# Mobile Communications

## Lecture (1)

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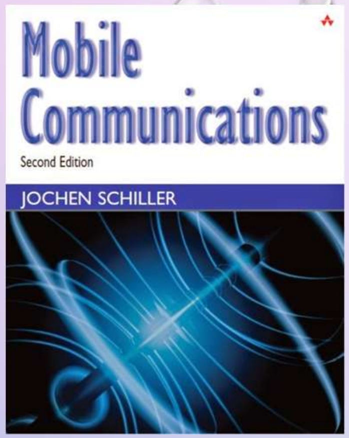
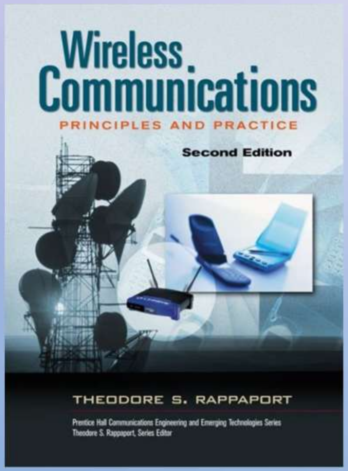
# Work Assessments

| | | | |
|---|---|---|---|
| **Year Work** | **50** | Mid Term | 10 |
| | | Project | 20 |
| | | Quiz | 10 |
| | | Attendance | 10 |
| **Final Lab Exam** | 20 | | |
| **Final Exam** | 80 | | |
| **Total** | **150** | | |

# References




**"Mobile-Communications", Jochen Schiller, Second Edition, 2003**




**"Wireless Communications_ Principles and Practice", (2nd Edition), Theodore S, Rappaport**

# Goal of Mobile Communication

"People and their machines should be able to access information and communicate with each other easily and securely, in any medium or combination of media – voice, data, image, video, or multimedia – any time, anywhere, in a timely, cost-effective way."

# Objective

- **The design objective** of early mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower.
- This approach achieved very good coverage,
- it also meant that it was impossible to reuse those same frequencies throughout the system, since any attempts to achieve frequency reuse would result in interference.
- But with the fact that government regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services,
- it became imperative to restructure the radio telephone system to achieve high capacity with limited radio spectrum while at the same time covering very large areas.

# History of Mobile Service

- The first wireline telephone system was introduced in the year 1877.
- Mobile communication systems as early as 1934 were based on Amplitude Modulation (AM) schemes
- In World War II, the development of Frequency Modulation (FM) technique by Edwin Armstrong achieved newer and better mobile radio communication systems
- Mobile telephone was introduced in the year 1946

# History of Mobile Service

- The development of the cellular concept in the 1960s at the Bell Laboratories, but mobile communication was restricted to **certain official users** and the cellular concept was never even dreamt of being made commercially available
- the development of newer and better technologies starting from the 1970s and with the mobile users now connected to the Public Switched Telephone Network (PSTN)
- Advanced Mobile Phone System (AMPS) was the first U.S. cellular telephone system and it was deployed in 1983

## Examples of Mobile Communication Systems

- Pagers-Simplex
- Hand held Walkie-Talkies-Half duplex
- Cordless phones-Full duplex
- Cellular telephones-Full duplex

pager


Walkie-Talkie


Cordless phone

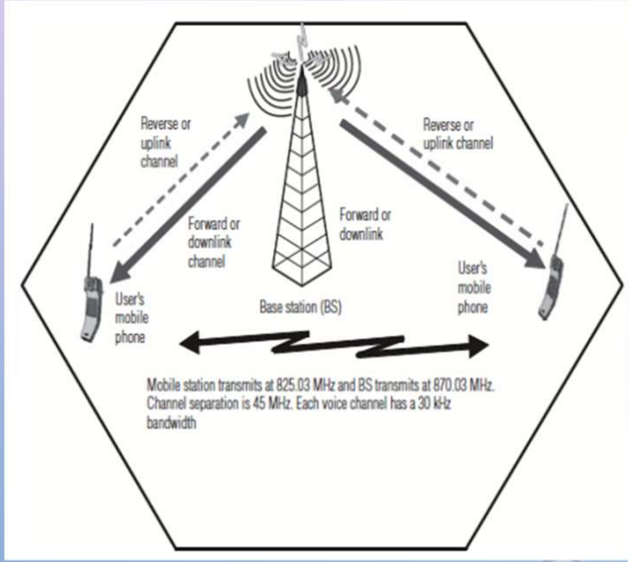
Cellular telephone

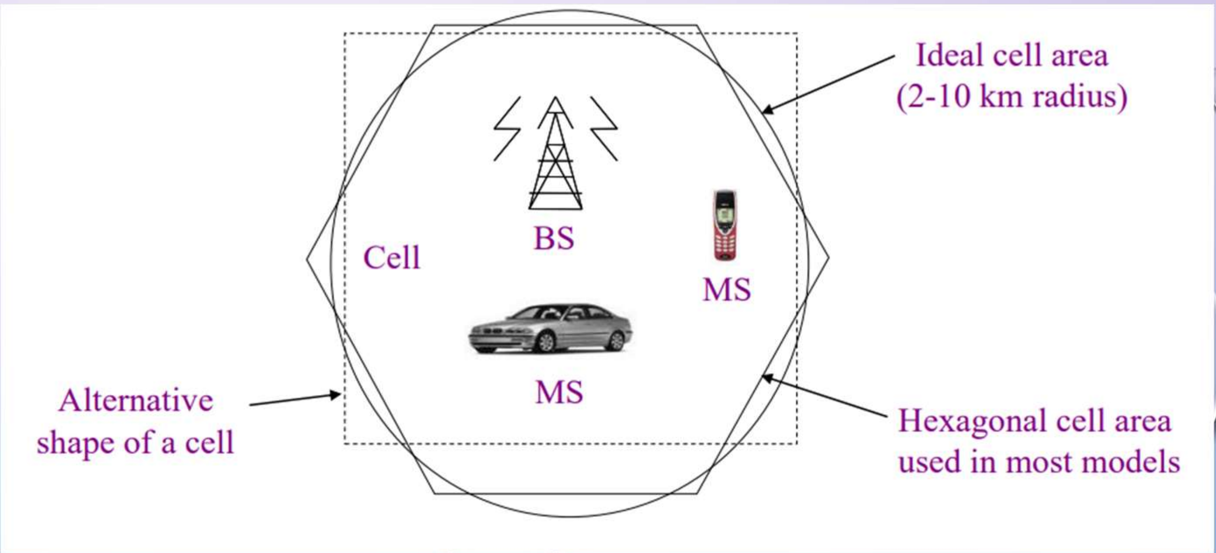
# What are Cellular Networks?

- **Definition**: Cellular networks divide large areas into smaller regions called **cells**, each controlled by a **base station**. This allows for efficient frequency reuse and enhanced capacity.
- Key Features:
  - Divides coverage into **small hexagonal cells**.
  - Each cell uses specific frequencies to avoid interference with neighboring cells.

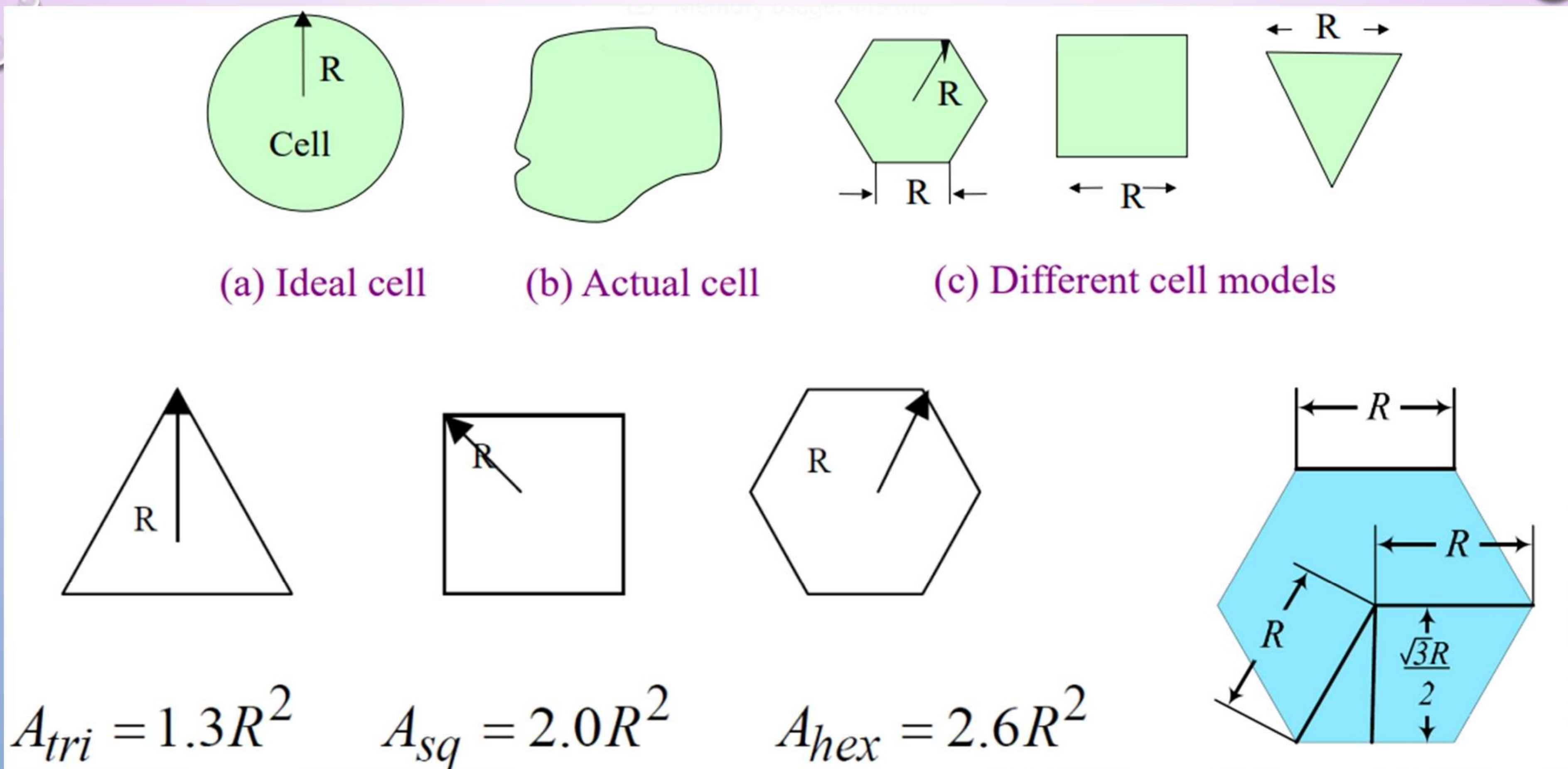
# Cell

- Cell is the small geographic area covered by the base station.
- The area around an antenna where a specific frequency range is used.
- Cell is represented graphically as a hexagonal shape, but in reality it is irregular in shape.

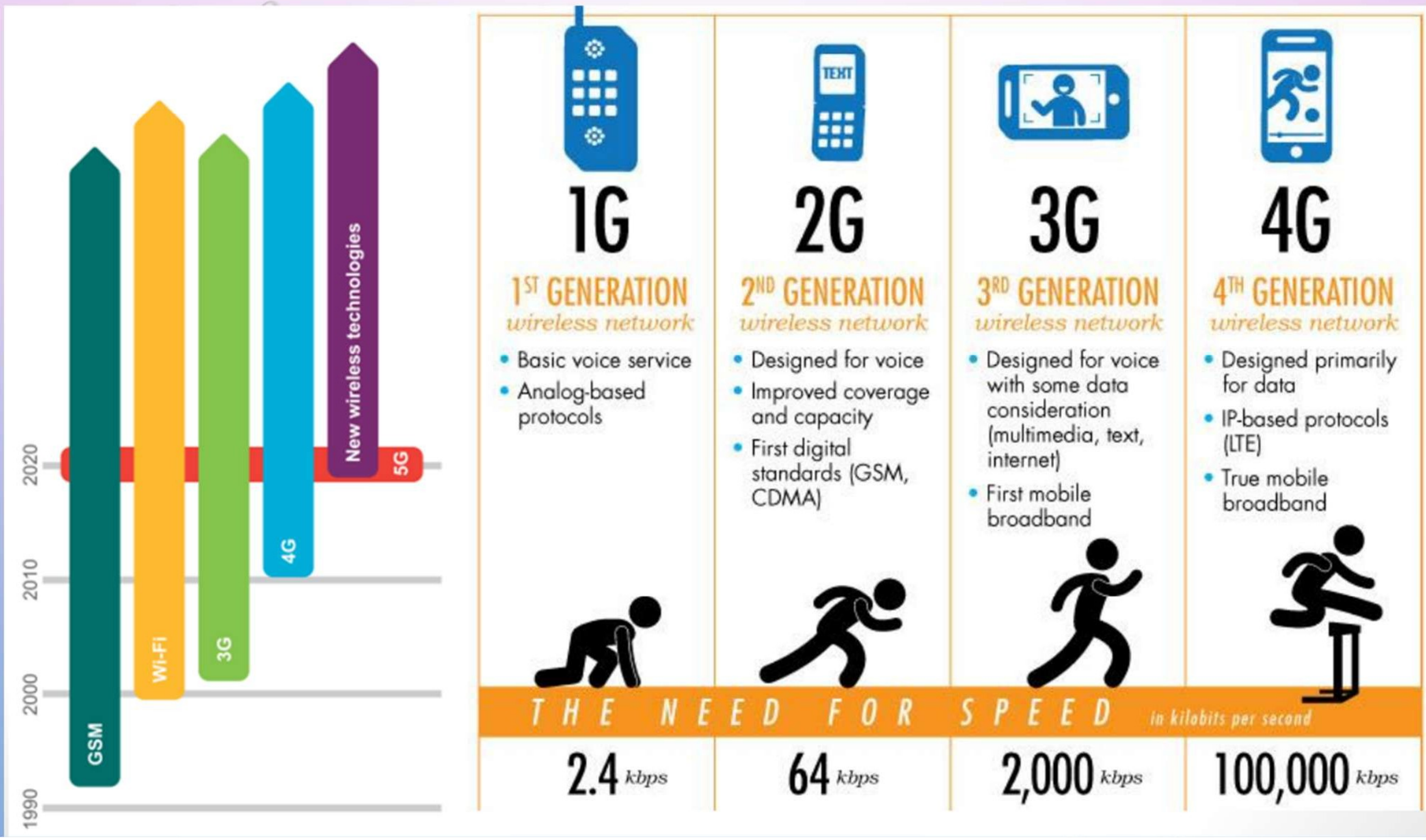


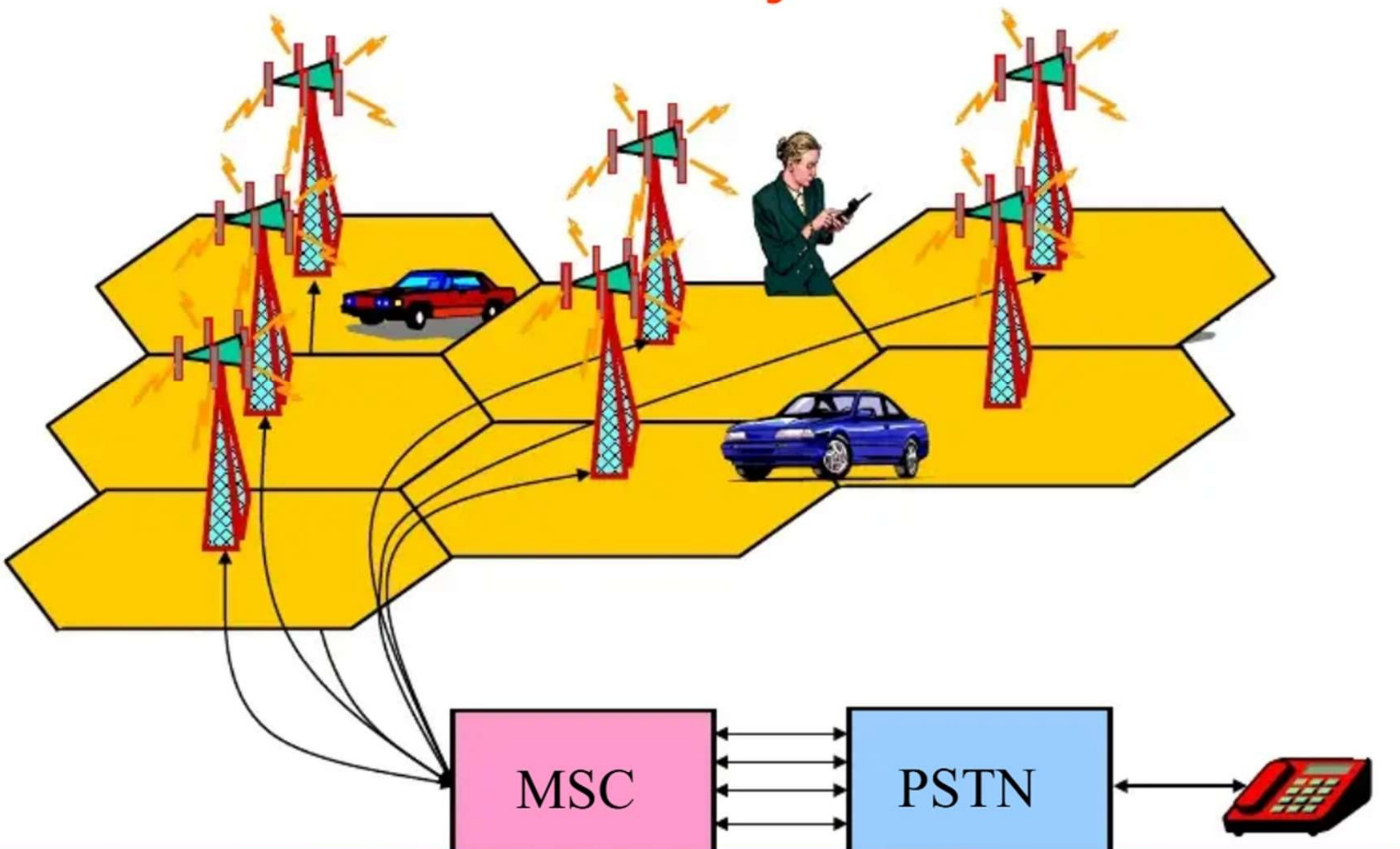
# Cell Shape


R
Cell
R
R
R
R
(a) Ideal cell
(b) Actual cell
(c) Different cell models
R
R
R
R
R
R
√3R/2
A_tri = 1.3R^2
A_sq = 2.0R^2
A_hex = 2.6R^2

# Cellular System Evolution

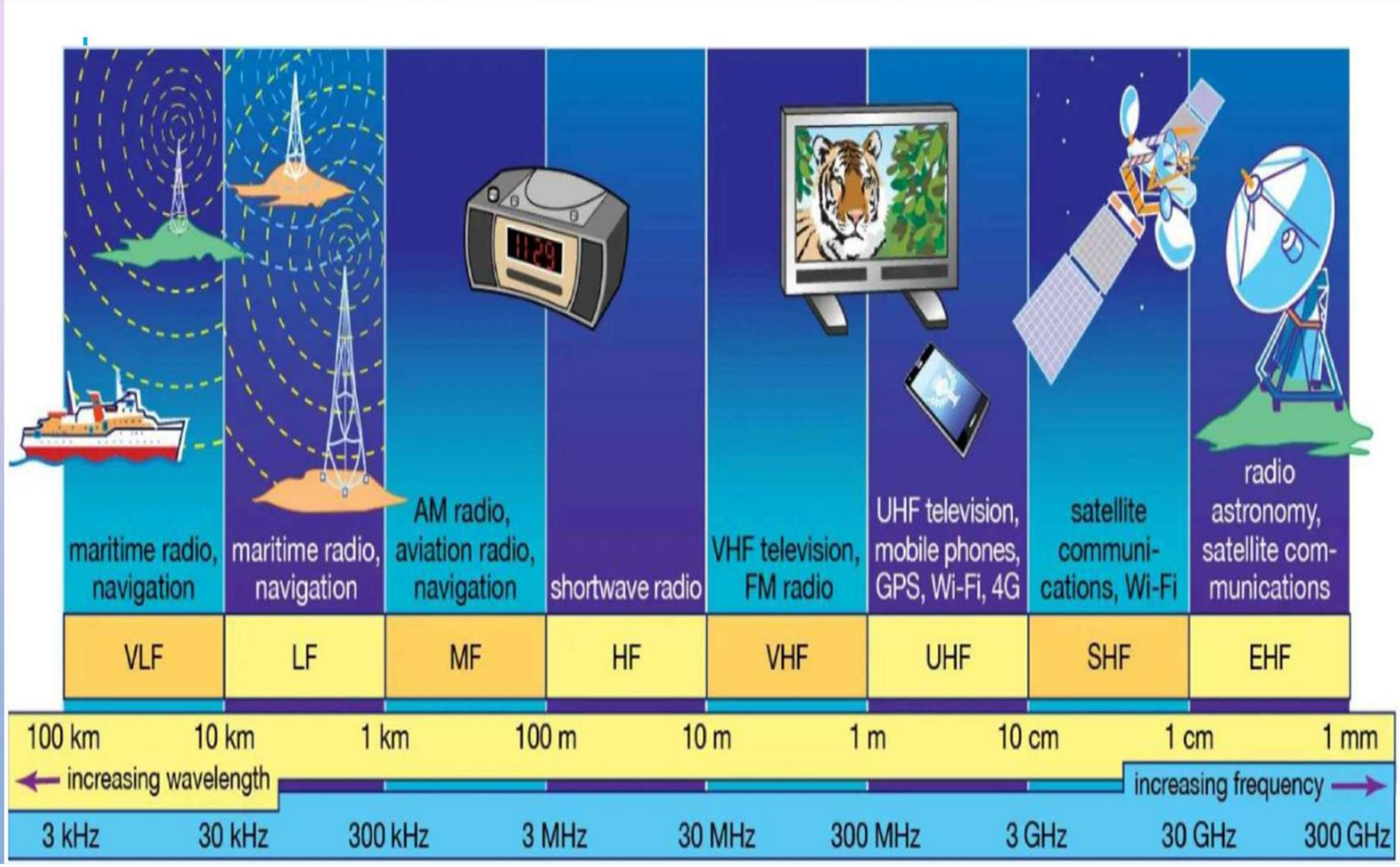


# Cellular System



- Basic cellular system consists of
  - Mobile stations (e.g. mobile phones) (MS)
    - users transceiver terminal (handset, mobile)
  - Base stations (BS)
    - fixed transmitter usually at centre of cell
    - includes an antenna, a controller, and a number of receivers
  - Mobile switching center (MSC)
    - Sometimes called a mobile telephone switching office (MTSO)
    - handles routing of calls in a service area
    - tracks user
    - connects to base stations and PSTN

# Radio Frequency Spectrum



- **Overview**: The **radio frequency spectrum** is the range of electromagnetic frequencies used for wireless communication.
- **Common Frequency Bands**:
  - **VLF (3 kHz - 30 kHz)**: Long-range communication (e.g., maritime radio).
  - **LF (30 kHz - 300 kHz)**: Submarine communication.
  - **MF (300 kHz - 3 MHz)**: AM radio.
  - **HF (3 MHz - 30 MHz)**: Shortwave radio.
  - **VHF (30 MHz - 300 MHz)**: FM radio, moderate range communication.
  - **UHF (300 MHz - 3 GHz)**: Mobile phones, GPS, Wi-Fi, and 4G.
  - **SHF (3 GHz - 30 GHz)**: Satellite communication.
  - **EHF (30 GHz - 300 GHz)**: Millimeter-wave communication (5G).

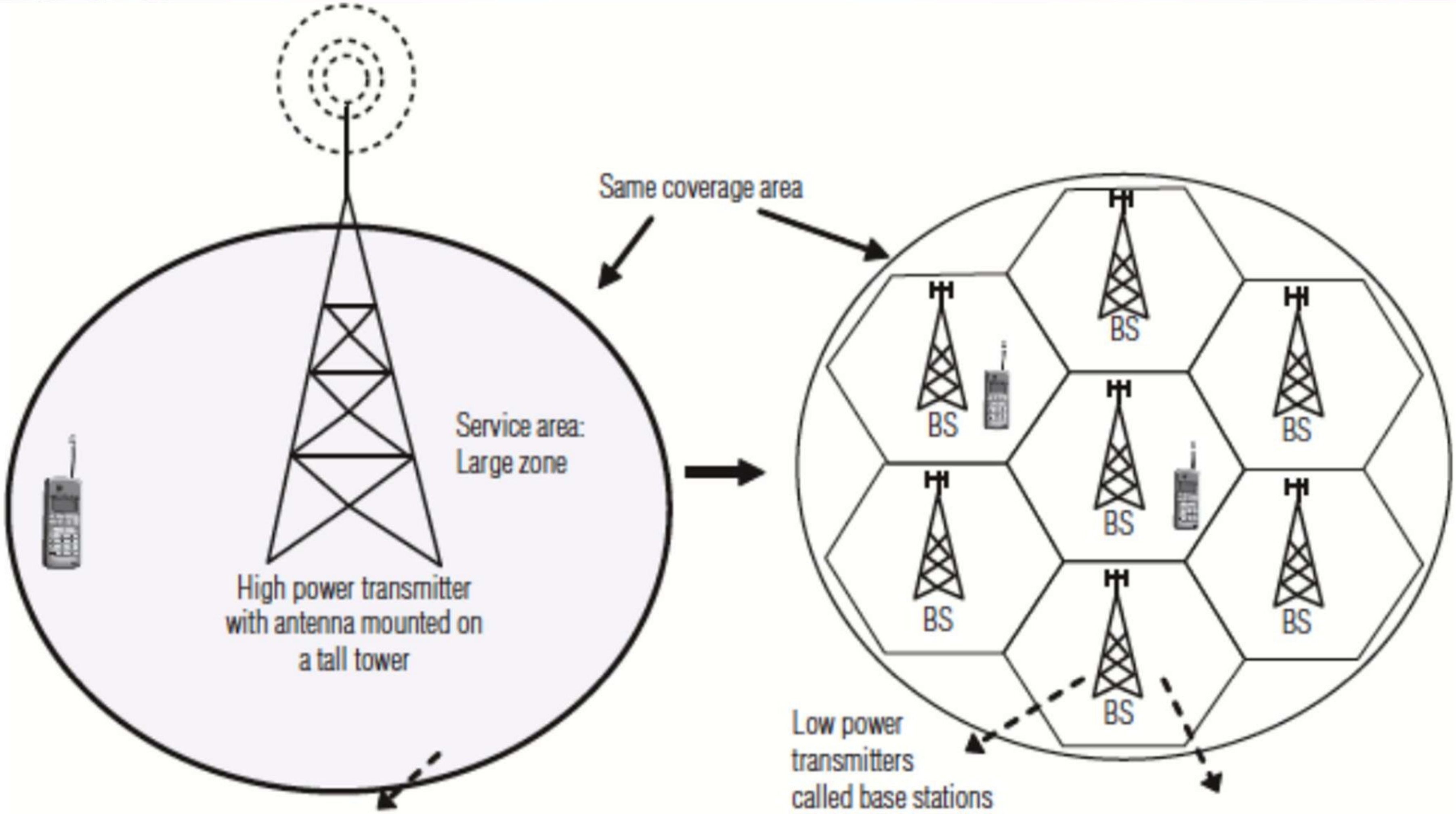
| Designation | Abbreviation | Frequencies | Free Space Wavelengths |
|---|---|---|---|
| VLF | Very Low-Frequency | 9KHz-30KHz | 33km-10km |
| LF | Low Frequency | 30KHz-300KHz | 10km-1km |
| HF | High Frequency | 3MHz-30MHz | 100m-10m |
| MF | Medium Frequency | 300MHz-3MHz | 1km-100m |
| VHF | Very High-Frequency | 30MHz-300MHz | 10m-1m |
| UHF | Ultra High Frequency | 300MHz-3GHz | 1m-100mm |
| SHF | Super High Frequency | 3GHz-30GHz | 100mm-10mm |
| EHF | Extremely High-Frequency | 30GHz-300GHz | 10mm-1mm |

# Spectrum Allocation at Egypt

- **Management by NTRA**: The **National Telecommunications Regulatory Authority (NTRA)** oversees the allocation of spectrum for wireless communication.
- **Mobile Spectrum Bands**:
  - **2G/3G**: 900 MHz and 1800 MHz – good coverage, low data capacity.
  - **4G**: 800 MHz, 1800 MHz, and 2600 MHz – higher speeds and better data capacity.
  - **5G**: Trials are ongoing in the 3.5 GHz band, offering ultra-high speeds but requiring more infrastructure due to shorter range.

# The Cellular Concept

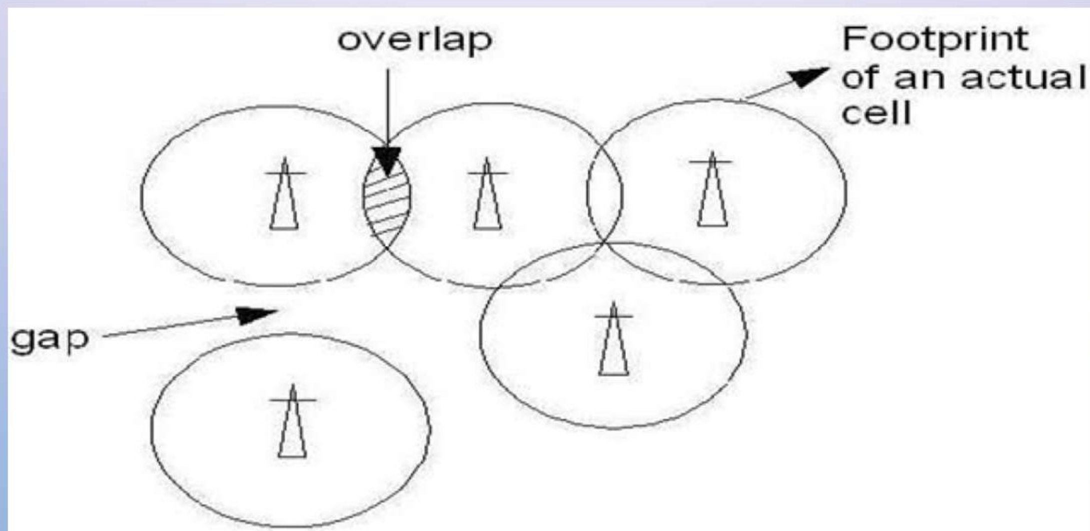
- **The cellular concept** is **a system-level idea which calls for replacing a single, high power transmitter (large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of the service area**.
- Each base station is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all the available channels are assigned to a relatively small number of neighboring base stations.
- Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is minimized.
- The available channels are distributed throughout the geographic region and may be reused as many times as necessary so long as the interference between co-channel stations is kept below acceptable levels




(a) Early mobile radio system: Large zone

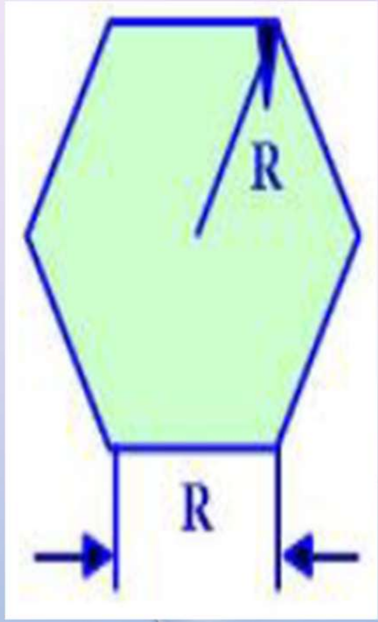
(b) Cellular system: small zone

- The power of the radio signals transmitted by the BS (Base station) decay as the signals travel away from it.
- A minimum amount of signal strength (let us say, x dB) is needed in order to be detected by the MS (Mobile Sets).
- The region over which the signal strength lies above this threshold value x dB is known as the coverage area of a BS and it must be a circular region.
- Such a circle, which gives this actual radio coverage, is called the foot print of a cell.
- It might so happen that either there may be an overlap between any two such side by side circles or there might be a gap between the coverage areas of two adjacent circles.

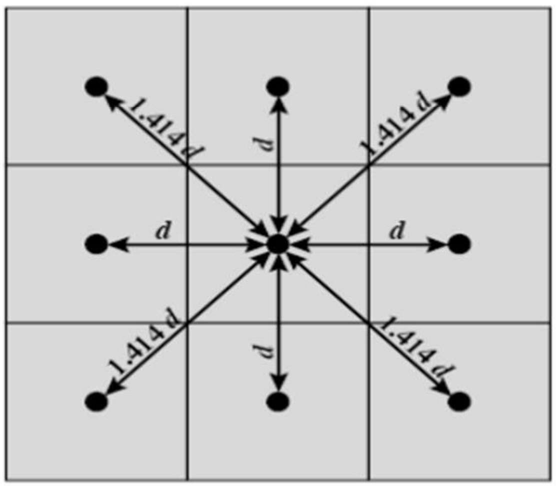


# Why use regular hexagonal geometry?

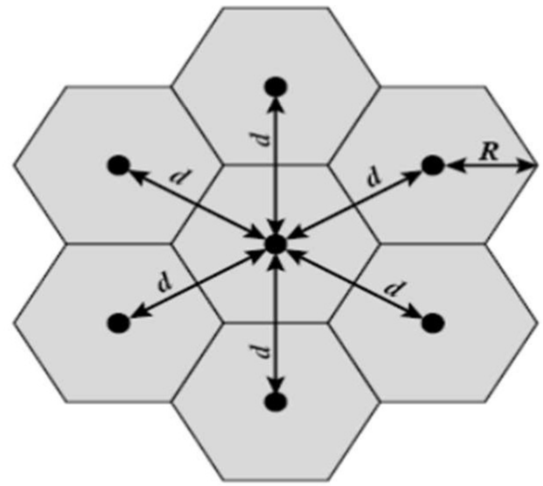
- We need a regular shape for cellular design which can cover the entire area without any overlap and gaps.
- Along with its regularity, a cell must be designed such that it is most reliable too, i.e., it supports even the weakest mobile with occurs at the edges of the cell.
- For any distance between the center and the farthest point in the cell from it, a regular hexagon covers the maximum area.
- Hence regular hexagonal geometry is used as the cells in mobile communication.



- The most common model used for wireless networks is uniform hexagonal shape areas
  - A base station with omni-directional antenna is placed in the middle of the cell



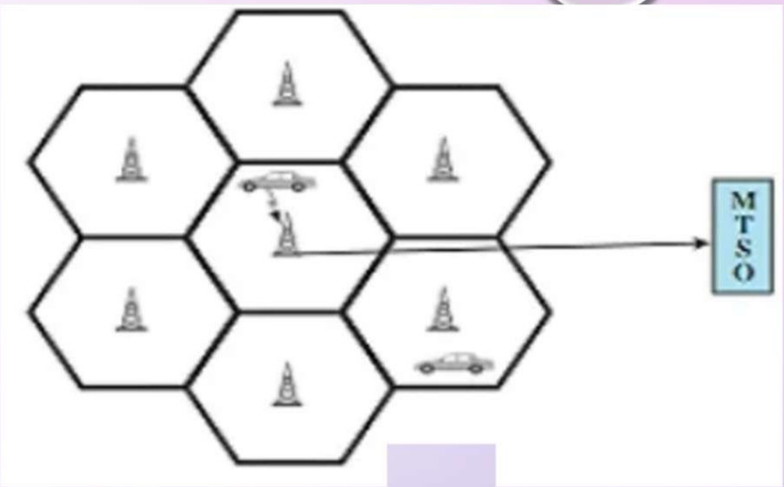

(a) Square pattern




(b) Hexagonal pattern

$$d = \sqrt{3}R$$

# Cluster




- Each MSC coordinates a number of base stations
  - The set of base stations controller by a single MSC is called a CLUSTER
  - The number of base stations in a cluster is usually denoted by the letter *N*

# Cellular Coverage

- The geographic area served by a cellular radio system is broken up into smaller geographic areas, or cells.
- Uniform hexagons most frequently are employed to represent these cells on maps and diagrams;
- in practice, though, radio-waves do not confine themselves to hexagonal areas, so that the actual cells have irregular shapes.
- All communication with a mobile or portable instrument within a given cell is made to the base station that serves the cell.

# System Capacity and Quality of Service (QoS)

- System Capacity:
  - **Definition**: The **maximum number of users** or calls that a cellular network can handle simultaneously.
  - How to Increase Capacity:
    - **Frequency Reuse**: Reusing frequencies in non-adjacent cells.
    - **Cell Splitting**: Dividing large cells into smaller ones.
    - **Sectoring**: Splitting a cell into multiple sectors using directional antennas.
    - **Additional Spectrum**: Allocating more frequency bands.

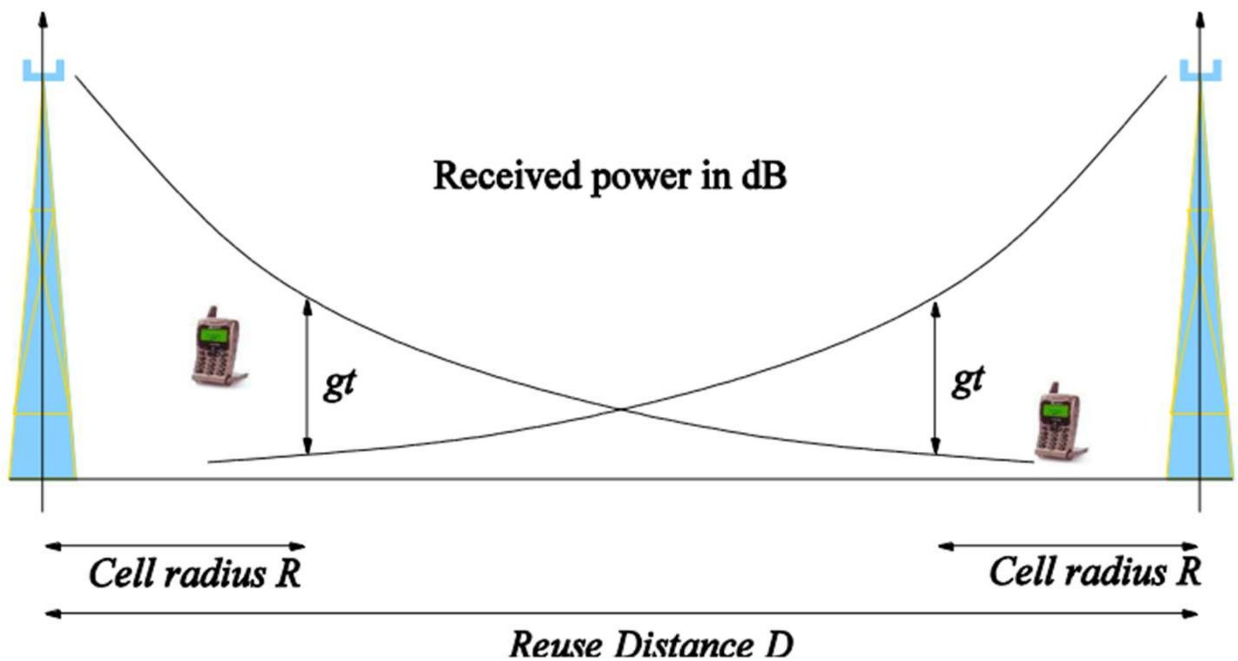
- **Quality of Service (QoS)**:
  - **Definition**: Ensures **clear calls, reliable connections, and fast data transfer**.
  - **Enhancing QoS**:
    - Reducing interference.
    - Implementing efficient **handoff** mechanisms.
    - **Traffic Management**: Trunking and managing available channels.
    - Optimizing **cluster size** to balance frequency reuse and interference.
- **Difference Between Capacity and QoS**:
  - **Capacity** relates to how many users a network can serve.
  - **QoS** focuses on how well the network performs for each user.
  - **Trade-off**: Increasing capacity (through frequency reuse) can lead to reduced QoS if interference is not managed.

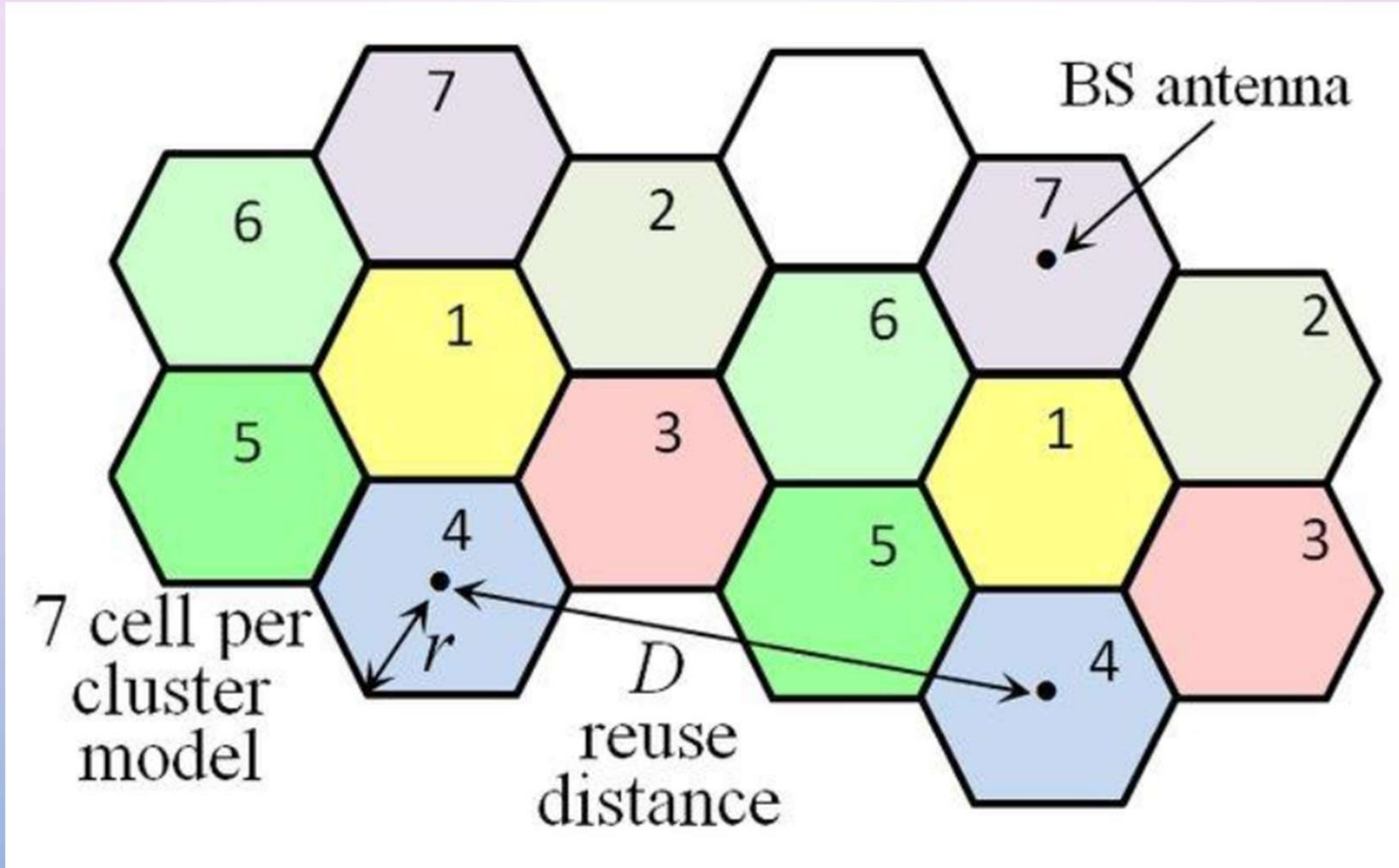
# Frequency Reuse

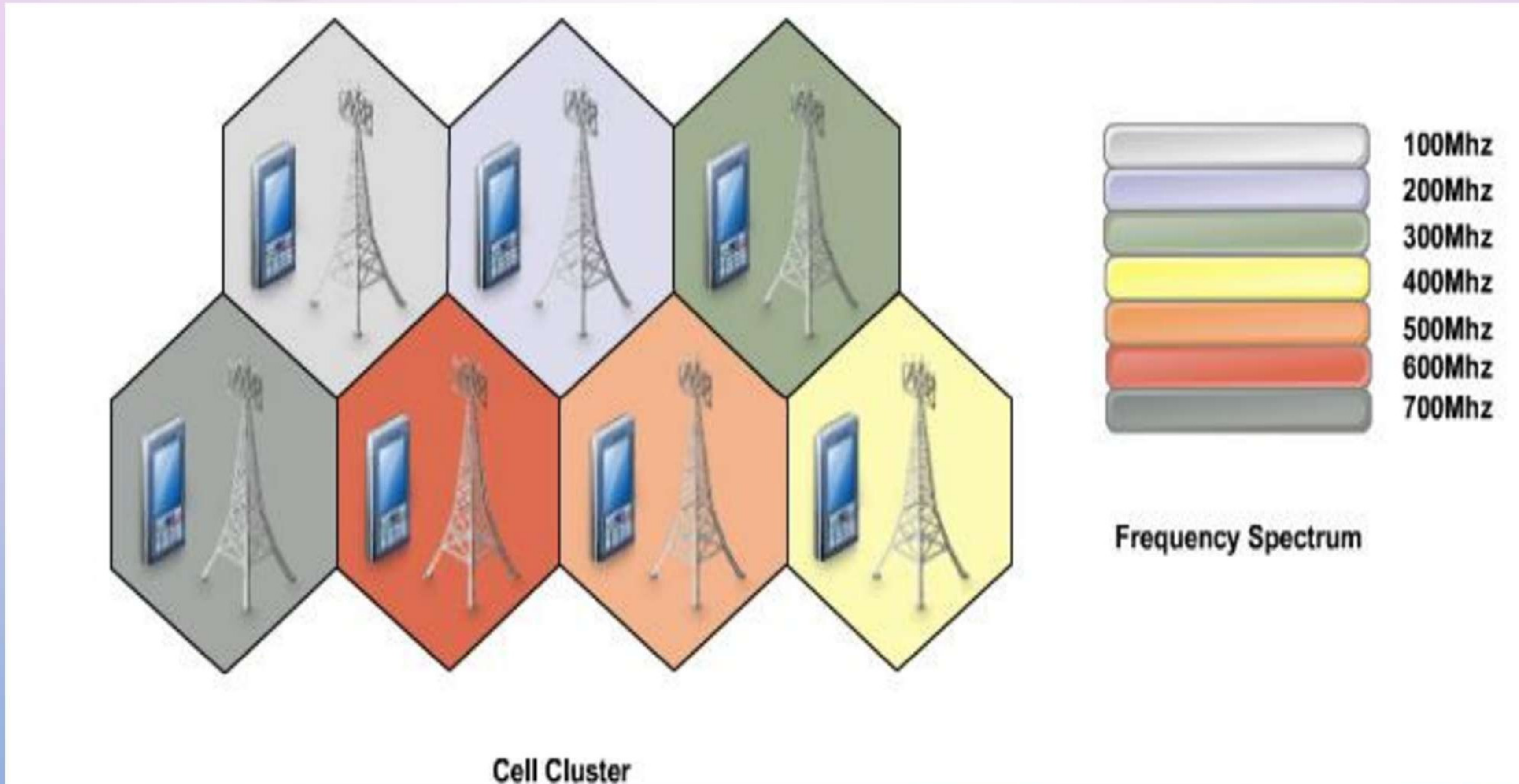
- Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell.
- Base stations in adjacent cells are assigned channel groups which contain completely different channels than neighboring cells.
- The base station antennas are designed to achieve the desired coverage within the particular cell.
- By limiting the coverage area to within the boundaries of a cell, the same group of channels 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 design process of selecting and allocating channel groups for all of the cellular base stations within a system** is called **frequency reuse or frequency planning**.

An efficient way of managing the radio spectrum is by reusing the same frequency, within the service area, as often as possible

This frequency reuse is possible thanks to the propagation properties of radio waves



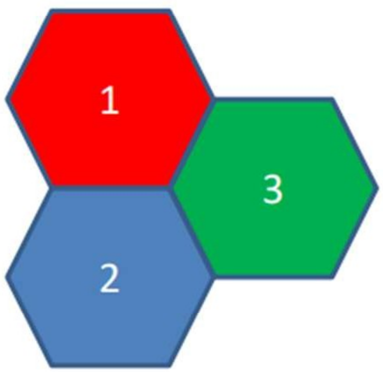

7
6
2
7
BS antenna
1
6
2
5
3
1
4
5
3
7 cell per
cluster
model
r
D
reuse
distance
4


100Mhz
200Mhz
300Mhz
400Mhz
500Mhz
600Mhz
700Mhz
Frequency Spectrum
Cell Cluster

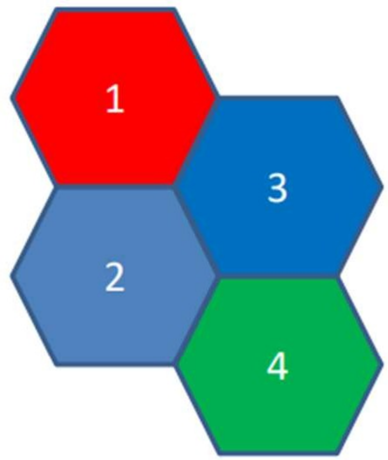
➢A cluster is a group of adjacent cells.

➢No frequency reuse is done within a cluster.

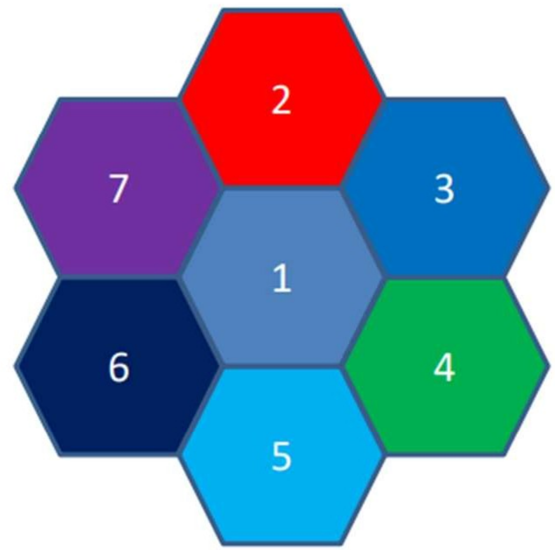
➢Number of cells in cluster $N=i^2+ij+j^2$



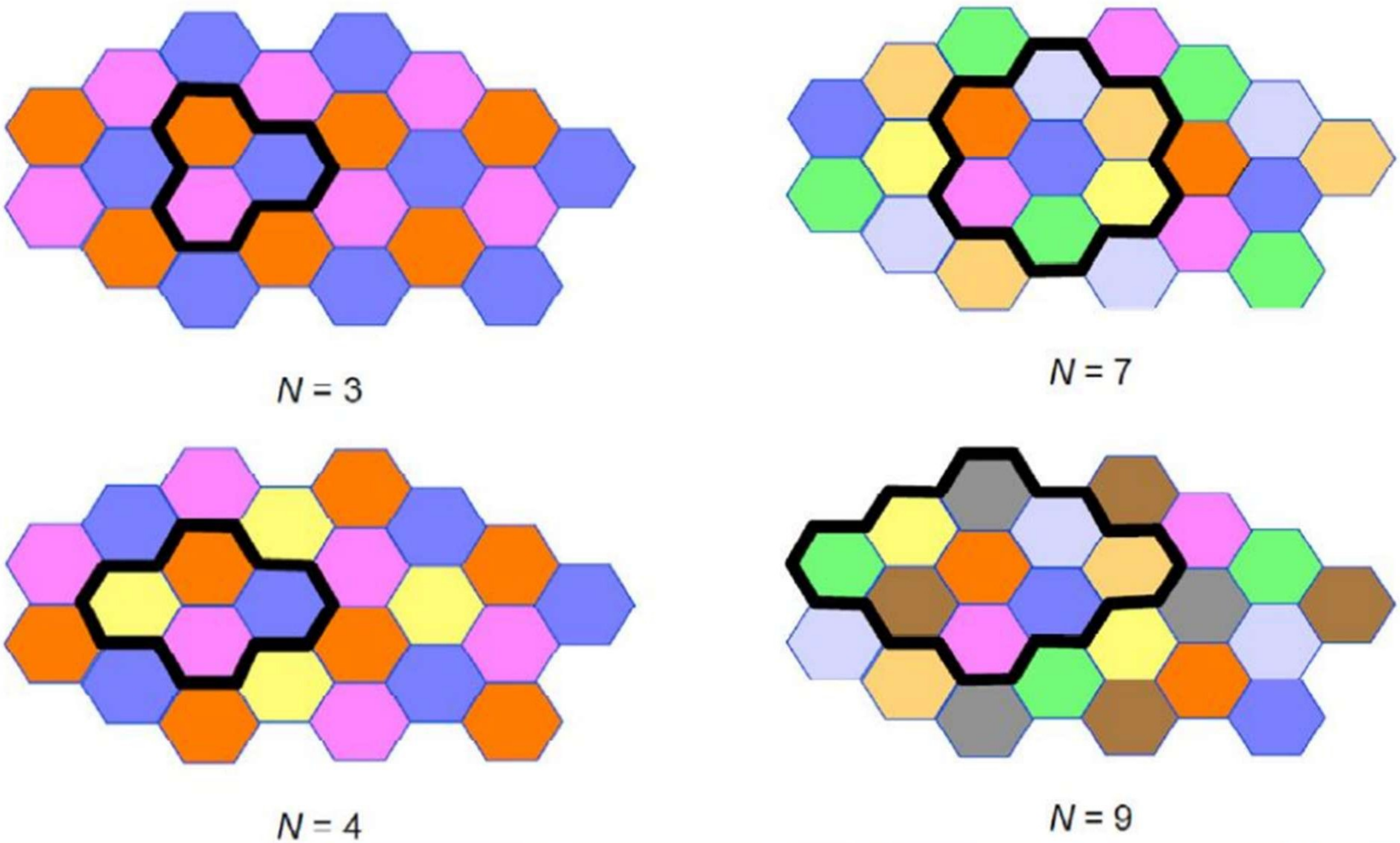

3-cell cluster




4-cell cluster




7-cell cluster


N = 3
N = 7
N = 4
N = 9

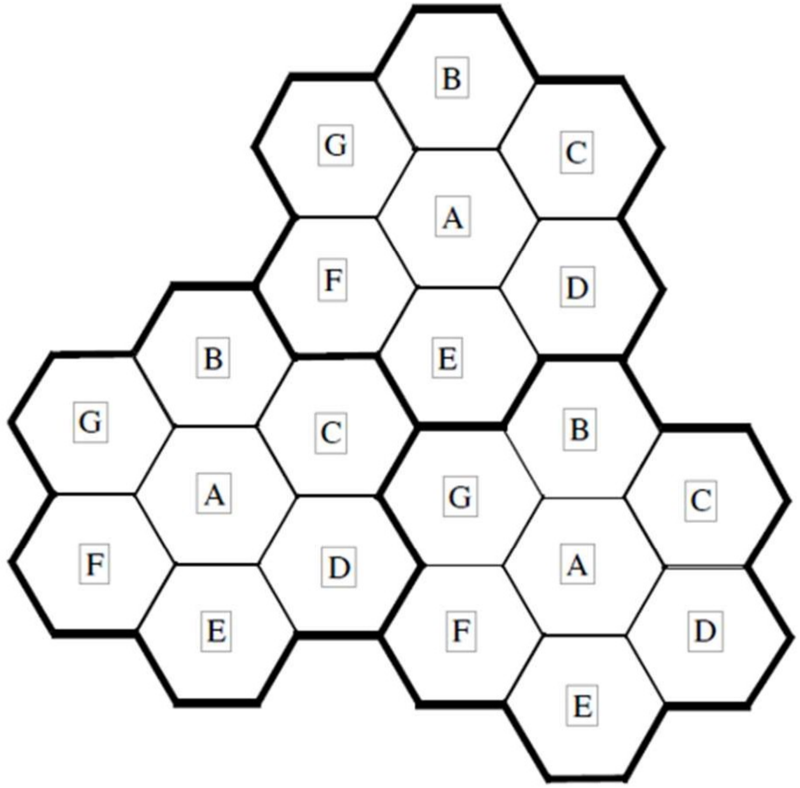



Figure: Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, N, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

# Frequency Allocation Concepts

- 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 4, 7, or 12.
- Small $N$ is desirable to maximize capacity.
- The frequency reuse factor is given by $1/N$

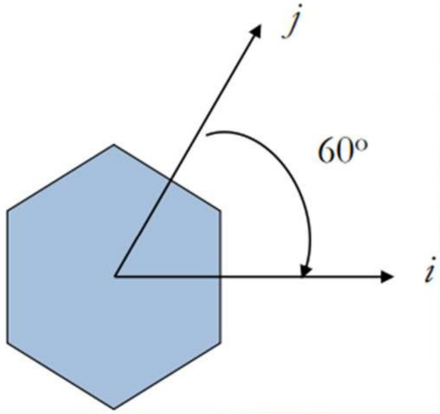
- Hexagonal geometry has
  - exactly six equidistance neighbors
  - the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees.
- Only certain cluster sizes and cell layout are possible.
- The number of cells per cluster, $N$, can only have values which satisfy

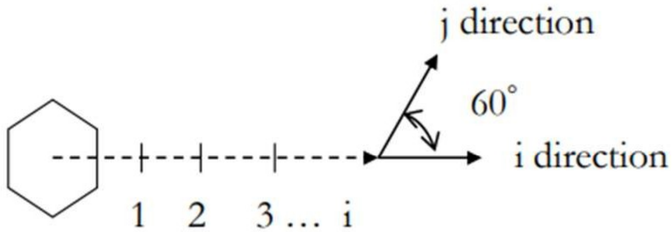
$$N = i^2 + ij + j^2$$

where $i$ and $j$ are integers.

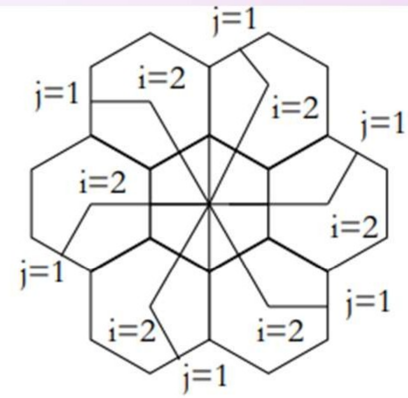
  - $N$ = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 28, …, etc.

    The popular value of $N$ being 4 and 7.

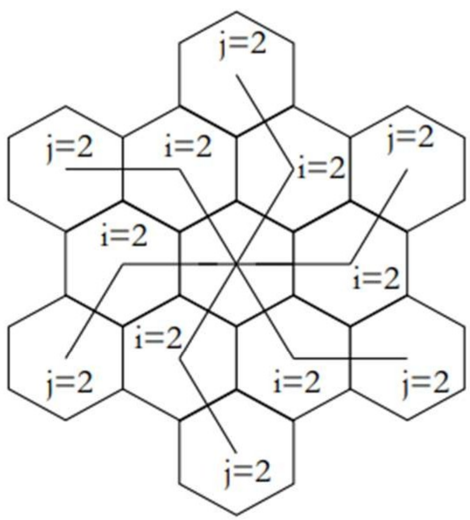




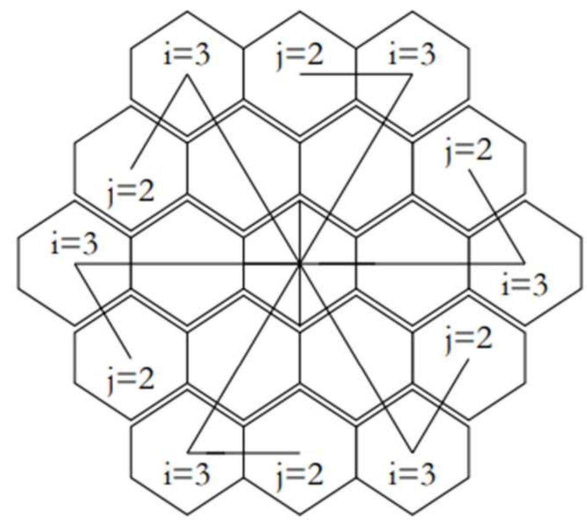

(a) Finding the center of an adjacent cluster using integers i and j (direction of i and j can be interchanged).



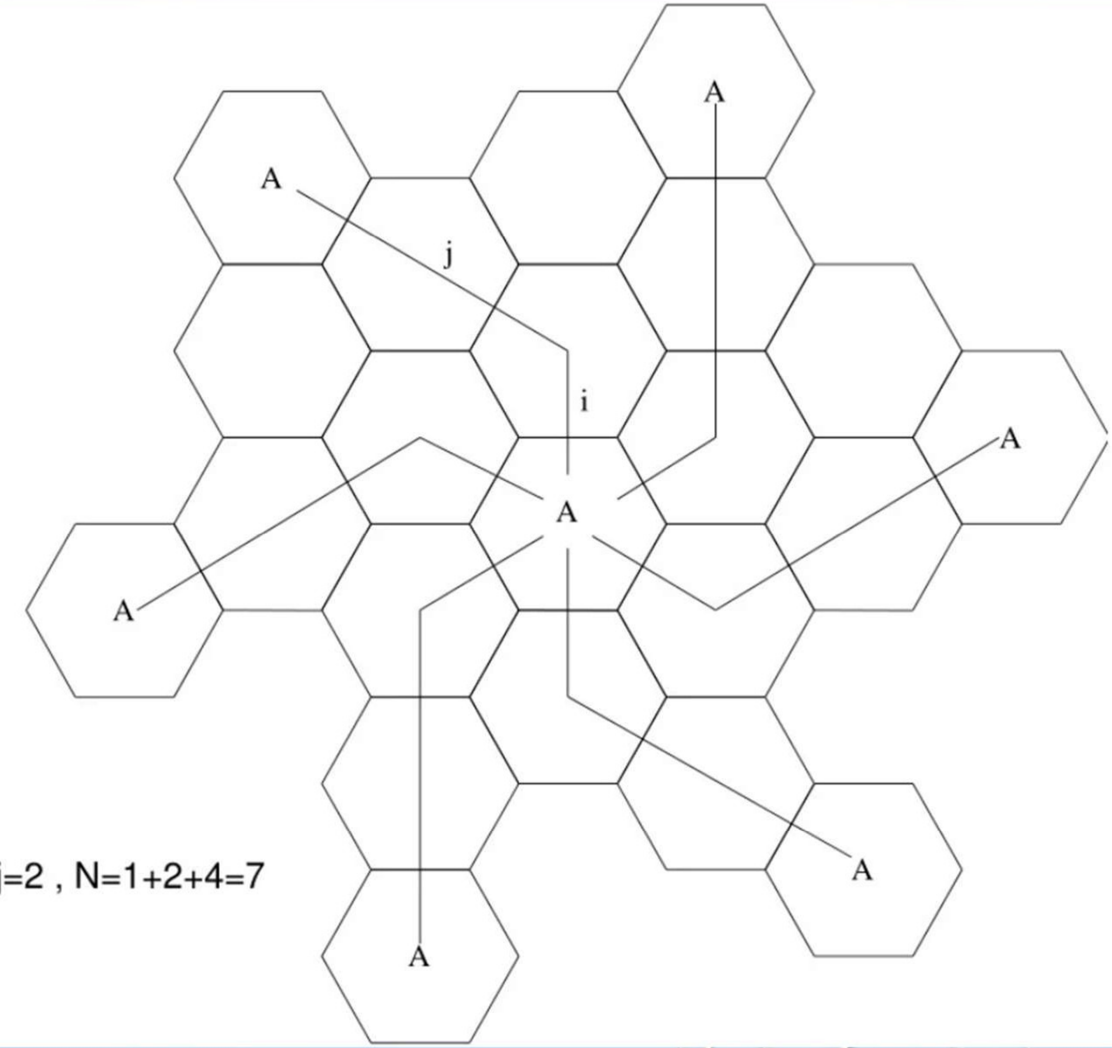

(b) Formation of a cluster for N = 7 with i=2 and j=1




(c) A cluster with N =12 with i=2 and j=2




(d) A Cluster with N = 19 cells with i=3 and j=2




i=1, j=2 , N=1+2+4=7

# Relationship between Cluster Size (N) and Reuse Distance (D)

- The **reuse distance (D)** is the distance between two cells that reuse the same frequency in the network. It ensures that the signals from these cells do not interfere with each other.
- The formula for the reuse distance **D** is:

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

Where:

  - **R** is the **radius** of a cell.
  - **N** is the **cluster size**, representing the number of cells in a cluster that use unique frequencies.

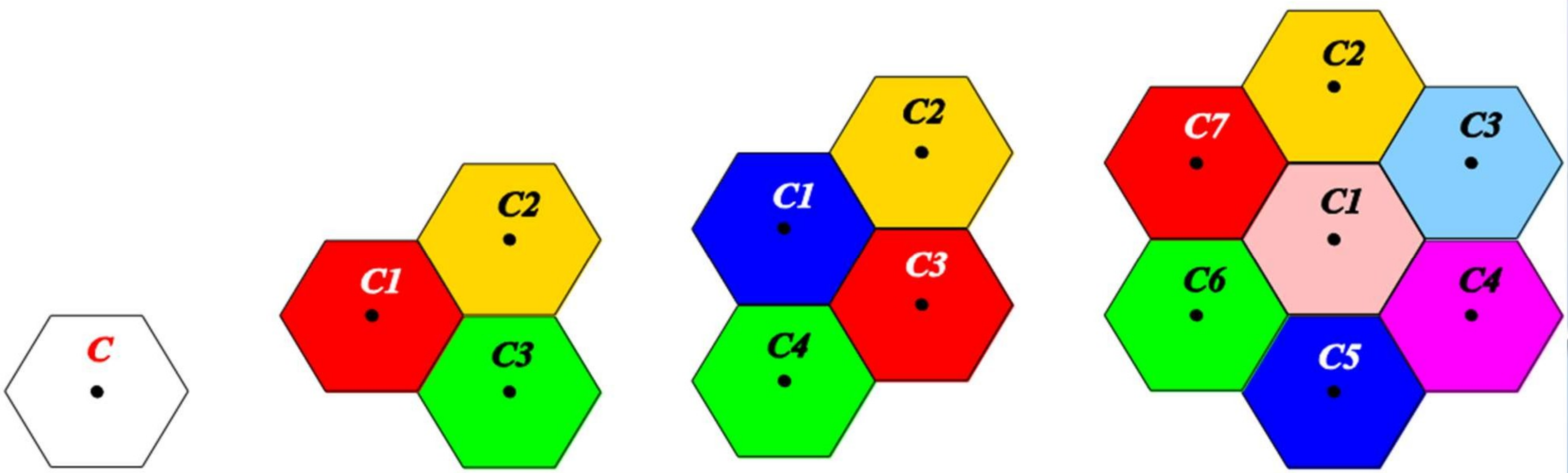
- As the cluster size **N** increases, the reuse distance **D** also increases. This means that cells using the same frequency are positioned further apart.

- For hexagonal cells, the number of cells in the cluster is given by

$$N = I^2 + J^2 + (I \times J), \quad I, J = 1,2,3,4...$$

$$N \in \{1,3,4,7,9,12,16,19,21,...\}$$

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



Numerical Example: How D Changes with N

- **Example 1**: Assume a cell radius **R = 1 km**.
  - For **N = 4**:

$$D = 1 \times \sqrt{3 \times 4} = \sqrt{12} \approx 3.46 \text{ km}$$

  - For **N = 7**:

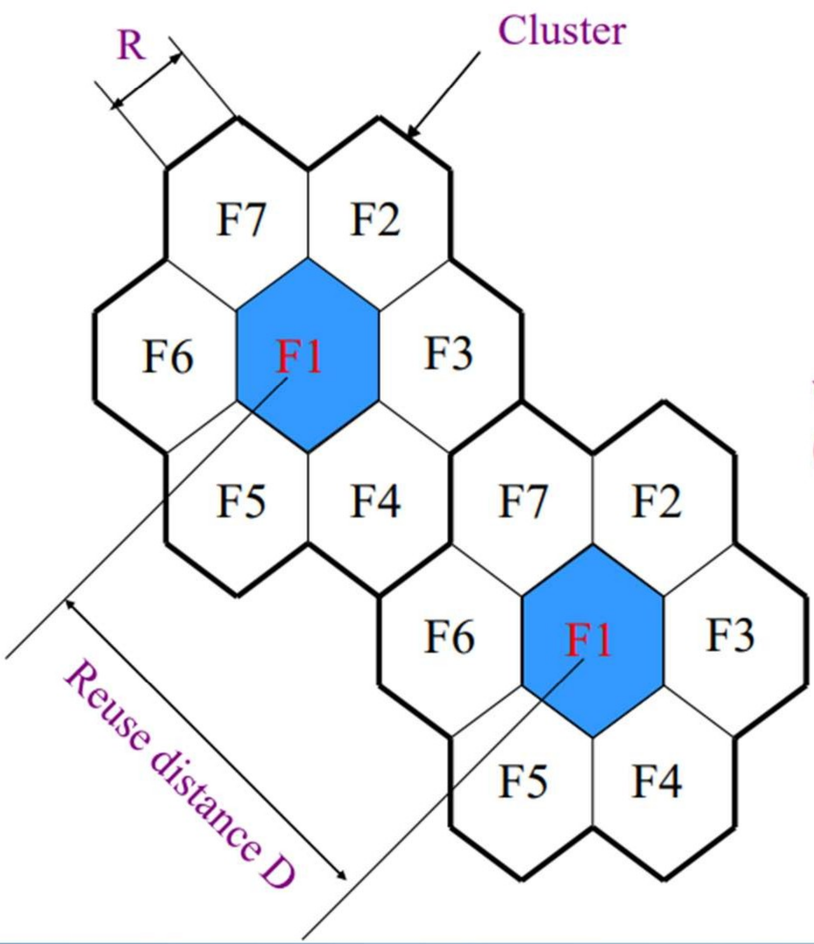
$$D = 1 \times \sqrt{3 \times 7} = \sqrt{21} \approx 4.58 \text{ km}$$

  - For **N = 12**:

$$D = 1 \times \sqrt{3 \times 12} = \sqrt{36} = 6 \text{ km}$$

- **Observation**: As **N** increases from **4** to **7** to **12**, the reuse distance **D** increases from **3.46 km** to **4.58 km** to **6 km**. This means that cells reusing the same frequency are positioned farther apart as the cluster size increases.

# Reuse Distance




- For hexagonal cells, the reuse distance is given by

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

where $R$ is cell radius and $N$ is the reuse pattern (the cluster size or the number of cells per cluster).

- Reuse factor is $$q = \frac{D}{R} = \sqrt{3N}$$

# Co-Channel Cell

- Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called c-channel cells, and the interference between signals from these cells is called co-channel interference.

# Co-channel Interference

- **Co-channel interference** occurs when cells that are too close to each other use the same frequency. The **reuse distance (D)** is crucial in determining how much interference will occur.
- As **N** increases, the **reuse distance (D)** also increases, which means that cells using the same frequency are farther apart, resulting in **less interference**.
- In the numerical example above, increasing **N** from **4** to **12** nearly doubles the reuse distance. This means that the signals from cells using the same frequency are less likely to interfere with each other, reducing co-channel interference significantly.

# Practical Example of Interference Reduction

- If **N = 4**, the reuse distance is **3.46 km**, and users in co-channel cells may experience interference, leading to call drops or poor quality of service.
- Increasing **N** to **12** makes the reuse distance **6 km**, ensuring that the same frequencies are used in cells that are much farther apart, resulting in a **better signal-to-noise ratio** and fewer interference issues.

# Impact on QoS

- **Quality of Service (QoS)** is directly affected by interference and the ability to maintain strong, reliable communication signals.
- **Increasing N Improves QoS**:
  - With a higher cluster size **N**, the reuse distance **D** increases, which minimizes co-channel interference. Reduced interference leads to a **higher quality of service**, as users experience clearer signals and fewer disruptions.
  - Higher **N** also means fewer call drops, better data rates, and improved user satisfaction.

# Practical Example of QoS and Capacity Trade-off

- If you increase **N** to improve **QoS**, it may mean that fewer calls can be handled simultaneously across the entire network. For example:
  - Suppose you have **21 frequency channels** available. If **N = 7**, each cell will be assigned **3 frequencies**, allowing for more reuse across clusters.
  - If **N = 12**, each cell will be assigned **fewer frequencies** (about **1 or 2 per cell**), which limits the number of simultaneous calls the network can support.

# Finding an Optimal Balance

- The key is to find an **optimal value for N** that balances **quality of service** and **system capacity**:
  - **Lower N**: More frequency reuse, increased capacity, but also **increased interference**.
  - **Higher N**: Less interference, improved QoS, but also **lower capacity** due to fewer frequency reuses.
- **Designers** must consider user density, traffic demands, and environmental factors to determine the best **N** value that ensures adequate **reuse distance (D)** for minimal interference while maintaining enough capacity to handle the number of users effectively.

## Summary

- **Higher N** increases the **reuse distance (D)**, reducing **interference** but also **reducing capacity**.
- **Lower N** decreases the **reuse distance**, which can lead to more **interference**, but it allows for higher **system capacity**.
- Striking the right **balance** is essential for optimizing network performance based on the **service area** and **user density**.

# Co-Channel Interference (CCI)

## Definition

**Co-Channel Interference (CCI)** occurs when multiple transmitters operate on the same frequency channel within a cellular network. This interference arises because signals from different cells using the same frequency overlap and interfere with each other.

## Causes of CCI

- **Frequency Reuse:** Cellular networks divide regions into cells and reuse the same frequency channels in non-adjacent cells to maximize spectrum efficiency.
- **Insufficient Reuse Distance:** If cells using the same frequency are too close, their signals can interfere.
- **High Traffic Demand:** Increased demand may lead to more frequent reuse of frequencies, heightening the potential for CCI.

## Impact of CCI

- **Degraded Signal Quality:** CCI can reduce the Signal-to-Interference Ratio (SIR), leading to lower data rates and higher error rates.
- **Reduced Capacity:** Excessive CCI may limit the number of users that can be effectively served in a given area.
- **Increased Call Drops:** Poor signal quality due to CCI can result in more frequent call disconnections.

## Mitigating CCI

- **Optimal Frequency Planning:** Carefully planning which frequencies are reused in which cells to maximize reuse distance.
- **Directional Antennas:** Using antennas that focus energy in specific directions can reduce interference.

# Adjacent Channel Interference (ACI)

## Definition

**Adjacent Channel Interference (ACI)** occurs when signals from neighboring frequency channels interfere with each other. Unlike CCI, which involves the same frequency, ACI happens between different but closely spaced frequencies.

## Causes of ACI

- **Spectral Overlap:** Imperfect filtering can cause parts of a signal to spill over into adjacent channels.
- **Wide Bandwidth Signals:** Signals with large bandwidths are more susceptible to spilling into adjacent channels.
- **High Power Transmission:** Strong signals can more easily interfere with adjacent channels.

## Impact of ACI

- **Interference Between Channels:** ACI can cause data corruption, leading to errors in transmission and reception.
- **Reduced Quality of Service (QoS):** Similar to CCI, ACI can lower data rates and increase error rates.
- **Limited Frequency Reuse:** ACI imposes stricter limits on how closely frequencies can be spaced, potentially reducing the overall frequency reuse efficiency.

## Mitigating ACI

- **Improved Filtering:** Using better filters in transmitters and receivers to minimize spectral spillover.
- **Guard Bands:** Introducing unused frequency spaces between channels to reduce interference.
- **Narrower Bandwidths:** Designing systems to use narrower bandwidths where possible to lessen the chance of overlap.