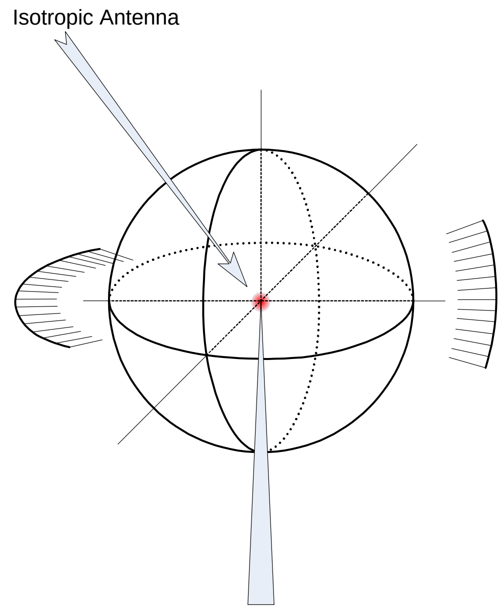
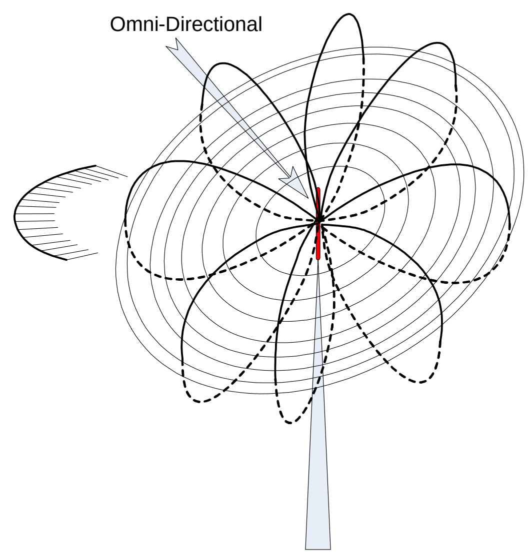
Lecture 2: The Concept of Cellular Systems

Radiation Patterns of Simple Antennas

Isotropic Antenna: the isotropic antenna is the simplest antenna possible. It is only a theoretical antenna and cannot be realized in reality because it is a sphere of size zero. It radiates power in all directions equally (0° to 360° around the antenna and -180° to +180° vertically). Even if this type of antennas was possible realizable, it would not be suitable for cell phone systems because it would be useless to transmit power at high angles above or below the horizon.



Omni-directional Antenna: this antenna is built using a metallic bar and radiates its energy equally in all directions around the antenna (0° to 360° around it). However, the antenna does not transmit equally in all directions vertically. The highest radiated power is in the direction perpendicular to the antenna and reradiated power drops as the angle increases above or below the horizon. Such an antenna is suitable for cell phone towers because most of the radiated power travels parallel to the horizon.

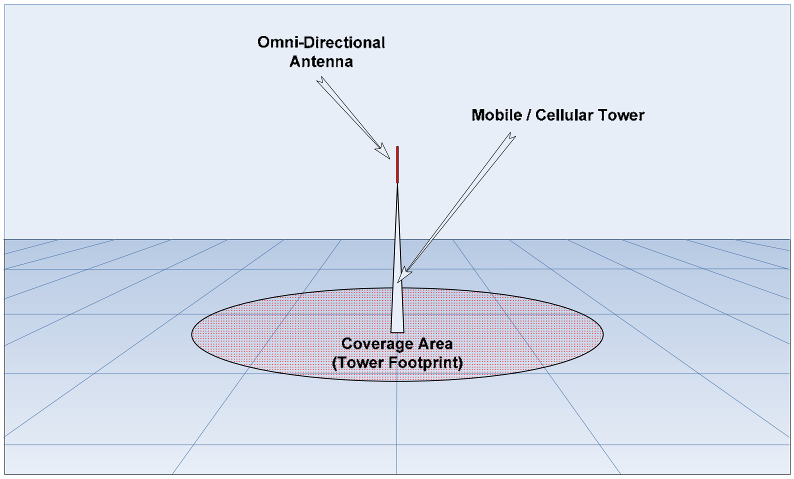


Old Mobile Systems vs. Modern Cellular Systems

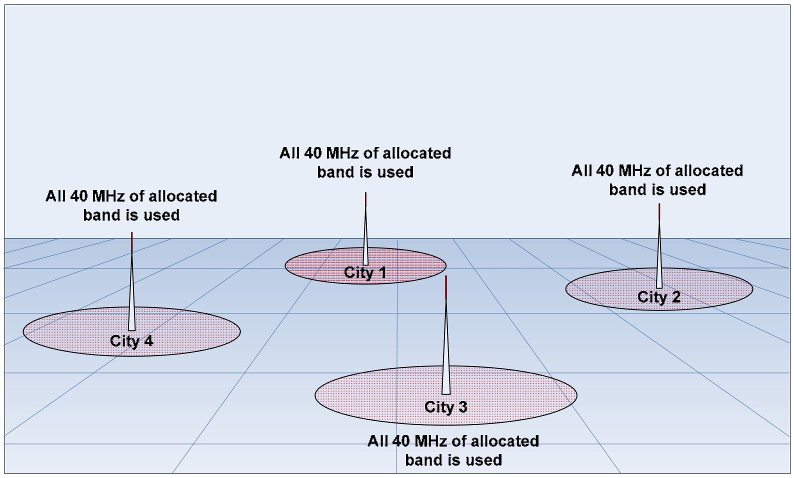
Old Mobile Phone Systems: In the first generations of mobile phone systems (these systems were **not cellular systems**), only large cities received mobile coverage such that:

- large cities received mobile service coverage through a single high-power tower that is placed in a central position to the city being covered.

- The coverage area (called tower footprint) of these towers was (theoretically) circular in shape with radius around 50 km.



- As long as cities being covered were far away from each other, no (or little) interference occurred between the transmissions in different cities.



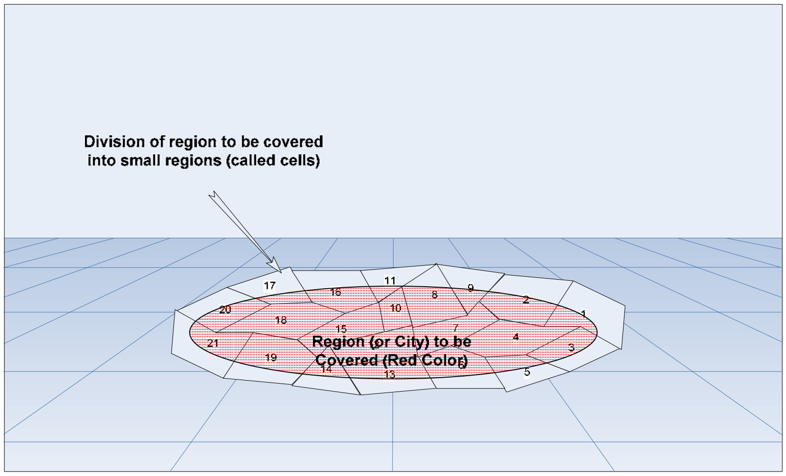
- The whole assigned spectrum (40 MHz or more) was used in every city being covered. With the bandwidth of a single-direction channel being 30 kHz and two different channels being used for full duplex transmission making a total of 60 kHz per user, the total number of users who can call or receive calls at the same time in any city was around 660 users only. In a large city with 10,000,000 residents for example, this is extremely low and the system would get congested so easily.
- Also, because of the relatively large distance that may be between the mobile station in the coverage area and the base station (up to 50 km or so), mobile phones had to transmit high powers resulting in the need for large batteries and therefore, phones were large in size and inconvenient.

An old Philips mobile phone
[www.mobilitywatch.com]

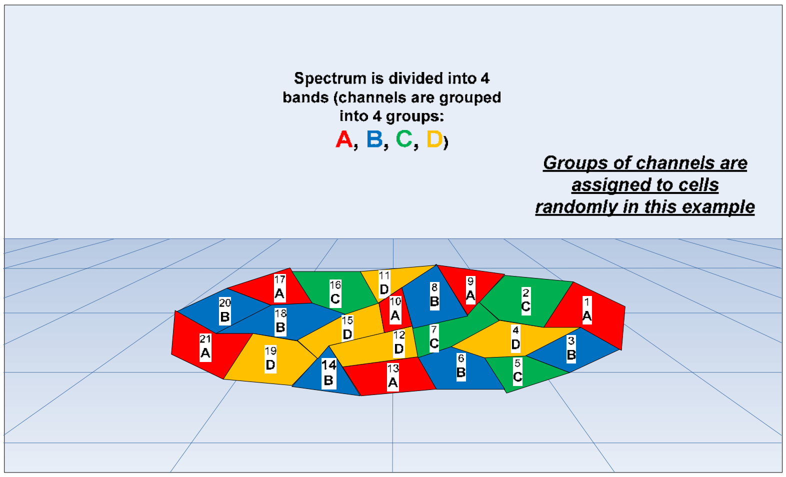
- Because of the necessity for separating the coverage areas of different cities, coverage was not continues and it was not possible to keep an active phone call once the mobile unit leaves a specific coverage area.

Modern Cellular Phone Systems: The solution to the problems of the need of mobile phones to transmit high power and the congestion of the spectrum was developed by AT&T Bell Labs in the 1960s and 1970s and it became known as Cellular Phone Systems. The idea of cellular phone systems was:

- Divide the region for which we would like to provide phone coverage into smaller regions of area 20 km or so (called cells).

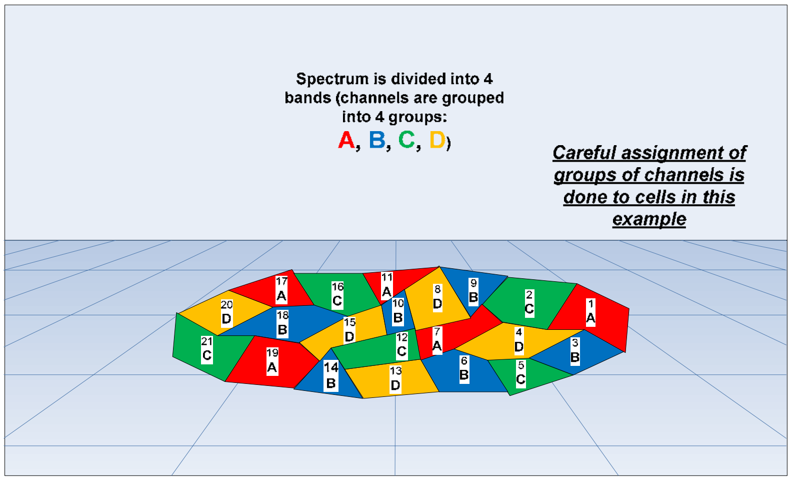


- Divide the allocated spectrum (40 MHz or more) into groups of channels (for example 4 groups).
- Place a relatively low power cellular tower near the center of each cell and assign it one group of channels for transmission and reception.



- To reduce interference between the communications that occur in different cells as much as possible, make sure that each cell uses a group of channels that is different from the groups of channels used in ALL ADJACENT (neighbor) cells (the same group of channels is never used in neighboring cells). In the above figure with random assignment of groups of channels, cells 2 and 7 are adjacent and have the same group of channels (C) assigned to both, cells 18 and 20 are adjacent and have the same group of channels (B) assigned to both, cells 12 and 15 and 19 are all adjacent and have the same group of channels (D) assigned to all of them. Such assignment results in high interference for calls initiating or ending in these cells.

- If all adjacent cells are using different frequency groups, frequency groups can be REUSED in far away cells. In the figure below, carful assignment is done to reduce interference as much as possible by ensuring that groups of channels are reused but not in neighboring cells.



- The reuse of frequency groups in far away cells produces little interference since the power transmitted by cellular phones and cellular towers in a particular cell with a specific frequency group is relatively low that it would drop down significantly by the time this transmitted power reaches another cell with the same frequency group.
- Because frequencies are reused over and over, the capacity of the cellular network is many times higher than the capacity of old mobile phone networks.
- Because the distance between a cellular phone and the cellular tower serving it is relatively small (around 3 or 4 km at most), cell phones do not need to transmit high power and therefore, need very small batteries that can operate for hours. This allows building small cellular phones.

The Cellular Concept – Frequency Reuse

So, in cellular systems, frequencies are used over and over to provide coverage to large areas using the limited spectrum. This frequency reuse concept results in increasing the capacity of the network possibly by a 100 times or more in highly populated areas compared to the old mobile systems. Now, we will study concept of frequency reuse in more details and try to answer questions like:

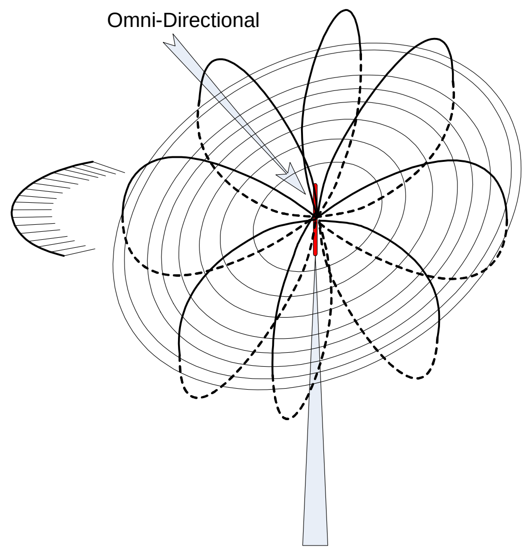
(1) What is the theoretical shape of cell?

(2) Do cells in reality have the same shape as the theoretical one?

(3) How often can we reuse frequencies?

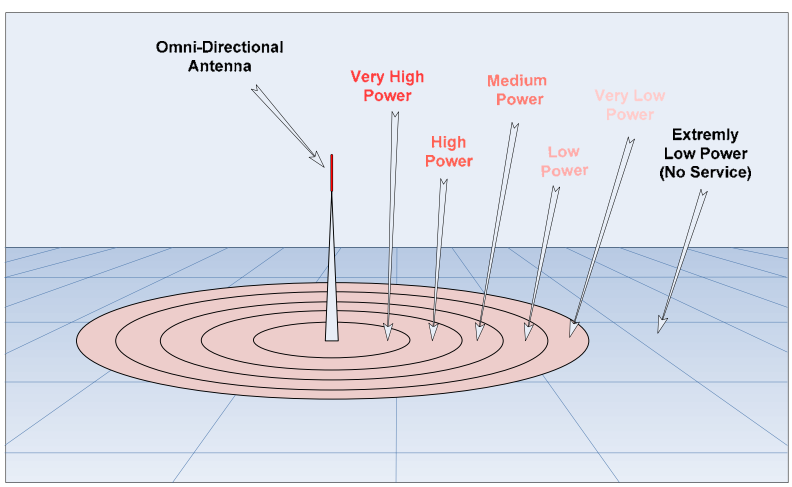
(4) What is the effect on increasing the frequency reuse on the network capacity?

Shape of a Cell



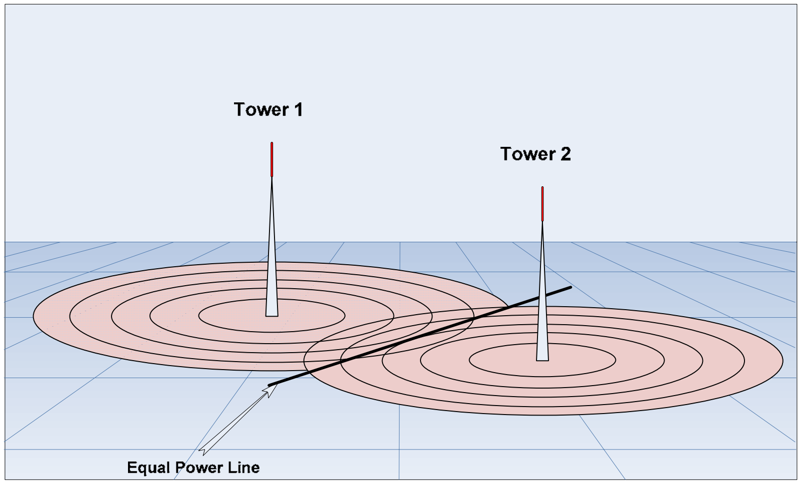
- We will assume that cellular towers use omni-directional antennas that are installed in a vertical form. Such antennas produce the radiation pattern shown previously and is repeated here for convenience. This radiation pattern indicates that equal power is radiated horizontally in all directions around the antenna (0° to 360°). Vertically, the radiated power has maximum power on the plain parallel to the earth surface. As the observation point goes above or below this plain, the radiated power drops. In fact, no power is radiated above or below the antenna directly.

- Assuming that no geographical features or buildings exist around the antenna and that only one cellular tower exist in the region, the radiation pattern of the omni-directional antenna produces circles with equal power at ground-level as shown in the figure below. The power drops as the radius of the circles increases. It may appear that no radiation will reach the region very close to the cellular tower because of the fact that the antenna is installed on top of a tower. But remember that distances away from the antenna are measure in kilometers while the height of the antenna usually around 10m – 30m only.

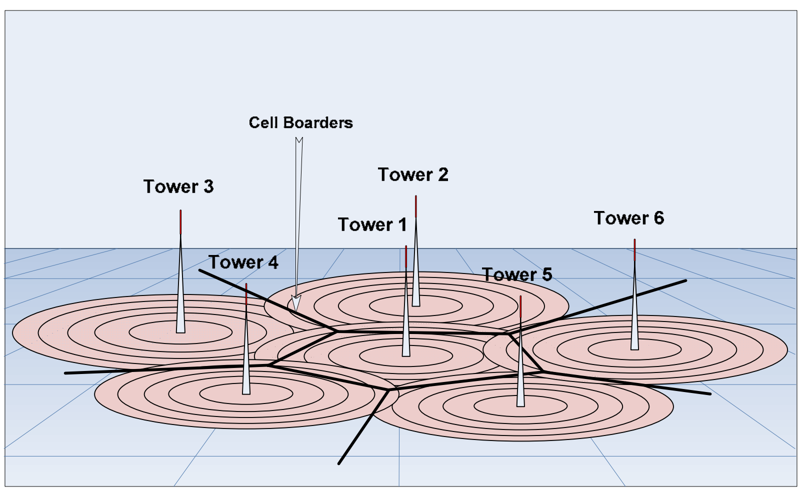


- As distance between the cellular phone and the tower increases the signal drops quickly until at some distance from the tower, the signal transmitted by the tower becomes so weak that the cellular phone can no longer demodulate the signal. At that distance, a mobile phone will indicate that there is no service.

- When two towers are close to each other, the transmitted power from each one enters the coverage area of the other. As you will see later, a cellular phone will connect to the cellular tower from which it receives a stronger signal. Assuming that both towers transmit equal power, the curve at which equal power is received from both towers is a straight line as shown below.



- When multiple towers are close to each other, a cell phone will communicate with the tower that provides it with the highest power. The curves that separate different regions belonging to different towers based on the highest power criterion are straight lines as shown in the following figure.



- In practice, cell boarders are never straight lines because of uneven power transmission by different towers, uneven earth surface, the existence of geographical features, trees, or buildings make the cell barriers random in shape. In fact, cell phone companies usually test cell barriers by having some drive around with sophisticated cell phones to determine were cell barriers are located for proper planning.

Most Efficient Cell Shapes to Cover Large Regions

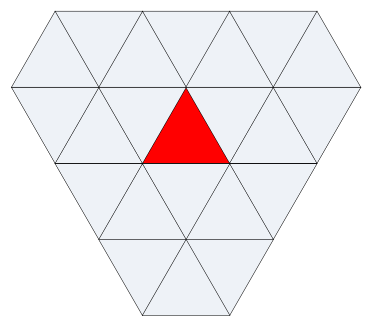
The question we would like to answer now is: What is the most efficient theoretical cell shape that will allow us to provide full coverage to a large area by stacking the minimum number of cells possible. Ideally, a circle is the best shape because it is the natural reach of electromagnetic waves when they are transmitted from an omni-directional antenna. However, it is not possible to stack circles near each other and cover the whole region of interest without leaving some gaps. For proper cell shapes, let us observe the following points:

- Boarders of cells are straight lines and cell shapes are polygons (Polygons are geometric shapes with all edges being straight lines like triangles, rectangles, pentagons, …).
- Full coverage of the whole region is necessary without leaving any uncovered spots.
- We will assume that all cells have the same shape.
- Cells should have some symmetry (cells can be rotated in place at angles less than one complete rotation without affecting cells layout)

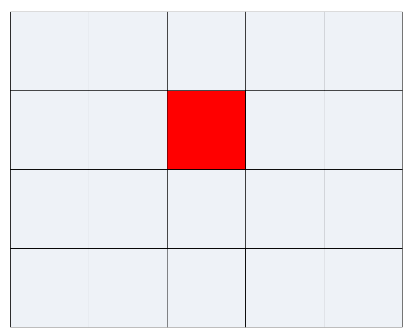
Cell shapes that meet the above constraints are one of the following:

1. **Equilateral Triangles:**

   (An equilateral triangle is one with all sides having equal lengths and all angles being 60°).

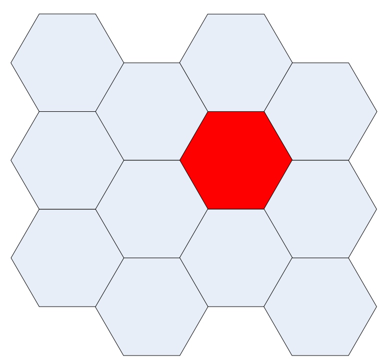


2. **Square:**

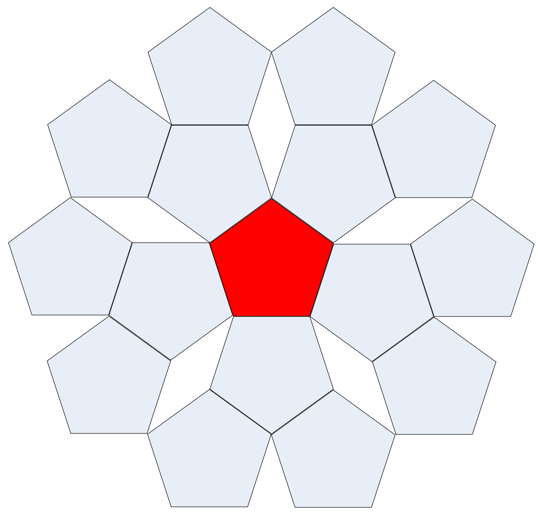


3. **Hexagons:**

   (a shape with six equal sides and six equal angles)



Note: other symmetrical polygons cannot cover the complete space. For example, a pentagon fails to cover the whole space as shown below. You will need cells of other shapes to cover the remaining regions.



Most Efficient Cell Shape:

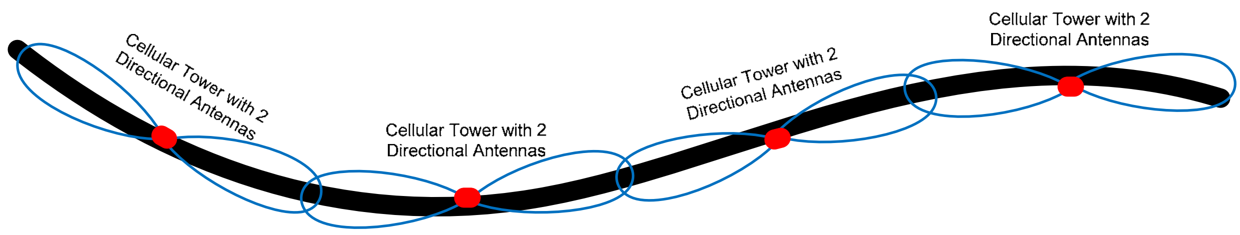
By studying the above three shapes (equilateral triangle, square, and a hexagon), we see that the **HEXAGON** is the most efficient cell shape because:

- It requires the least number of cells to cover a specific area using hexagons than using triangles or squares.
- It is the closest to the shape of a circle which is the natural transmission pattern of an omni-directional antenna (the difference between the distances of different points on its perimeter are the smallest with hexagons compared to squares or triangles).

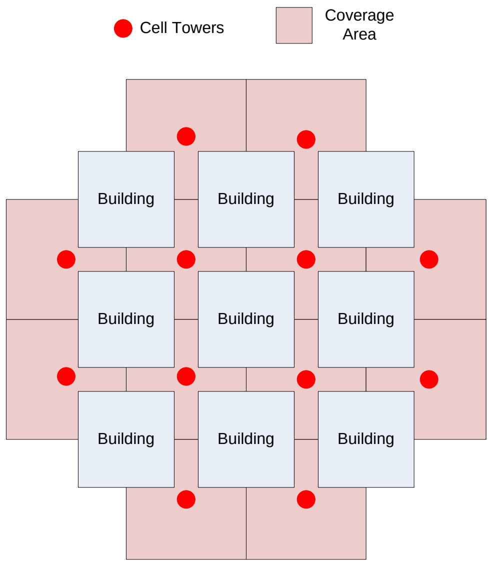
Are Cells Sometimes Intentionally Made Non-Hexagonal?

Yes. Two of the most spread non-hexagonal cell shapes are the (1) highway style coverage and (2) the Manhattan style coverage.

(1) **Highway Style Cells:** used to cover long stretches of highways in an almost deserted region (for example, the highway between Dammam and Riyadh).



(2) **Manhattan Style Cells:** used to cover cities with high building in the shape of rectangles or blocks (such as Manhattan in New York).



Do Cells in Reality have the Hexagonal Shape?

The answer is certainly **NO**. It is very rare that you see a cell that is close to hexagonal because of many reasons:

1) Geographical features such as mountains and valleys alter the shape of a cell significantly. Even small variations in height around the cellular tower affect the shape of the cell.
2) The inability of a cell phone company to place the cell towers in exactly the desired location due to geographical features or buildings.
3) The inefficiency of insuring hexagonal cells as sometimes the population density within the coverage area may vary making it more efficient to place more towers in regions with high population and less towers in regions with low population.

Why Do We Study Hexagonal Cells and not Non-Hexagonal Cells?

Because hexagonal cells are easier to analyze and they give a good understanding of the analysis techniques for non-hexagonal cells without the complication of irregularly shaped cells. So, we will limit our discussion to hexagonal cells only.