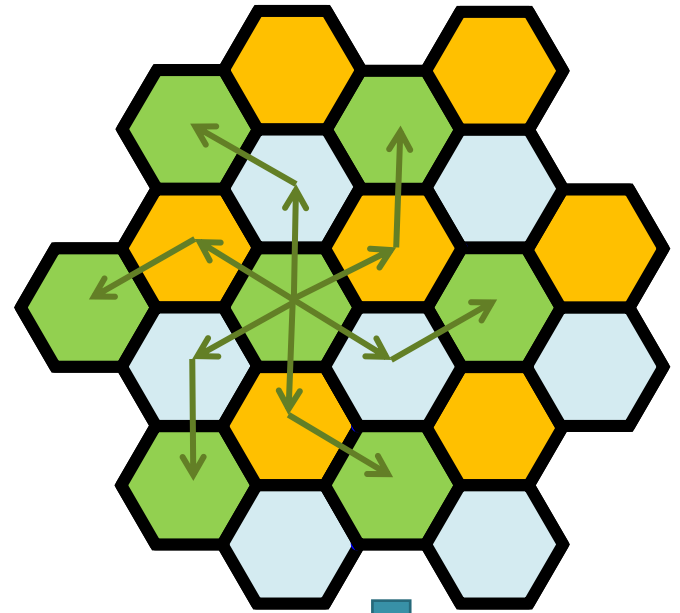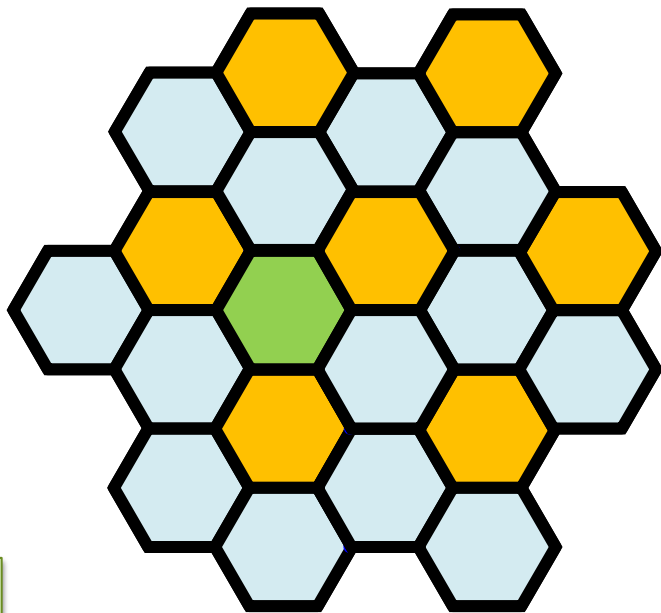
N = 3
i = 1
j = 1

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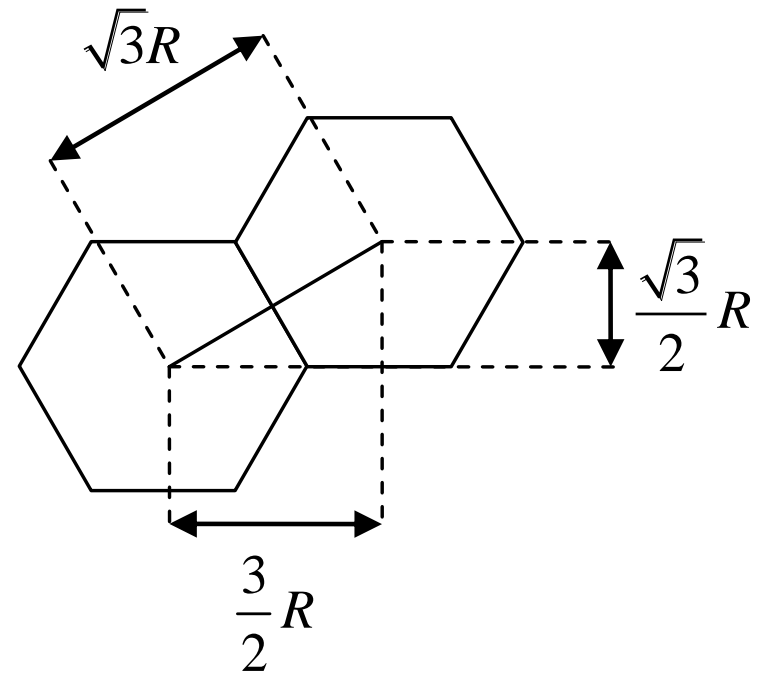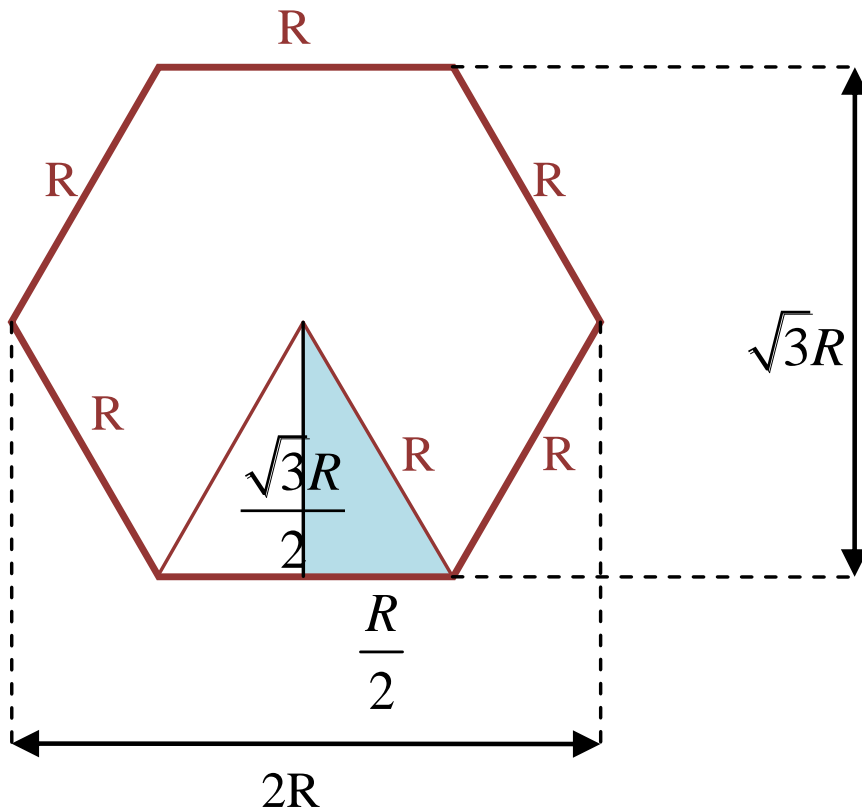
Locating co-channel cells (N = 4, N = 7)

(i = 2, j = 0)

(i = 2, j = 1)

Hexagon

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

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