ΕΠΛ 427:
ΚΙΝΗΤΑ ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ
(MOBILE NETWORKS)

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Cellular Concepts

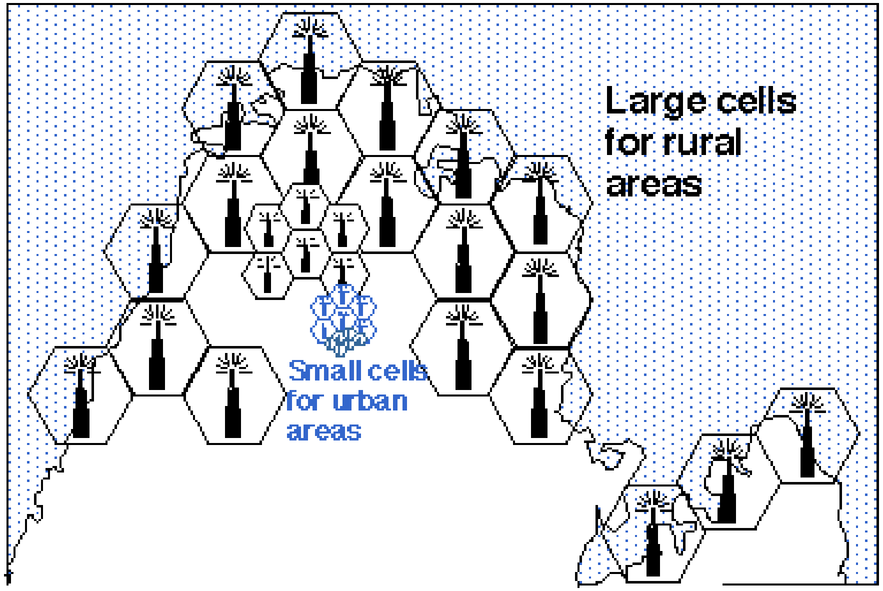
Βασικές Έννοιες Κυψελοειδών Δικτύων

Topics Discussed

- What is the main concept of Cellular Networks?
- Main Components of a Cellular Network.
- Cellular Network Advantages and Problems Encountered
- How Does Cellular Systems Work
- What are the main types of cells based on their size?
- What is the main difference between Hard and Soft Handover?
- Define the Frequency Reuse issue. What is its main objective?
- Definition of Cell Cluster.
- List the main techniques used to:
  - Decrease the Co-Channel Interference (CCI)
  - Increase the cellular system Capacity

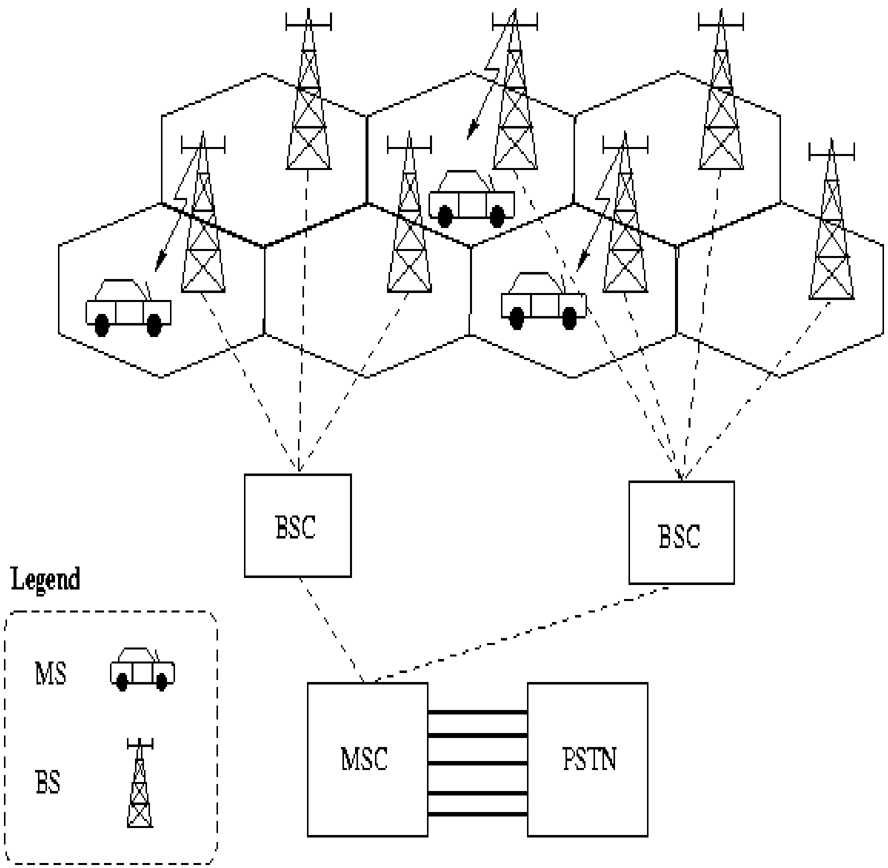
Cellular Network

- In a **Cellular Network** a **geographical area** is **split into smaller land areas** called **Cells,** each served by a fixed **Base Station (BS)**.
- A **Mobile Station (MS)** located in the Cell's area **is attached to the Network** through the **Base Station**.



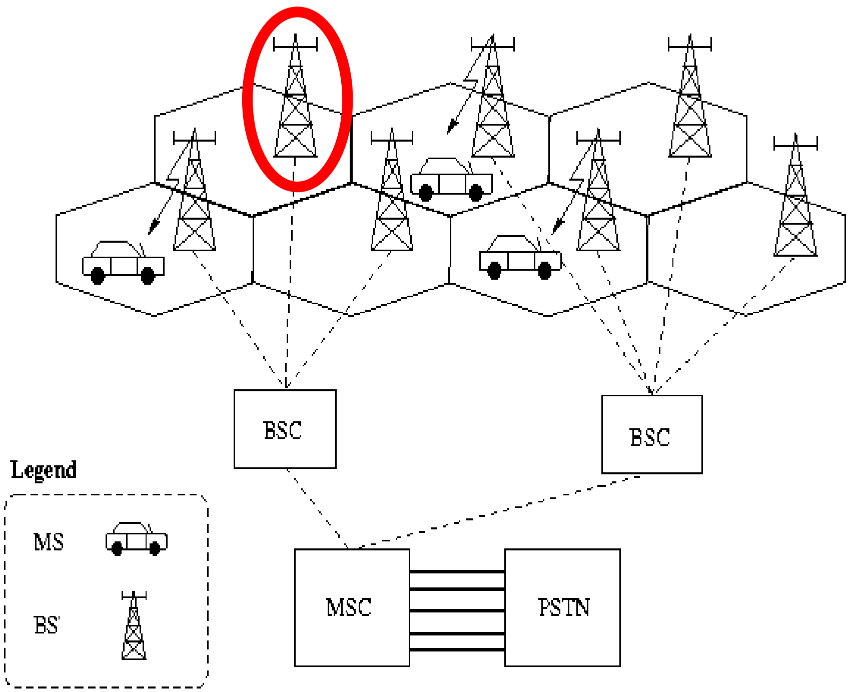
Cellular Network

- **When joined together**, these cells **provide radio coverage** over a **wide geographic area**.
- **Continues service coverage** within this area is achieved by **handoff (or handover)**, which is the **seamless transfer** of a **call** from one Base Station to the other as the **Mobile Station (MS)** crosses Cell boundaries.



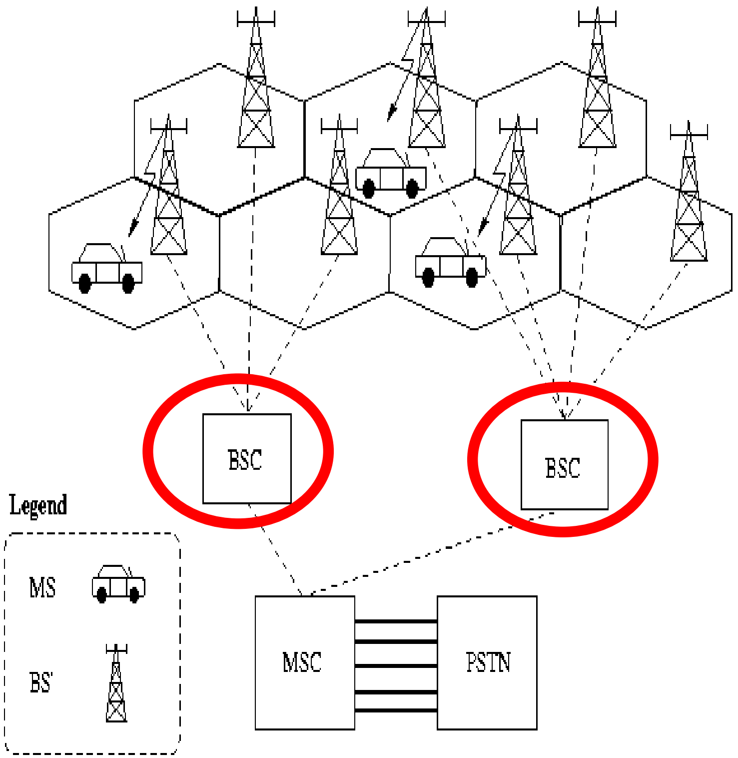
Cellular Network: Main Components Base Station (BS)

- Also known as **Base Transceiver Station (BTS)** or **NodeB (in 3G)**
- Is a piece of network equipment that **facilitates wireless communication** (i.e., is the interface) between a **Mobile Station (MS)** and the **Core Network.**
- **Mainly Responsible for establishing the physical channels (using electromagnetic waves) and relaying messages** between the **MSs** and the **Network.**



Cellular Network: Main Components Base Station Controller (BSC)

- **Provides** the **Intelligence behind** the **Base Stations. Known as Radio Network Controller (RNC) in 3G.**
- Typically a **BSC has tens or even hundreds** of **BSs under its control**
- **The BSC mainly handles/controls:**
  - **Radio Resource (Frequency) Control: Controls** and **Reserves** the **radio frequencies** that will be **used by each BS** that is **under its control.**
  - **Allocation and Deallocation of Radio channels for the MSs (e.g., frequency bands, time slots, spreading Codes)**
  - **Transmission Power of the BSs and MSs**



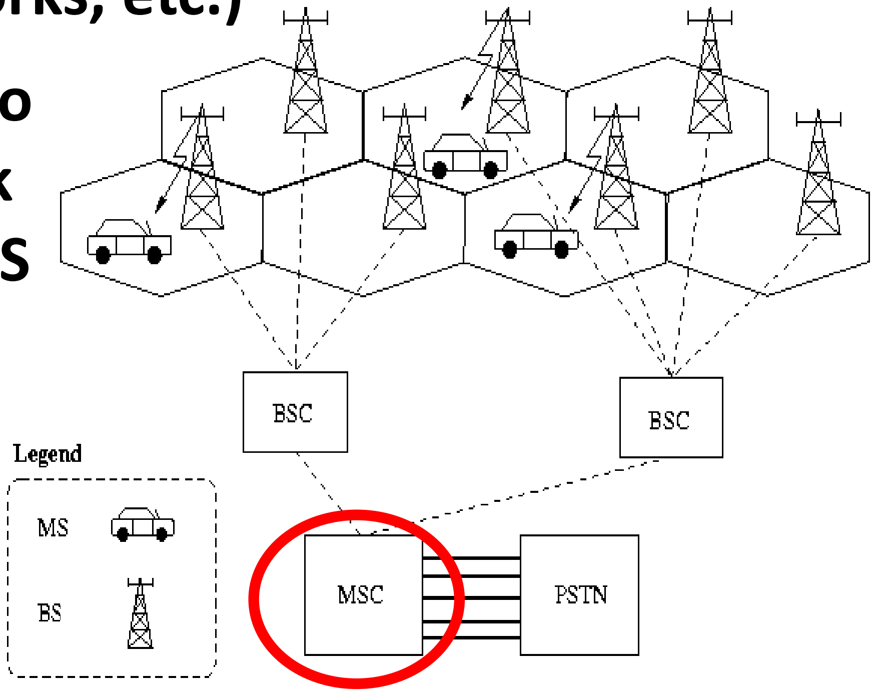
Cellular Network: Main Components
Base Station Controller (BSC)

- Paging Control to **locate a MS based on its reported location** (done in cooperation with the MSC – the **MSs' "approximate" location** is **stored** in the VLR **located in the MSC**)
- Call Setup **(allocation of needed network (RN and CN) resources) between the calling and the called MSs** (done in **co-operation** with the Mobile Switching Center (MSC))
- Controls Handovers **of MSs moving between BSs** that **are under its control**
  - Note: In the case of an **inter-BSC handover (i.e., handover between two BSs controlled by different BSCs),** handover control is part of the responsibility of the **anchor MSC**

Cellular Network: Main Components Mobile Switching Center (MSC)

- Provides the **link (connection):**
  - **Between the MSs supported by the Network's Base Stations.**
  - **To other external Networks, e.g., other PSTNs (Public Switched Telephone Networks, etc.)**

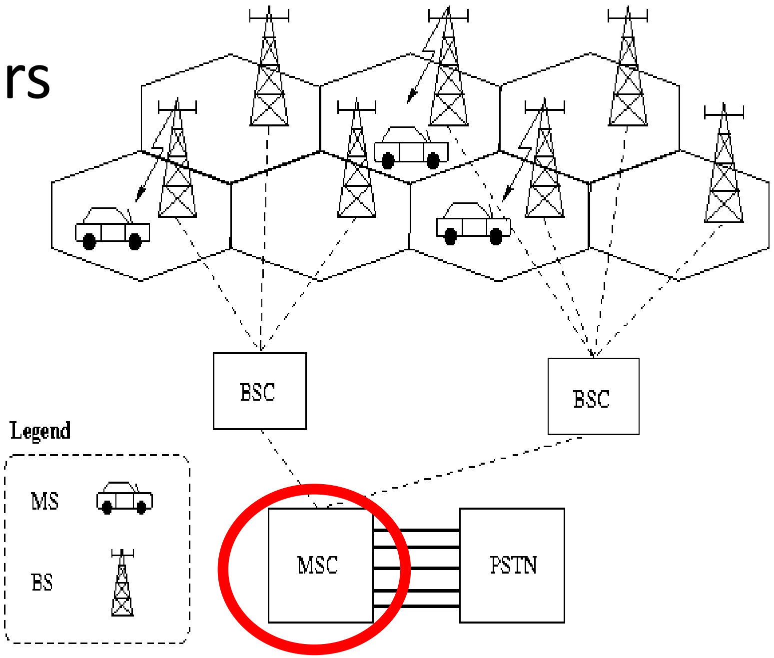
All Communications between two MSs within the Cellular Network or between a MS and another MS in another Network, travel through the MSC.



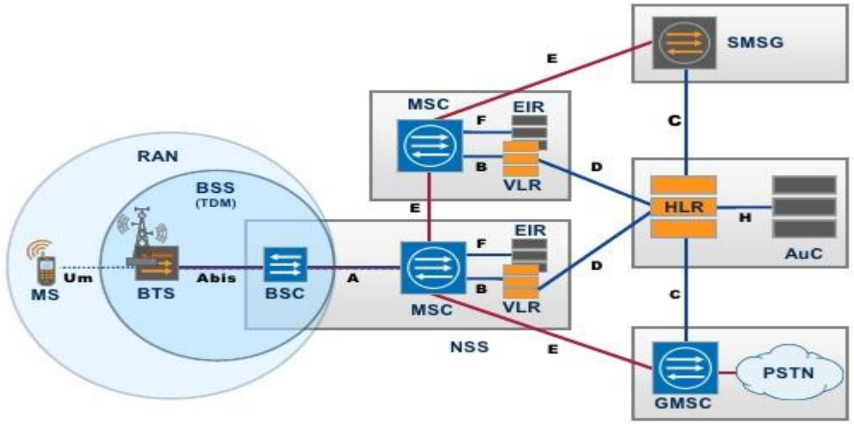
MSC has a number of BSCs under its control.

Cellular Network: Main Components Mobile Switching Center (MSC)

- Performs **functions**, such as **Call Set-up/Release** and **Routing of data** **(in association with the BSCs) to MSs**.
- **Controls Handovers of MSs moving** between cells (BSs) controlled by different BSCs (known as **inter-BSC handovers**)
- **Authenticates** and **validates** Users
- **Charge users' accounts**.

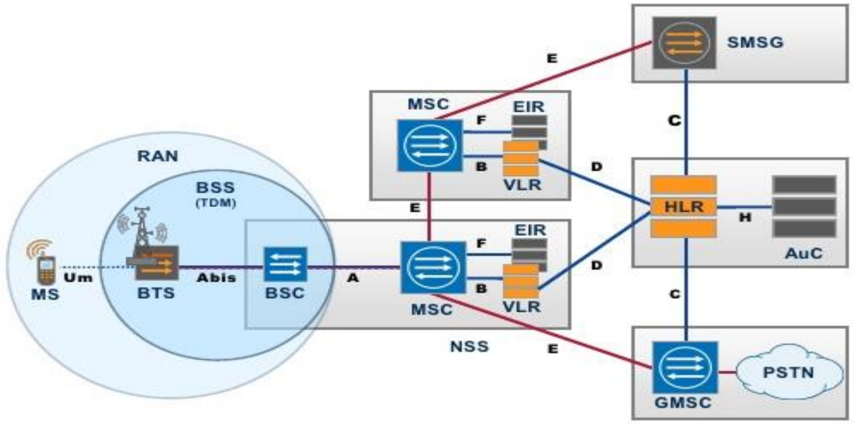


Cellular Network: MSC – HLR/VLR



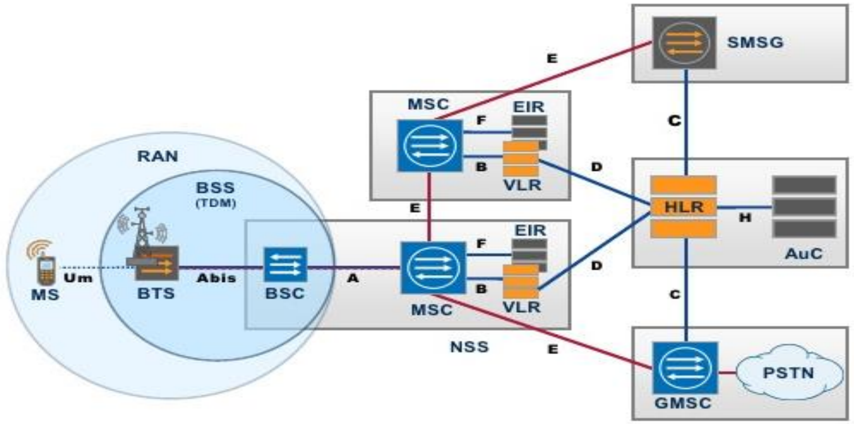
- As **Mobile Stations move, it is important for the MSC to be able to determine their "location" (i.e., at least the Cell ID that the MS is within) in the coverage area,** to **effectively facilitate routing of communications** between them.
- For this task, the Network maintains a **large database** known as the **Home Location Register (HLR),** which stores **relevant Location** for each **Mobile Station** and **other permanent information, (i.e., IMSI, Name, Identity, services supported for the customer, etc.) regarding the** Cellular Network's **subscribers**.
  - **IMSI** (**International Mobile Subscriber Identity**) **uniquely identifies the user** of the Cellular Network. Identifies also the **Country** and the **Network Operator** the User is subscribed. Stored in the **Subscriber Identity Module (SIM) card** and serves as the **primary key for each HLR record.**

Cellular Network: MSC – HLR/VLR



- Because **accessing the HLR** consumes **MSC's processing resources** **(heavy queries will have to be performed due to the great amount of subscribers records included)**, most operators employ a **Visitor Location Register (VLR)** **database in the MSCs.**
- A **VLR** is a database that **contains information** **only for the subscribers currently "active" and roaming** within the **geographical area that is supported by the MSC**.

Cellular Network: MSC – HLR/VLR



- The **MSC obtains** **information about a user currently roaming** within its coverage area, by **signaling the HLR** **where the user is subscribed,** and creates and maintains a **temporary record** **in the** **VLR** **while the user is within its coverage area.**
  - Note that the kind of **data stored in a VLR** is **similar to that stored in the HLR**, but are **not permanent.**
  - In case the user is **subscribed to another Cellular Network**, it signals the **Gateway-MSC/HLR** of that network **using the** **IMSI** **of the user.**
  - ***Recall:*** *The* ***user is uniquely "Internationally" identified by the IMSI.***

Cellular Network: Main Components MSC – HLR/VLR

- The **VLR contains the** **“location”** of **all mobile phone subscribers** **currently roaming** in the **service area of the MSC**. This information is **necessary to** **route a call** to the **right Base Station**.
- The **database entry of the subscriber** **is deleted from the VLR** when the **subscriber leaves** **the MSC’s service area**.
- The primary role of the VLR is to **minimize the number of queries** **that MSCs have to make** to the **Home Location Register (HLR)** (which holds the full list of all the users subscribed at the MSC – i.e., all the subscribers of the Cellular Network).

Cellular Network Advantages

Question: **Why** mobile network providers install several thousands of Base Stations throughout the country (**which is quite expensive**) and do not use powerful transmitters with huge cells?

Cellular Network Advantages

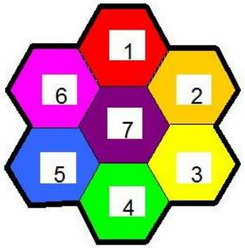
Answer: Because Cellular Network provides:

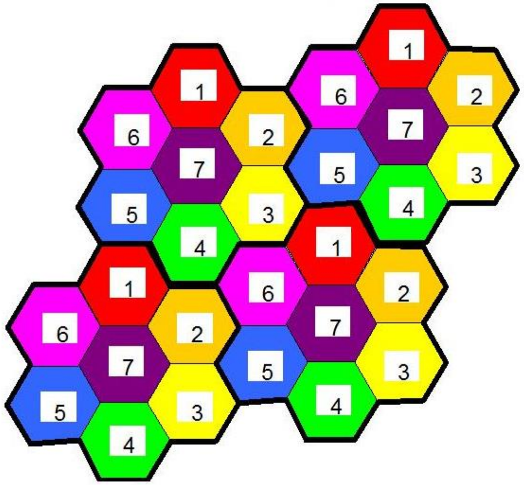
- **Higher Capacity since smaller cells are used and the frequency reuse concept is applied**
- **Less Transmission Power is required by the MS to reach the BS, and vice versa, in shorter distances → Thus less the energy consumption (improves battery life for the MSs, lower power emissions thus positive health impacts, etc.)**
- **Interference is Reduced as less transmission power is required for the signal to cover shorter distances, thus less intra- and inter- cell interference.**
- **More Robustness to the network as if one BS fails, only one small part of the network will be affected.**

Cellular Network Advantages
Higher Capacity

- Higher capacity comes from the fact that the **same radio frequencies can be reused in different smaller areas** for a **completely different transmission**
  - **"Frequency Reuse" concept:** The **same frequency band** can be **assigned to two or more cells** that are **far enough apart** such that the **radio Co-Channel Interference between them is within a tolerable limit**.

7 cell cluster. The available Bandwidth (F) is divided between these 7 cells in the cluster.





The cluster is repeated until the selected service area is covered.

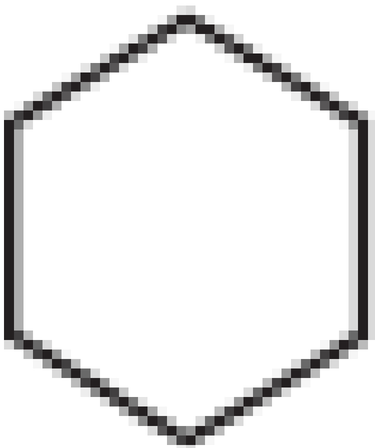
Cellular Network Advantages
Higher Capacity

- **Each Network Operator is given** a **specific amount of frequencies (Bandwidth)** that a BS can use to **establish the channels** that will be assigned to the users under its control → The **amount of channels**, and thus the number of **concurrent users** within a cell, **is limited**.
- When a **certain amount of frequencies, from the given BS's bandwidth, is assigned to a certain user**, this **frequency band is blocked for other users within the same cell**.
- Thus, **huge cells do not allow for more users!!!** On the contrary, they are **limited to less possible users per km^2**!!!

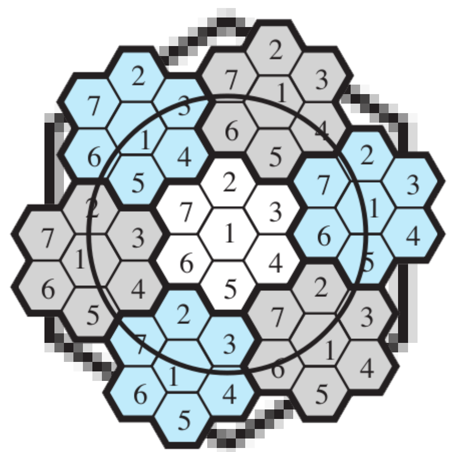
Cellular Network Advantages Higher Capacity

- Using the **Frequency Reuse concept** and a **number of smaller cells** to cover an area, **much more users can be supported per Km^2**.
- This is also the reason for **using very small cells in cities** where many **more people use mobile phones**.

Cellular Network Advantages
Higher Capacity



Only one BS supporting a large coverage area using a specific range of frequencies (F)



Frequency Reuse Concept: A number of smaller cells are used to cover the same coverage area. In this example the same cluster of cells is repeated 7 times → The same range of Frequencies (F) is reused 7 times → Can accommodate seven times more users.

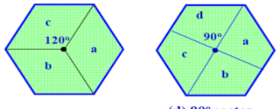
- **The number of times a cluster is re-used, is the number of times the entire spectrum (F) can be re-used → and thus the number of times the capacity is increased (more users can be supported)**

Cellular Network Advantages
Less Transmission Power Required

- While **transmission power aspects** are **not a big problem for Base Stations**, they are in fact a **very serious problem for Mobile Devices** which are **powered by batteries.**
- A **Mobile Device far away from** the **Base Station** would **need much more transmission power** for its signal to reach the Base Station.
- Thus, **with small cells** the **amount of transmission power required by the Mobile Device** to reach the BS **is reduced**,
  - So **Mobile Devices can last longer between battery charges** and **batteries can be smaller**.
- Moreover, **lower power emissions** help in **addressing health concerns**.

Cellular Network Advantages
Reduced Interference

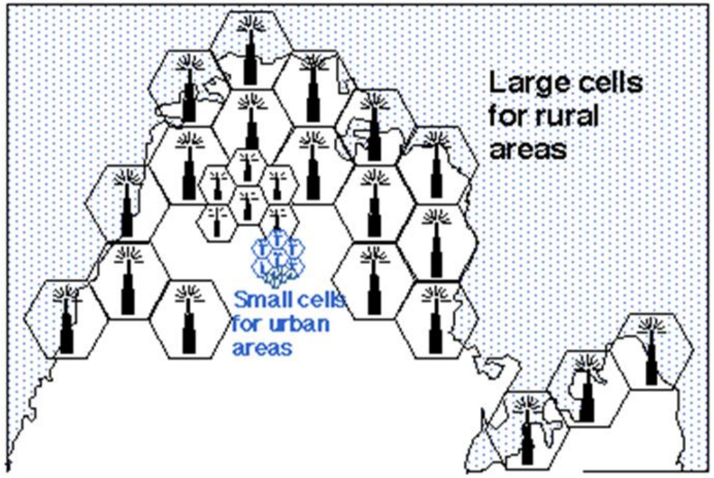
- Having **long distances between a MS** and **a BS** results in even **more interference problems** **(Longer Distance → Higher Transmission power required → more interference in the Radio Access Network)**.
- With **small cells** and the **use of "frequency reuse" concept**, the problems of **adjacent channel** and **co-channel interference** can be **greatly reduced.**
- The **interference is reduced even further** with the use of **Sectorized antennas**.



  - In Sectoring, the **cell coverage remains the same**, however **is divided into several sectors by using Directional antennas** at the Base Station instead of a single omnidirectional antenna (*we will see later how CCI is reduced*)

Cellular Network Advantages Robustness

- Cellular systems **are decentralized (i.e., uses a number of smaller cells, distributed in a large geographical area, to cover the area)** and so, **more robust against the failure of simple components**.
  - If one **antenna fails** this **influences communication only within a small area of the whole coverage**.



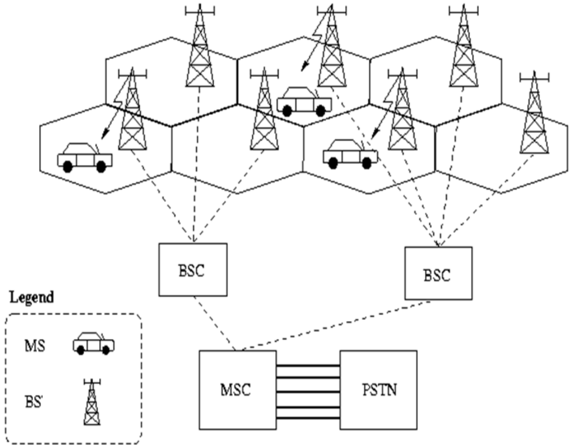
Cellular Network
Problems Encountered

- The cellular solution **resolves the basic problems of radio systems in terms of radio system capacity constraints**, but raise new problems, such as:
  - **Infrastructure Needed:** Cellular systems need a **complex infrastructure** to **connect all Base Stations**.
    - This includes **many antennas**, **switches for call forwarding**, **Location registers** to find a Mobile Device in the Network, etc., which makes the whole system **quite expensive**.

Cellular Network Problems Encountered

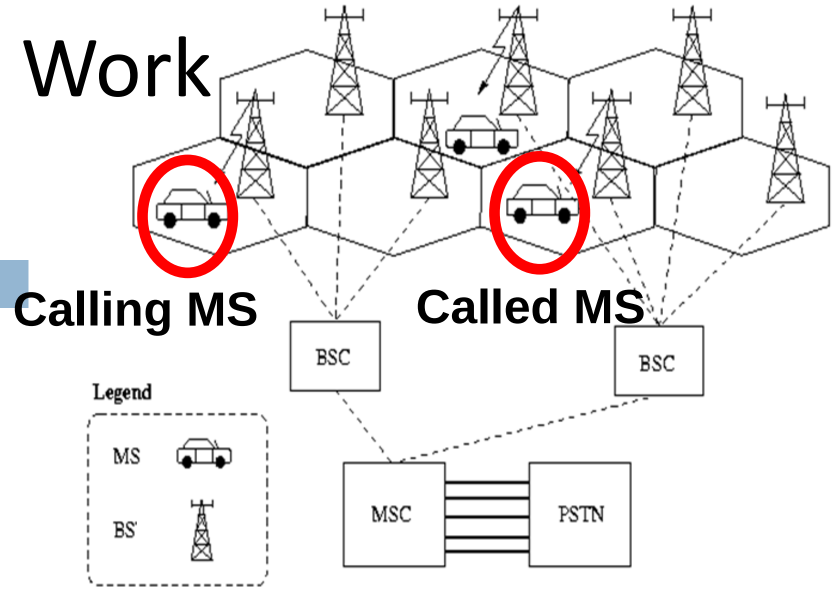
- **Problems due to Mobility:** The Mobile Device has **to perform a handover** when **changing from one cell to another → Handover Control (and also more complex Mobility Management functions) is needed!**
  - **Depending on the cell size** and the **speed** of movement, this **can happen quite often** (i.e., the **smaller the size of the cell** or the **higher the speed** of the user, **the more frequent the handovers**)

How Does Cellular System Work
Location Management



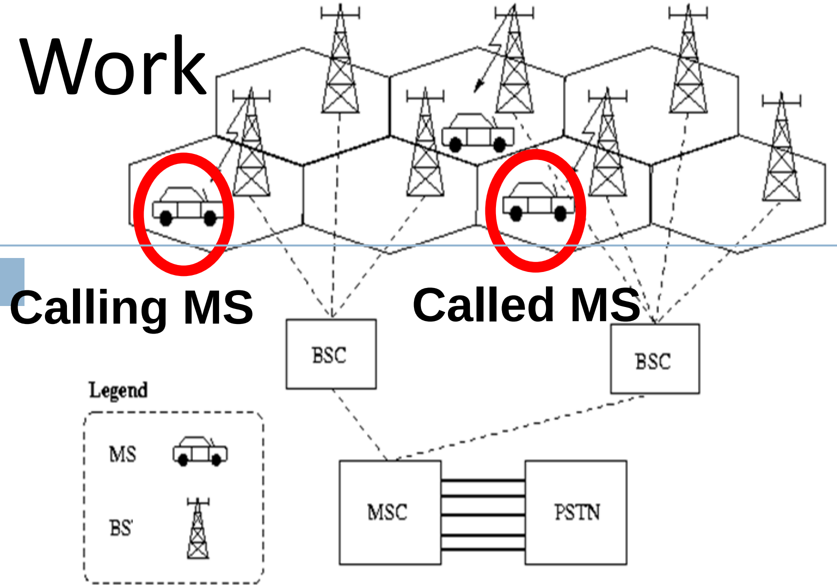
- **Aim: Track the MS in order to deliver data to it.**
  - The MS **Periodically sends Location Updates** to the MSC (these are registered in the **VLR** and later updated in the **HLR**)
  - **MSC locates the MS** by **Paging** the MS **in a group of cells (BSs)** the **MS may be located in.**
    - To **avoid signaling overhead** and **MS battery consumption**, the **Location Updates are Periodic** and **Not continuous**. Therefore we **may not know the exact BS of the MS**. → **That is why the paging message is sent to a group of cells**

How Does Cellular System Work
Paging Process



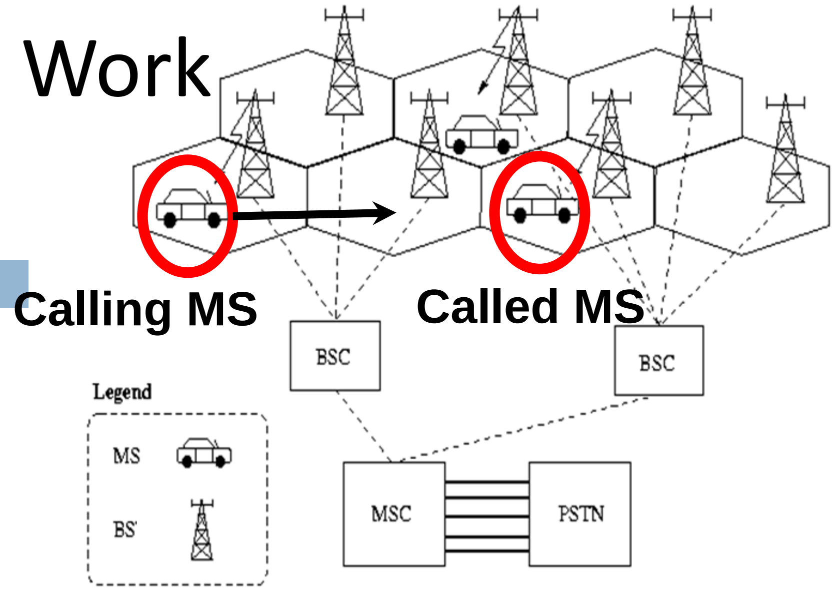
- A **MS initialize a call**, by **sending** to the **BS the Phone Number of the MS that it wants to reach**.
- The **BS relays** the **request** to **the MSC**.
- The MSC **sends a Paging message to a group of BSs (i.e., cells) that** the **called MS may be located,** based on **its location registered in the HLR/VLR.**
  - **Note that the Phone Number of the called MS (which is also unique and mapped to a unique IMSI) can be used to locate its record in the HLR/VLR**.

How Does Cellular System Work
Paging Process



- **Each BS** **(that receives the Paging message)** **broadcasts** the **Paging signal** in its cell coverage area.
  - *If the MS is not located in that group of BSs, then the MSC broadcasts the Paging Message to the next group of BSs (cells) in that Location Area.*
- The **called MS receives** **the** **Paging signal** **and** **responds to the BS**.
- **The** **BS** **then** **sends the response** **to the** **MSC and the call is established**.

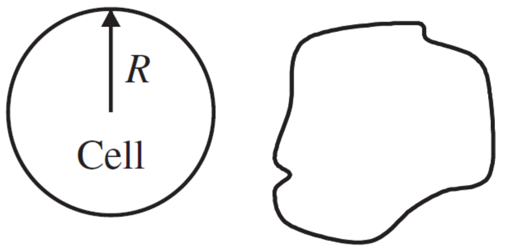
How Does Cellular System Work
Mobility Management



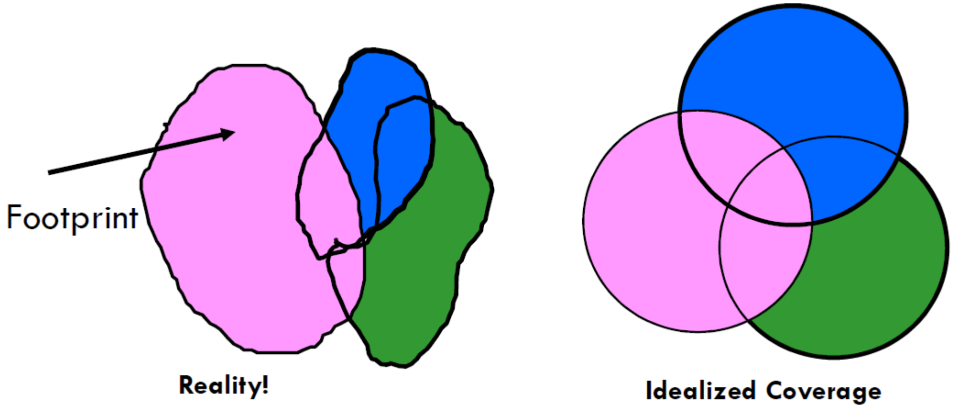
- If the **MS moves from one cell to another** during **the data exchange**, **handover** may be required:
  - **Handover:** If a **MS moves out of the range** of **one cell** and into the **range of another**, the BSC (or sometimes the MSC) **establishes and assigns another channel for the MS** in the **new cell** and **release** the **channel in the old cell**.

Cell Area

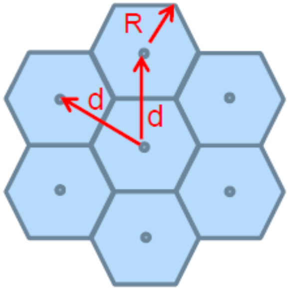
- A **cell** is the **radio area covered** by a **BS**.
- **Ideally**, the area covered by a BS can be represented by a **circular cell**, with a **radius R from the center** of the BS
- However, the **actual shape** of the cell is **determined** by the **received signal strength** in the **surrounding area**.
  - **Due to many factors** (multipath propagation, fading, terrain, mountains, tall buildings, rain, snow, etc.), the **radio area (the shape of the cell) may be a little distorted**.



(a) Ideal cell (b) Actual cell

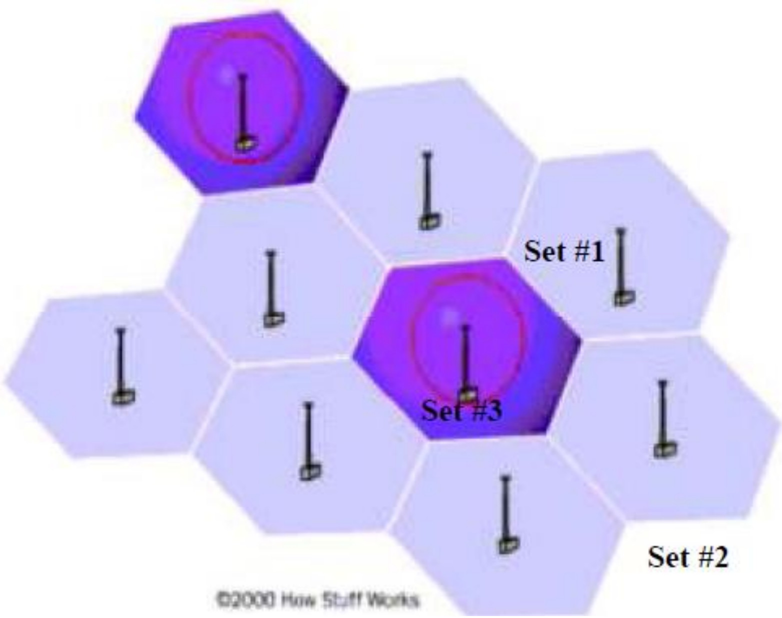


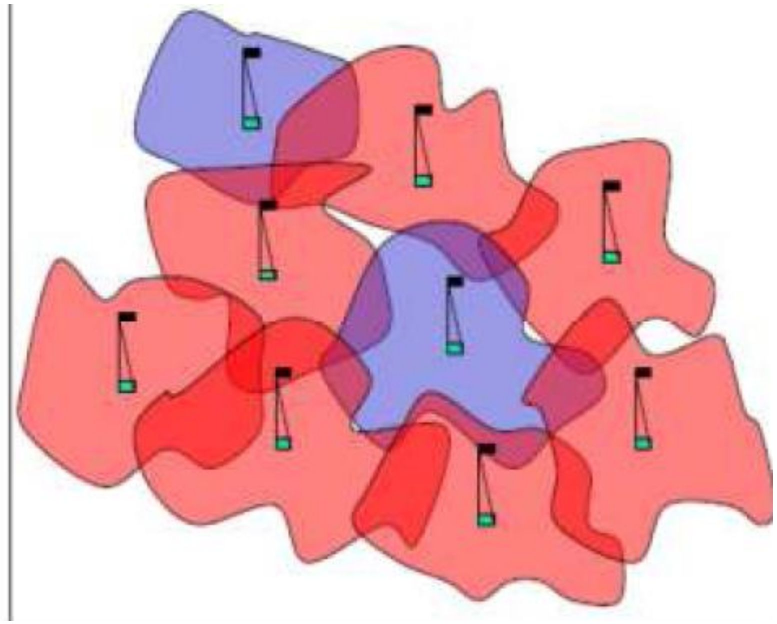
Cell Area



- In **most modeling and simulation**, **hexagons** are used.
  - **Hexagon is closer to a circle** achieved **by an omnidirectional antenna**
  - **Multiple hexagons can be arranged next to each other**, **without having any overlapping area** and **without leaving any uncovered space in between**.

Cell Area





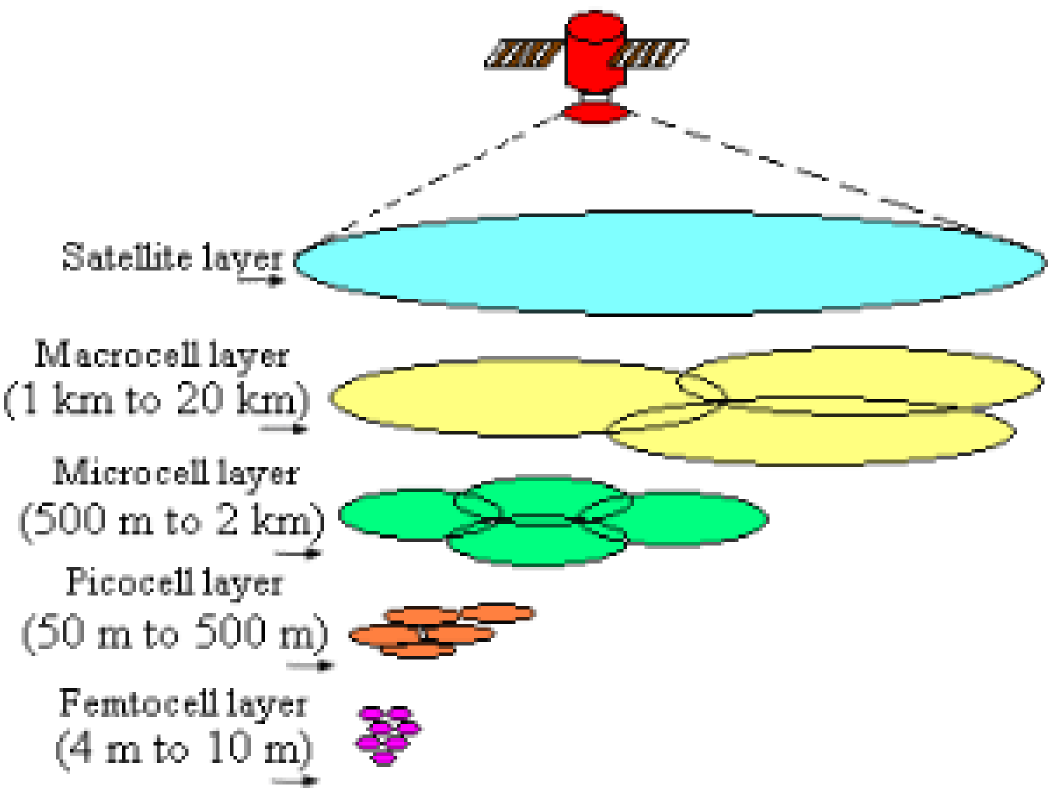
Hexagonal Shape
Used in design (simulations)

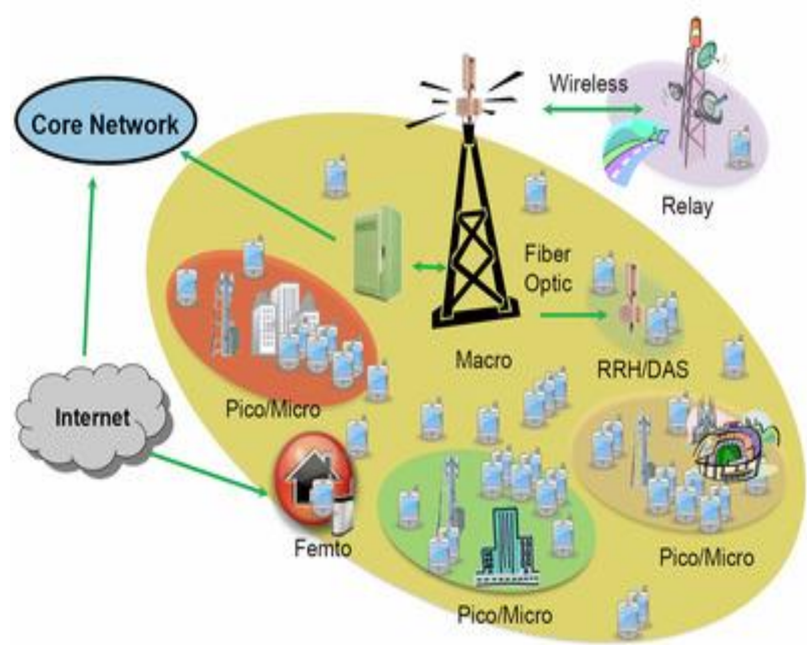
Irregular Shape
*Actual Cell Layout (**Footprint**)*

Footprint is the **actual radio coverage of a cell**. It **can be determined from field real measurements** or by using **Propagation Prediction Models** (e.g., Ocumura, Hata models, etc.)

Cell Sizes

- **Depending on their size**, cells can be categorized as **Macro**, **Micro**, **Pico** and **Femto Cells**





Cell Sizes

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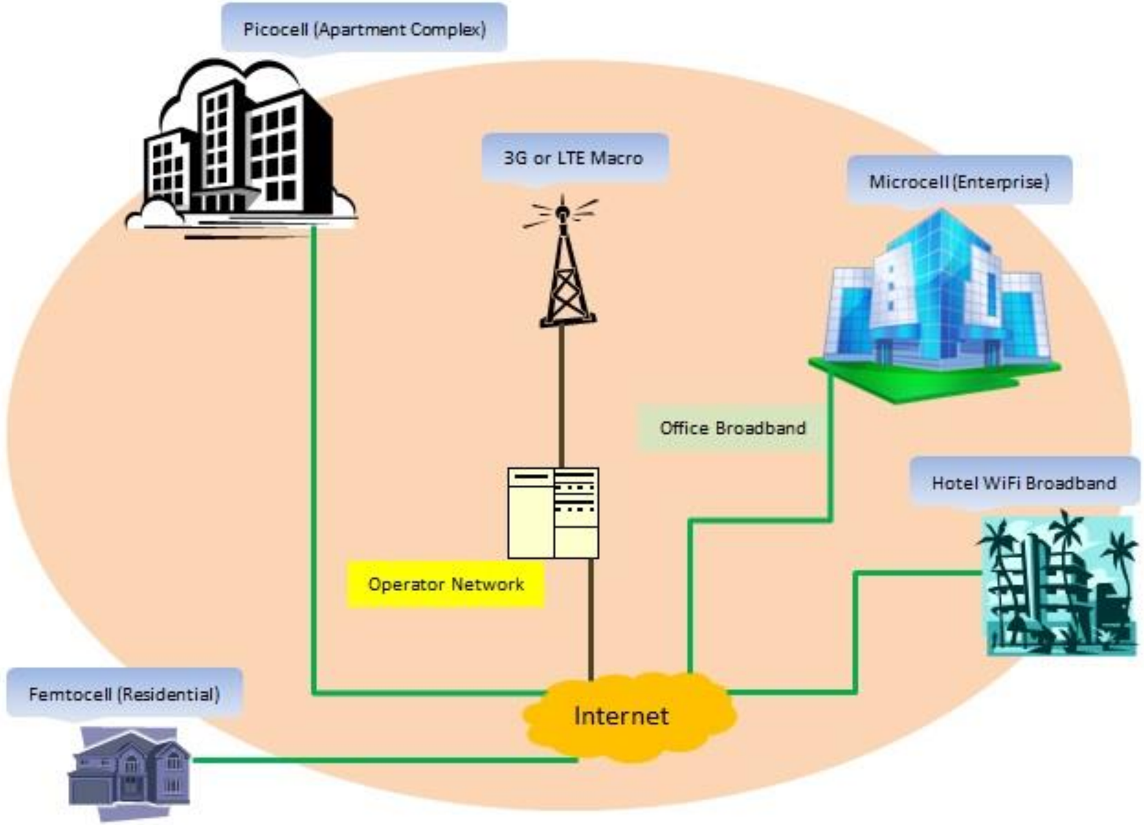
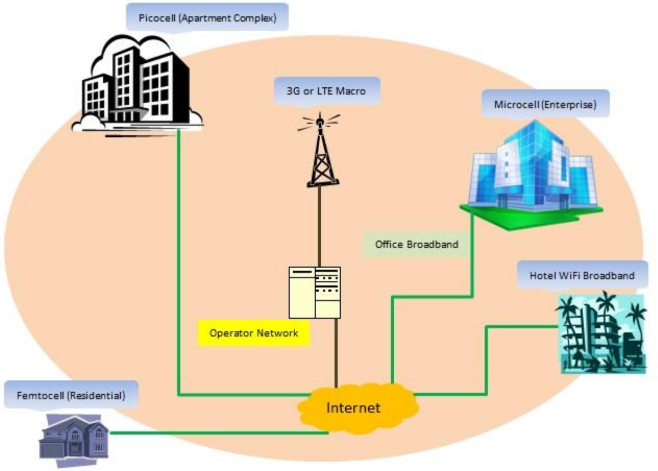


Wireless Network with Small Cells

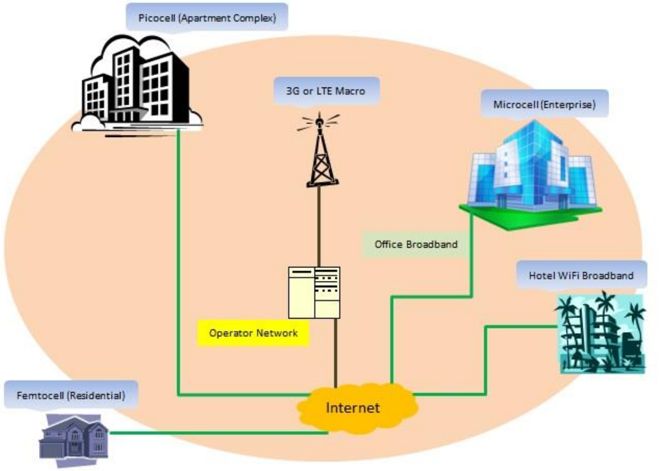
Cell Sizes – Macro Cell



Wireless Network with Small Cells

- **1 to 20 Km radius (and more…)**
- A **macro cell** provides the **largest coverage area within a mobile network** – perhaps an entire metropolitan area (e.g., area of Nicosia).
- The antennas for macro cells are placed at a **height that provides a clear view over the surrounding buildings and terrain**.
- Provides radio coverage served by a **high power (typically tens of watts) cellular BS** (tower).
- Macrocells are mainly found in **rural areas (αγροτικές περιοχές)** or **along highways**.

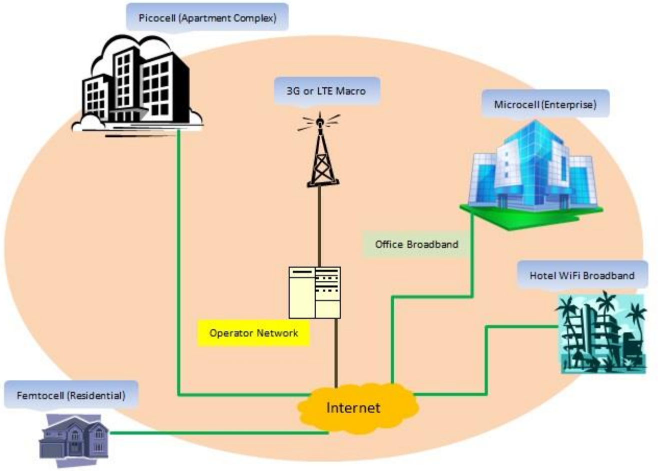
Cell Sizes – Micro Cell



Wireless Network with Small Cells

- **500 meters – 2 Km radius**
- A micro cell is a cell served by a **low power cellular BS (some watts)**, **covering a limited area.**
- Micro cells are **usually used** to **add network capacity in areas** with **very dense phone usage**, such as **train/metro stations, hot spot areas, etc.**
- Micro cells are also **often deployed temporarily during sporting events** and **other occasions** in **which extra capacity is known to be needed** at a **specific location** in advance.

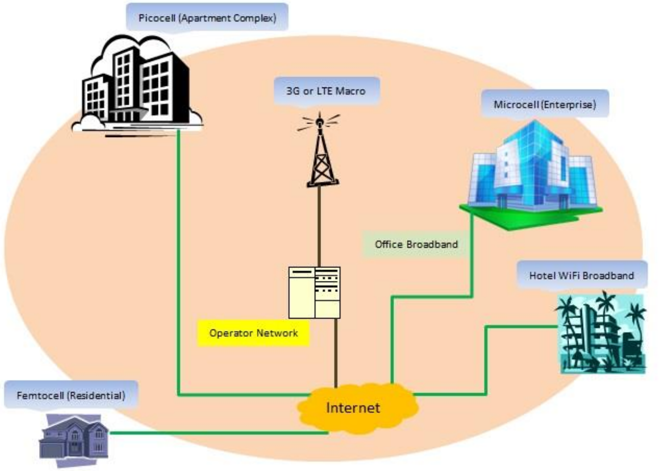
Cell Sizes – Pico Cell



Wireless Network with Small Cells

- **50 - 500 meters radius**
- **Most commonly used** for **covering a small area**, such as a **street corner**, **in-building** (offices, shopping malls, etc.), or more **recently** an **airplane cabin**.
- Typically used to **extend cellular coverage to indoor areas** where **outdoor signals do not reach well (e.g., underground metro stations)**, or si**milarly to micro cells**, to **add network capacity in areas with very dense phone usage**, such as train stations or stadiums.

Cell Sizes – Femto Cell

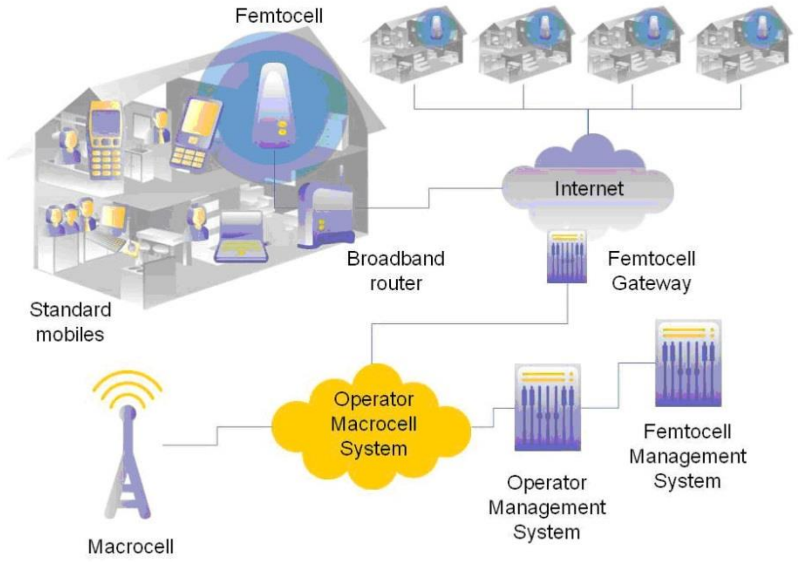


Wireless Network with Small Cells

- **4 – 10 meters radius**
- Currently, the **smallest area of coverage** that is proposed to be implemented is with **a femto cell**.
- A **femto cell** is a **small**, low-power cellular BS, typically **designed for use** in a **home** or **small business**.
- These are perhaps the **most exciting products** and **challenging technology emerging in the communications market today**.

Cell Sizes – Femto Cell

- Current designs typically support **2 to 4 active mobile phones** in a **residential setting**, and **8 to 16** active mobile phones in **enterprise settings**
- **3G/4G Connections are established between the BS of the femto cell and the MSs.**
- A Femto cell **connects the MSs** to the **service provider's network via broadband internet connection.**



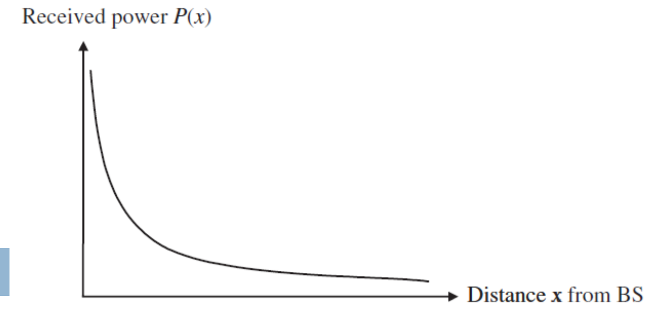
Cell Sizes

- The **sizes of cells** can be different **depending on the environment and the purpose that will be used**.
- Cells designed to cover **suburban/rural areas (προαστιακές ή αγροτικές περιοχές) (where we have few users) or long highways (where the Users move with Vehicular Speeds)** have antennas **on tall towers** and **cover a large area** (**Macro cells**).
- In **urban areas (αστικές περιοχές)** antennas are usually located **low in height** and their **transmitting powers are also low**. Therefore the coverage areas are **small for two reasons**:
  - Since the **population density is high, more smaller Cells are needed so as to support more users per km^2**
  - **Buildings may block radio wave transmission**, therefore **more cells (BSs) may needed to cover an area in a city.**

Cell Sizes

LICENSED SMALL CELLS				
	Femto	Pico	Micro/metro	Macro
Indoor/outdoor	Indoor	Indoor or outdoor	Outdoor	Outdoor
Number of users	4 to 16	32 to 100	200	200 to 1000+
Maximum output power	20 to 100 mW	250 mW	2 to 10 W	40 to 100 W

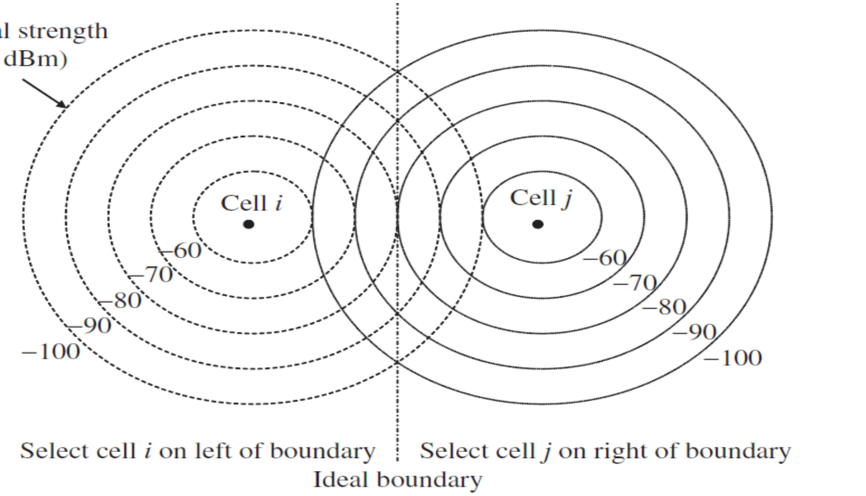
Signal Strength



- The **strength of a signal** transmitted from a BS **attenuates as it propagates longer distances** → **The longer the distance of the MS from the BS, the weaker the signal strength will become**.
- Thus, **as the MS moves away from the BS of the cell**, **the signal strength weakens,** and **at some point** a phenomenon known as **Handover, occurs**.
  - This implies a **radio connection to another adjacent cell**.

Signal Strength contours (περιγράμματα) around two adjacent cells

Ideal Case (Not feasible due to the different propagation effects caused on the signal)

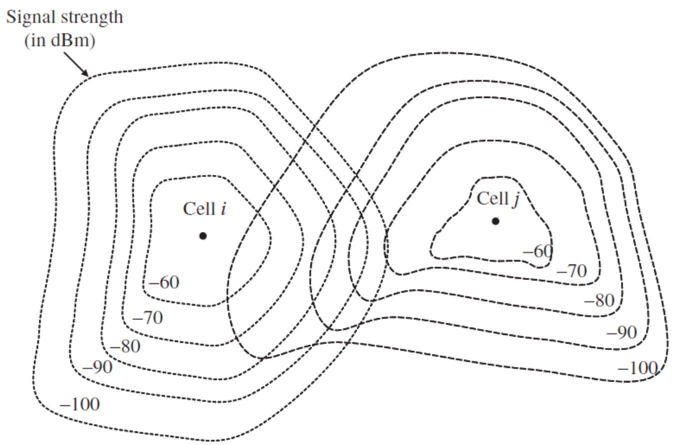


Signal Strength

- However, the **distance** is **not the only factor affecting signal strength → Environmental factors and multipath propagation affects the signal strength, too**.
- The **signal strength contours** may **not be concentric circles as signal strength** can be **distorted by a lot of factors**:
  - Atmospheric conditions, presence of obstacles, terrain, interference, noise, multipath propagation, etc.

Signal Strength contours (περιγράμματα) around two adjacent cells

Actual Case



Signal Strength

- **Recall what dBm is…**

dBm is used to denote a power level (ένταση ισχύς) with respect to 1mW as the reference power level.

Power(dBm) = $10\log_{10}$(Power/1mW)

mW	dBm
100	20
10	10
1	0
0.1	-10
0.01	-20
0.001	-30
0.0001	-40
0.00001	-50
0.000001	-60
0.0000001	-70
0.00000001	-80
0.000000001	-90
0.0000000001	-100

Signal Strength

- **Recall what dB is…**

Decibel (dB) is a logarithmic unit that is used to describe a ratio between two Power Levels (e.g., Received (P1) and Transmitted (P2) Power Levels)

$$10 \log_{10} (P1/P2) \text{ dB}$$

-40 dB means that the Received signal strength is 10,000 times weaker than the Transmitted Signal Strength

-100 dB means that the Received signal strength is 10,000,000,000 times weaker than the Transmitted Signal Strength

Decibel Conversion Table

dB	X	X		dB	X
10 dB	10	10^1		3 dB	2
20 dB	100	10^2		6 dB	4
30 dB	1,000	10^3		9 dB	8
40 dB	10,000	10^4		12 dB	16
50 dB	100,000	10^5		15 dB	32
60 dB	1,000,000	10^6		18 dB	64
70 dB	10,000,000	10^7		21 dB	128
80 dB	100,000,000	10^8		24 dB	256

Negative Decibels

dB	X		dB	X
-10 dB	1/10		-3 dB	1/2
-20 dB	1/ 100		-6 dB	1/4
-30 dB	1/ 1000		-9 dB	1/8
-40 dB	1/ 10000		-12 dB	1/16

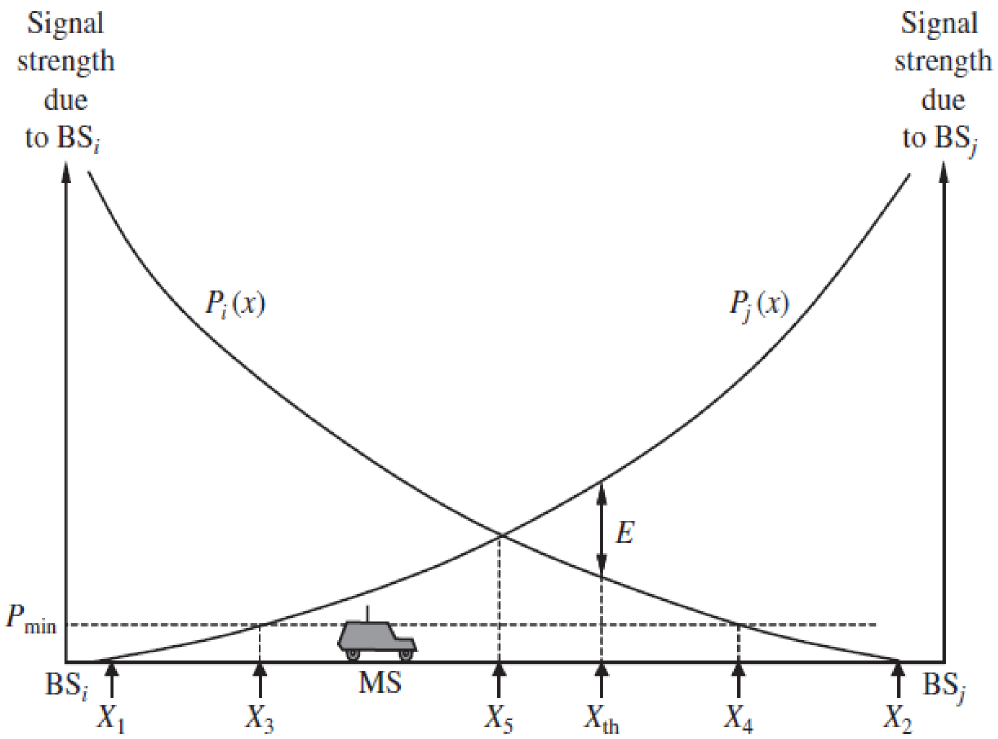
Handover Control

- **During a call**, a Mobile Station (MS) may **move out of coverage area of a cell** and **move into the coverage area of a different cell**
- The **Base Station Controller** (BSC; or sometimes the Mobile Switching Center (MSC)) **must identify the new BS that will handle the call.**
  - The BSC must **seamlessly transfer** the **control** of the call to **the new BS** and **assign to the call a new channel** from the available **channels of the new BS.**

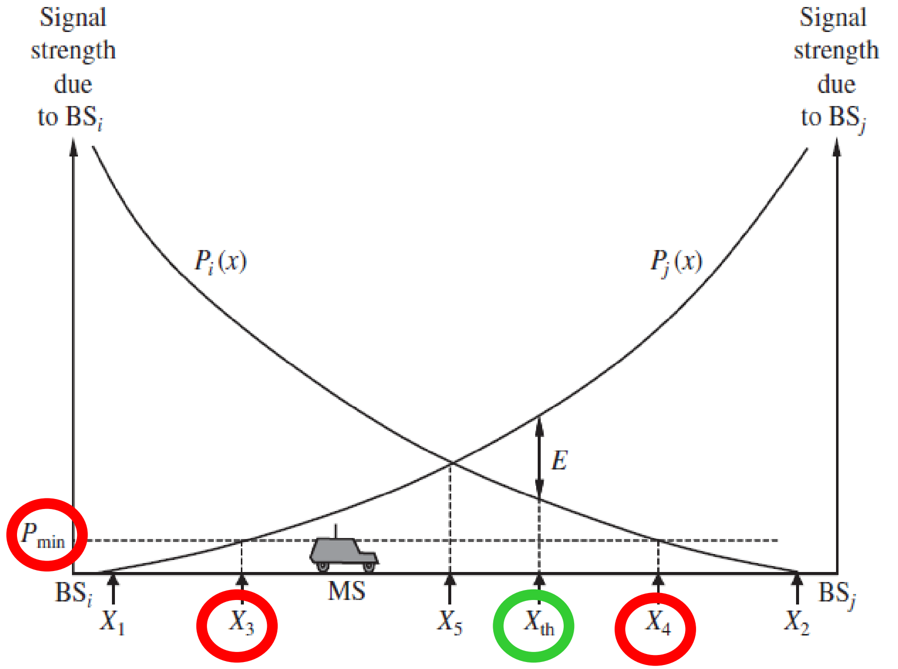
Handover Control

Handover algorithm: The Handover from BS_i *(**the Old or Current Cell**) to* BS_j *(**the New or Target Cell**) is triggered when the CPICH Signal Strength received* from BS_j *(**$RSSI_{j\_NEW}$**) exceeds the CPICH Signal Strength received from* BS_i *(**$RSSI_{i\_OLD}$**) by a pre-defined threshold* ***E*** ***(e.g., $RSSI_{j\_NEW}$ - $RSSI_{i\_OLD} \geq E$)**.*

RSSI: Received Signal Strength Indicator

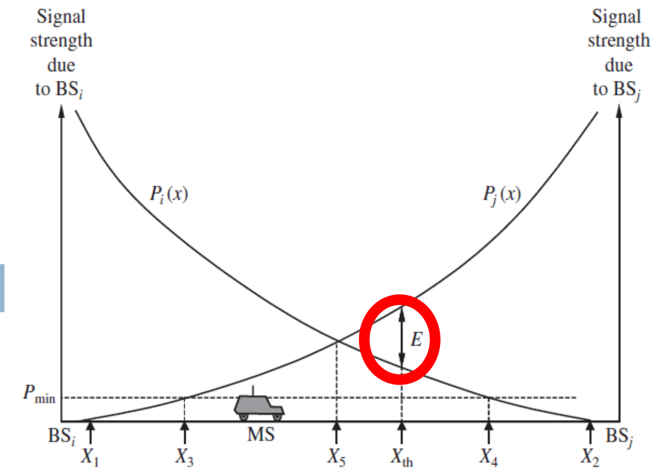


Handover Control



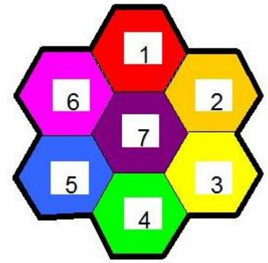
- **P_{min}** denotes the **minimum power level (i.e., the minimum RSSI received from CPICH) that the signal should have** at the MS so **as to receive and interpret the signal correctly.**
- Thus, in the **region between** the points **X_3** and **X_4** the MS **can be served by both *BS_i and BS_j***
- Therefore, we **have to determine the optimum point (X_{th}) between X_3 and X_4 regions,** that the **handover must be triggered.**

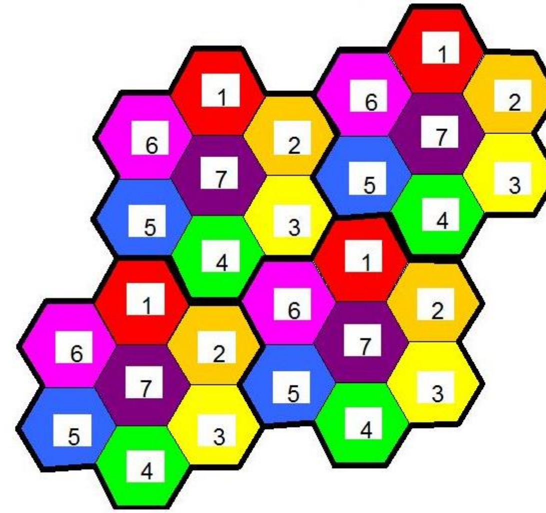
Handover Control



- **Important handover parameter determining the point of Handover Triggering is the pre-defined threshold E:**
  - **When $RSSI_{j\_NEW}$ - $RSSI_{i\_OLD}$ ≥ E → Handover is Triggered**
  - If **E too small**, **unnecessary handovers will occur** if the Mobile Station is very close to point X_5 (i.e., the **$RSSI_{j\_NEW}$ ≈ $RSSI_{i\_OLD}$**) and **moves back and forth** (Referred to as the Ping-Pong Effect).
  - If **E too large**,
    - The **$RSSI_{i\_OLD}$** may become **too weak and the signal will be lost**
    - **The downlink transmission power used by the old Cell will be "unnecessarily" increased to reach the MS in greater distance.**
  - **Thus the threshold E should be selected with care so as to avoid the aforesaid inefficiencies**

Frequency Reuse



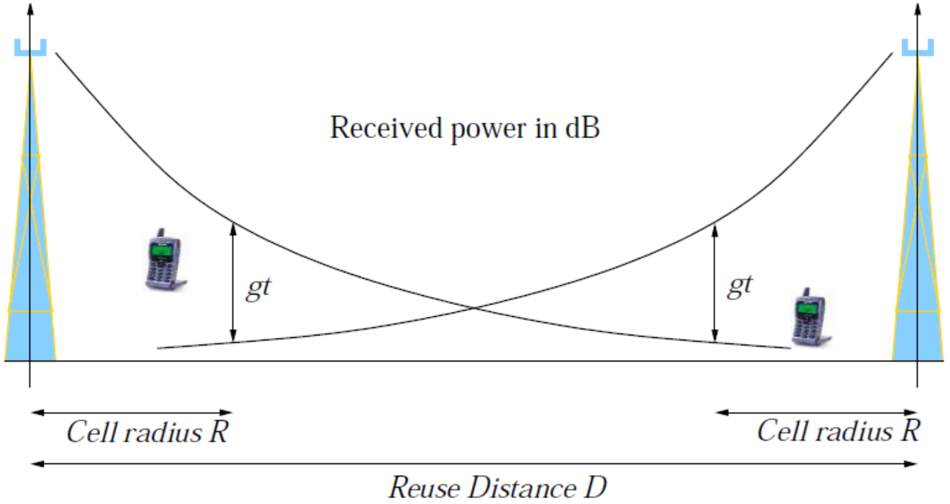


- **"Frequency Reuse" Concept:** The **same frequency band** can be **assigned to two or more cells** that are **far enough apart** such that the **radio co-channel interference between them is within a tolerable limit**.

- With this concept, **higher capacity** (i.e., more users can be served by the network) can be achieved as the **same radio frequency band** can be **reused in different smaller areas** for a **completely different transmission.**

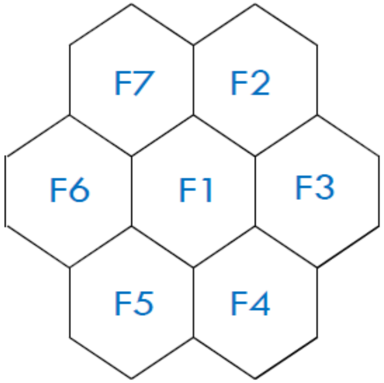
Frequency Reuse

- **Frequency reuse** is **possible thanks to the propagation properties of radio waves** (i.e., radio waves **attenuate as they travel longer distances**)
- Thus, the **BSs using the same frequency band** should be **located in a distance** (**Reuse Distance D**) **far enough apart between them** so that to keep **Co-Channel Interference (CCI) levels within a tolerable limit**.
- **The Issue is to determine how many cells must intervene, between two cells that will use the same frequency band.**



Frequency Reuse Main Steps

- Given a **Service Area (A)** and total **amount of frequencies (S; i.e., total available bandwidth)**, we mainly do the following:
  - We **form a cluster of cells**, i.e., with size **N cells.**
  - The **total amount of frequencies (S)**, are divided into **N groups** of **k amount of frequencies** each, where **S = k x N**.
    - **Each cell of the cluster** is **assigned one** of the N groups (**F_N**) each including **k** amount of frequencies (**k = S/N**).
    - All the frequencies within the cluster are **orthogonal** (i.e., **No interference between cells of the same cluster**)

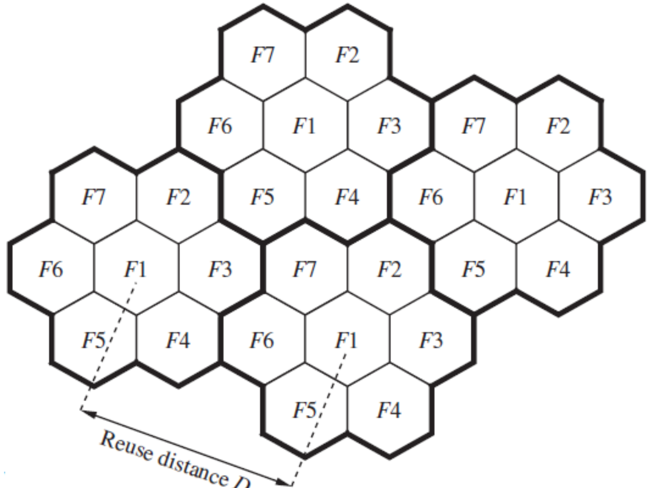


Example of a cluster with 7 cells (N = 7)

S = F1 + F2 + F3 + F4 + F5 + F6 + F7

Frequency Reuse Main Steps

- We **repeat the cluster M times** over the remaining service area **until all area A is covered.**
  - The **same group of frequencies** can **be reused by two different cells** provided that they are **sufficiently far apart (Reuse Distance D – The distance between two cells using the same Frequency Group (or channels))**.
  - The **total number of system channels (C)** is used as a **measure of capacity** of the system.
  - Given that **F** channels can be supported with **S** amount of frequencies, if the **cluster of cells is repeated M times → C = *M* x *F***

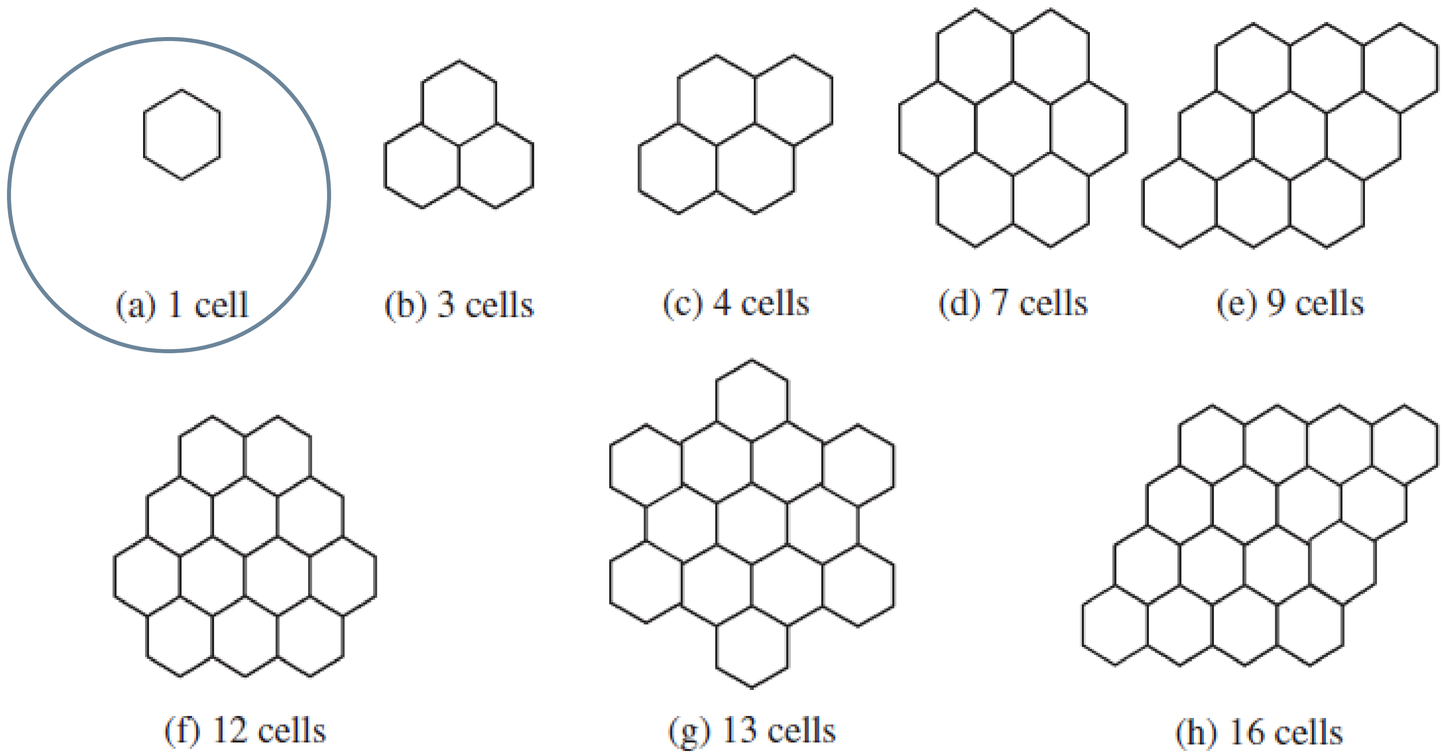


Fx: A set of frequency bands

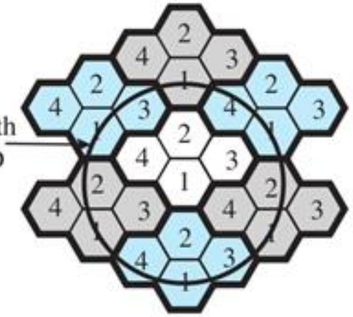
Frequency Reuse Main Steps

- **We can have different cluster sizes.**
- **Most popular is 4 cell and 7 cell clusters.**

1 cell cluster is used with CDMA (3G Networks)



Frequency Reuse – Capacity Enhancement



(a) Frequency reuse pattern for $N = 4$

Example 1: Assume we have a bandwidth (S) that can be used for 36 voice channels, and using this bandwidth we have to cover a 200 square km area.

- If we divide the area into **28 cells**, and **form clusters of 4 cells each (i.e., each group of 4 cells** can use the **entire frequency spectrum (S))**, then the **bandwidth will be used 7 times** → **With a cluster of 4 cells, the available spectrum (S) will be divided to four group of frequencies (F1, F2, F3, F4), and each group will be allocated to one cell of the cluster.**
- **Each time the entire spectrum is used**, **36 users can be supported**.
  - All together 36 x 7 = 252 users will be supported. It's a **7 time increase** of the **capacity**.

Frequency Reuse – Capacity Enhancement

Example 2: We have a **total bandwidth of 25 MHz** and **each user** requires **30 KHz** for voice communication. We need to cover the Strovolos area.

- **Scenario 1**: Only one high power antenna is used.
  - We can support **833 simultaneous users (25MHz/30KHz)**

- **Scenario 2**: 20 low power antennas are used.
  - We **divide the area into 20 cells and form clusters of 4 cells each** → We divide the **entire frequency band into 4 sub-bands** and **assign one to each cell**,
  - **Each cell will have a bandwidth** of **25MHz/4** = **6.25MHz.**

Frequency Reuse – Capacity Enhancement

Example 2 (Scenario 2 Continue….):

- The **number of simultaneous users supported by each cell** is **6.25MHz/30KHz = 208**.
- In this example, **4 cells form a cluster**. Since there are total of **20 cells, the town is covered by 5 clusters** (20/4=5).
- **Each cluster will use the entire frequency band**, so the **number of users per cluster is 833**, as calculated earlier, and **the total number of simultaneous users for 5 clusters** is **833 x 5 = 4,165 → 5 five times increased in the capacity than with** a single antenna.

Some Capacity Expansion Techniques

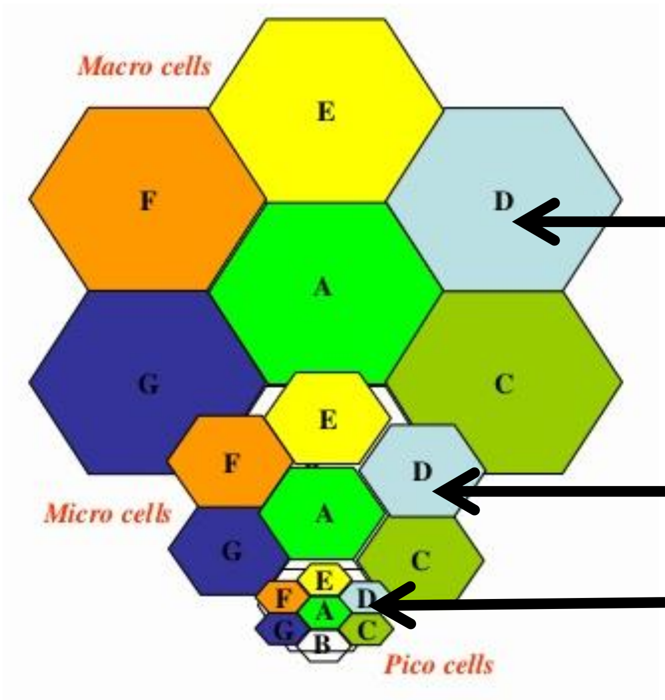
- **Frequency Borrowing:** In the simplest case, **congested cells** can **take ("borrow") frequencies from their adjacent cells**. The **frequencies** can also be **assigned to cells dynamically**.
- **Cell Splitting:** In practice, the **distribution of traffic** and **topographic features** **(i.e., the way the users are distributed in the geographical area) is** **not uniform**, and this presents opportunities of capacity increase. **Cells in areas of high usage** **can be** **split into smaller cells**.
- **Cell Sectoring:** With cell sectoring, a **cell is divided** **into a** **number of Slice shaped sectors**, each **with its own set of channels**, typically **3 or 6 sectors per cell**. Each sector is **assigned a separate subset of the cell's channels**, and **directional antennas** at the Base Station are used to **focus on each sector.**

Cell Splitting

- Until now we have been **considering the same size cell across the board**. **This implies** that **the BSs** of **all cells transmit information at the same power level** so that the **net coverage area for each cell is the same**.
- **Some times**, this **is Not Feasible, due to the terrain environment of the geographical area; e.g., high buildings, mountains, open area, etc.)**,
- And in general, this **may Not Be Desirable → Service providers** would like to **service users** in a **Cost-Effective way**, and **resource demand may depend** on the **concentration of users (i.e., traffic density)** in a **given area**.

Cell Splitting

- One way to cope with **different terrain environments** and **increased traffic** is to **split a cell into several smaller cells.**

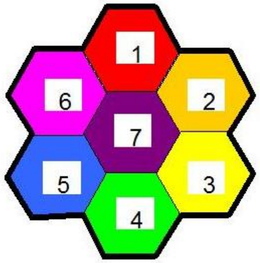


Large Cell - Macro (Low Traffic Density)

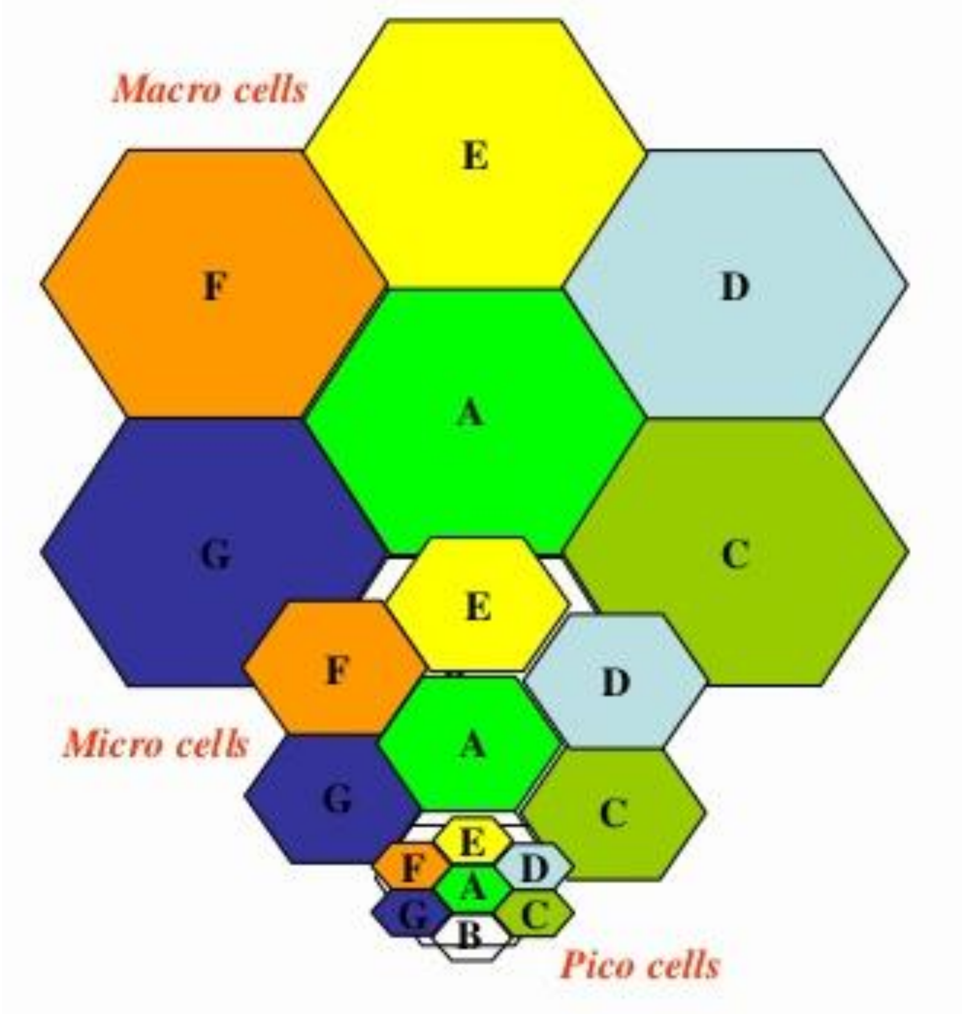
Small Cell - Micro (High Traffic Density)

Smaller Cell – Pico (Higher Traffic Density)

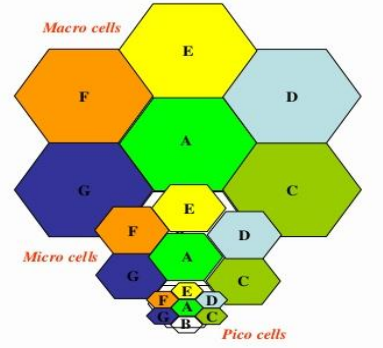
Cell Splitting – Example



- We start with macro cells to support Rural Areas – i.e., Low Traffic Density
- We split macro cells into micro cells for more crowded areas – i.e., sub urban or medium traffic Density in Urban Areas.
- Micro cells are further split into Pico cells to support high crowded areas (hot spot areas).

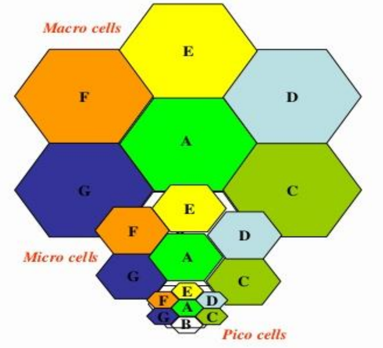


Cell Splitting



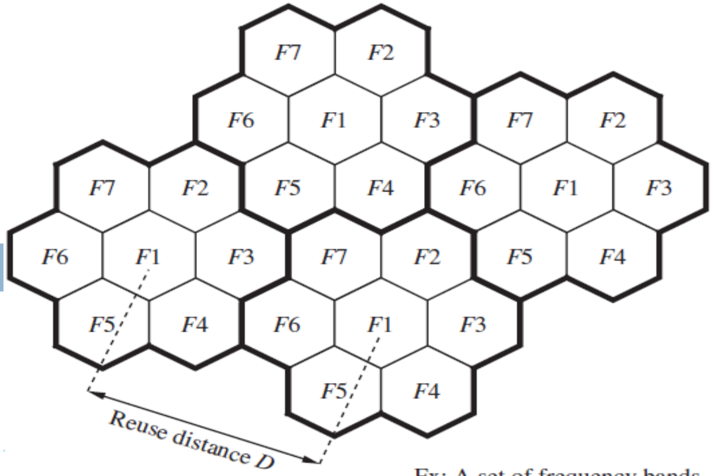
- This implies that **additional BSs need to be installed** at the **center of each new cell that has been added** so that the **higher density areas** can be **handled effectively**.
- As the **coverage area of new split cells is smaller**, the **transmitting power levels are lower**, and this helps in **reducing Co-Channel Interference**.
- **Also cell splitting increases the capacity** of cellular system since it **increases** the **number of times the channels are reused, increasing thus the additional number of channels per unit area.**

Cell Splitting



- Also, **depending on** **traffic patterns**, the **smaller cells** may be **dynamically activated** **or** **deactivated** in **cases where extra capacity is known to be needed** (e.g., at a stadium during a football match).
- **Weakness of cell splitting**:
  - **Reduced capacity of the bigger cell** (that is because **the frequencies allocated by the smaller cells** **cannot be used** **by the bigger cell**)
  - **Increased handovers** (this is because with smaller cells, the BSs are closer to each other and thus MSs' handovers can occur more frequently).

Co-Channel Interference (CCI)

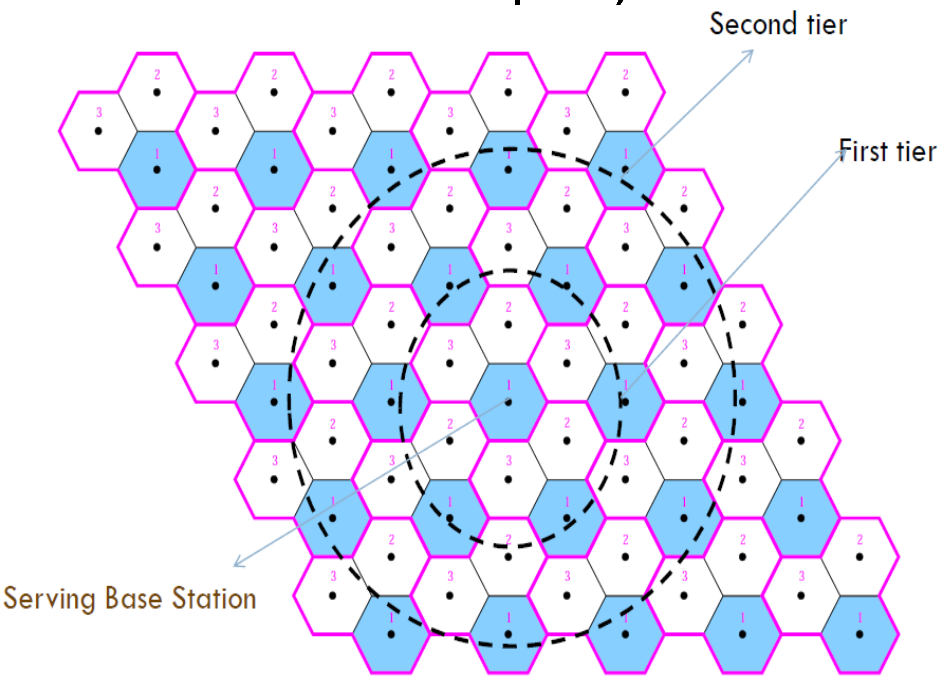


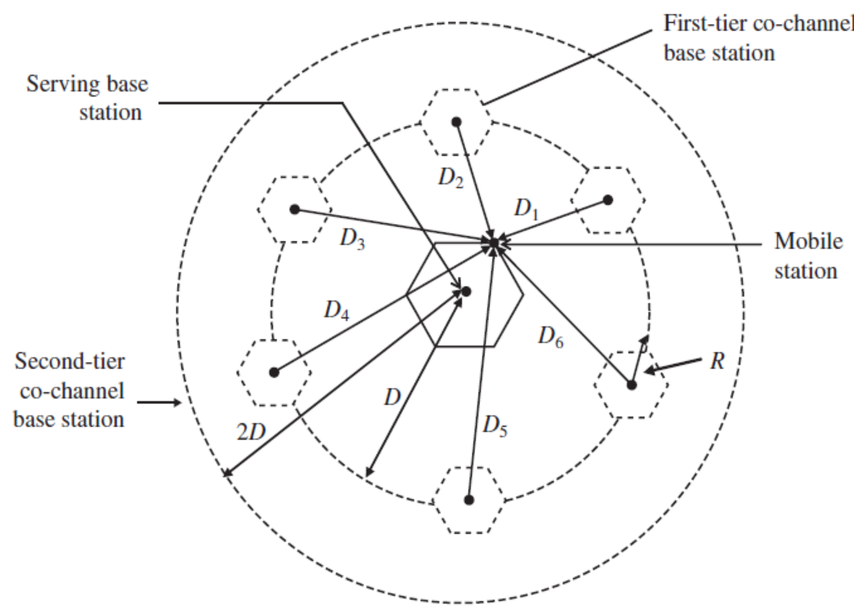
Fx: A set of frequency bands

- When using the **Frequency Reuse pattern**, all the **cells using the same channels** **(i.e., the same frequency range)** are **physically located apart** by at least a **Reuse Distance**.
- **Even though the power level is controlled carefully,** so that such "co-channels" do not create a problem for each other, **still some degree of interference remains**.
  - Called **Co-Channel Interference (CCI)**
  - **CCI increases** as the **cluster size N becomes smaller**

Co-Channel Interference (CCI)

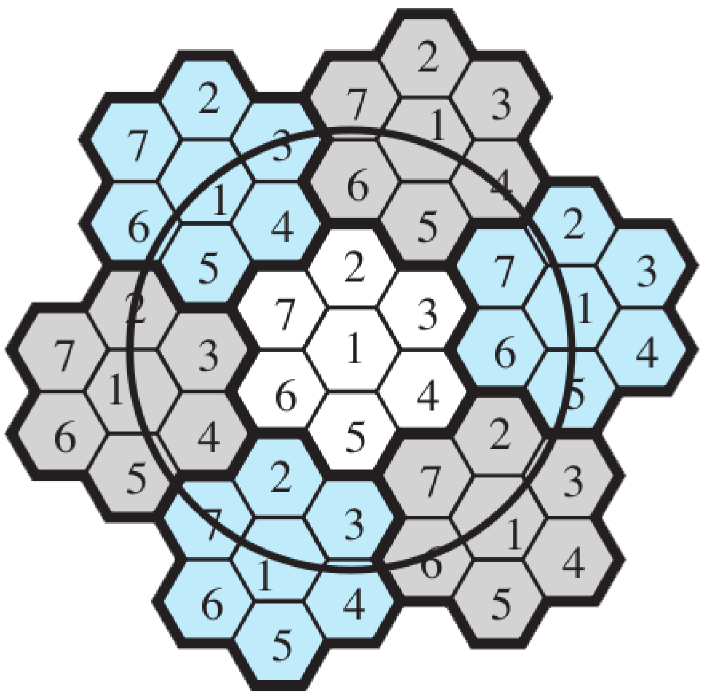
- In a **cellular system**, with a **cluster of three, four, seven, … cells**, there will be **six cells using co-channels** at the **Reuse Distance (D)**.
  - **Most Co-Channel Interference (CCI)** comes **from the First-tier**.
  - The **Second-tier co-channels**, are at **two times** the **Reuse Distance** apart, and their **effect on the serving BS is negligible**.

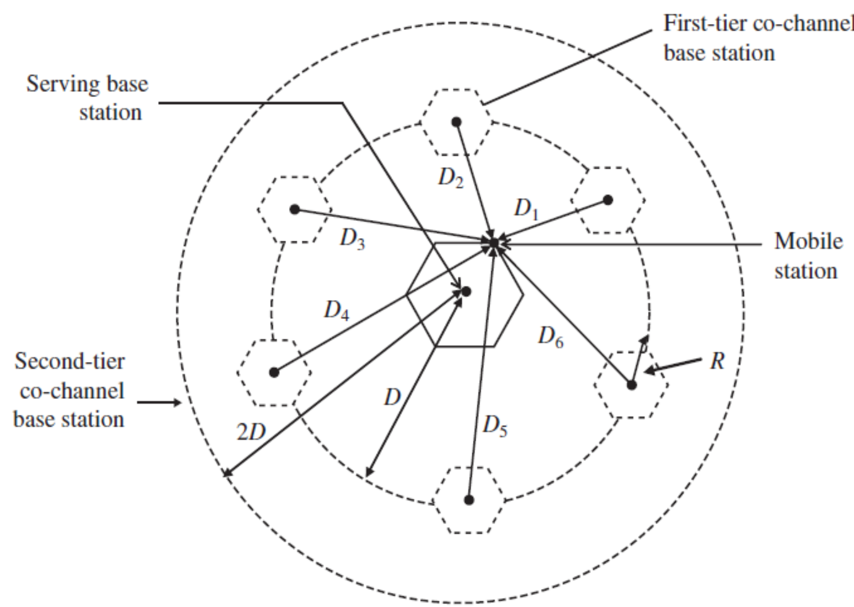




Co-Channel Interference (CCI)

- Using Omni-Directional Antennas





Co-Channel Interference (CCI)

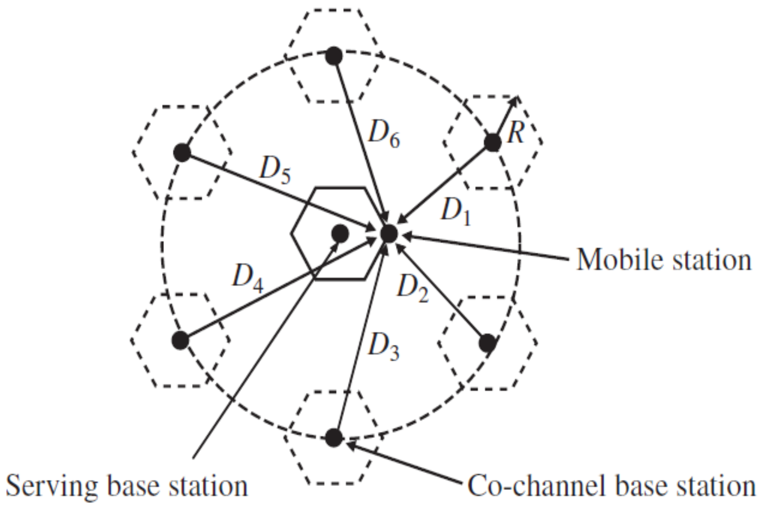
- The Co-Channel Interference ratio (CCIR) is given by

$$\frac{C}{I} = \frac{\text{Carrier}}{\text{Interference}} = \frac{C}{\sum_{k=1}^{M} I_k},$$

  - Where
    - I_k is the Co-channel interference from BS_k and
    - **M** is the **maximum number** of **Co-Channel Interfering cells**.

Co-Channel Interference (CCI)

- For cluster size of 7 (i.e., M = 6) the CCIR is given by

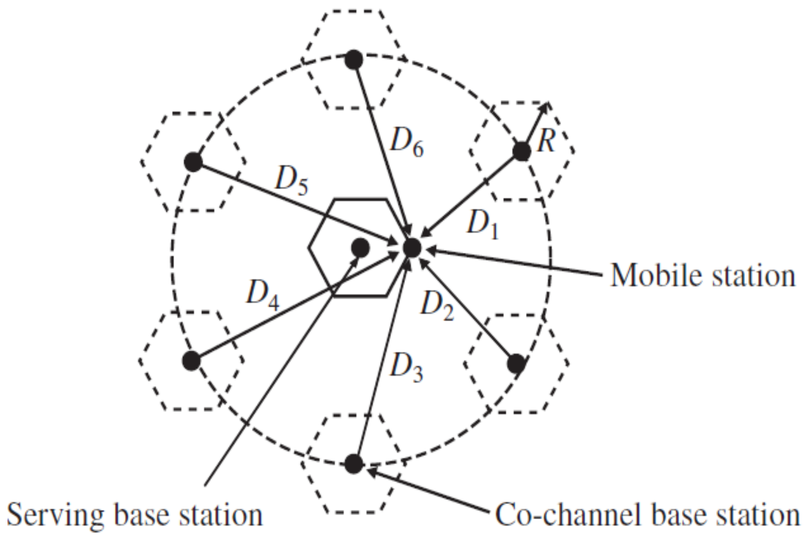


$$\frac{C}{I} = \frac{\left(\frac{D_s}{R}\right)^{-\gamma}}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-\gamma}}$$

  - ***γ*** is the **propagation path loss slope** and **varies between 2 and 5**.
  - **D_s is the distance of MS from its Serving BS**
  - **D_k** is the **distance of BS_k from the MS**
  - **R** is the **Radius of the cells**

Co-Channel Interference (CCI)

- **The worst case for co-channel interference,** is when the distance between the MS and its Serving BS is **R (i.e., the MS is located on cell's edge)**.



- In this case
  - D1 = D2 = **D – R**,
  - D3 = D6 = **D**, and
  - D4 = D5 = **D + R**

$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-\gamma}}$$

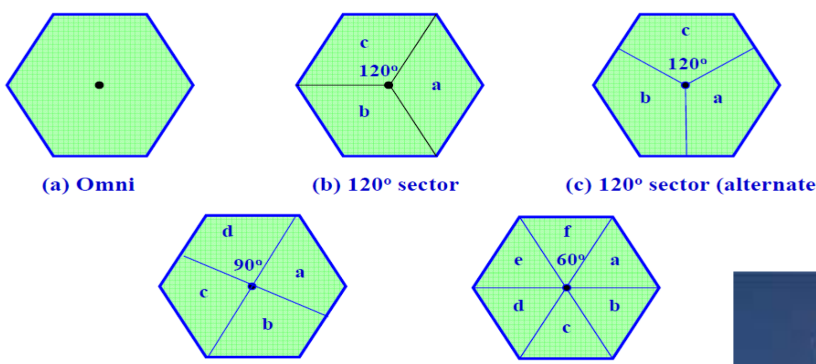
- And the CCIR in case is given as:

$$\frac{C}{I} = \frac{1}{2\,(q-1)^{-\gamma} + 2q^{-\gamma} + 2\,(q+1)^{-\gamma}},$$

- ***Where***
  - ***q** (=$\frac{D}{R}$) is the **frequency reuse factor** → lower q **means** higher interference*
  - *γ is the **propagation path loss slope** and varies **between 2 to 5***

Cell Sectoring

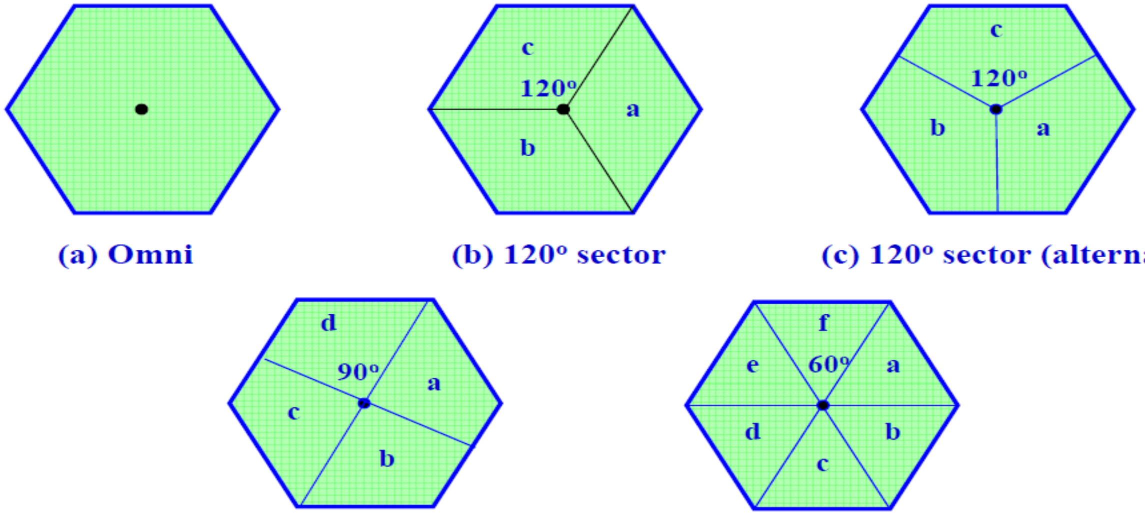
- With cell sectoring, a **cell is** **divided** **into a** **number of wedge shaped sectors**, typically **3 or 6 sectors per cell**.
  - **Replacing a single Omni-directional antenna by several Directional antennas each radiating within a specified sector.**



(a) Omni (b) 120° sector (c) 120° sector (alternate) (d) 90° sector (e) 60° sector

Cell Sectoring

- **Each sector** is **assigned a** **separate subset of the cell's frequencies (i.e., channels)**, and **directional antennas** at the Base Station are used to **focus radiation on each sector.**
- **With cell sectoring and the use of directional antennas the Co-Channel Interference (CCI) is decreased** while the **cell radius R remains unchanged.**



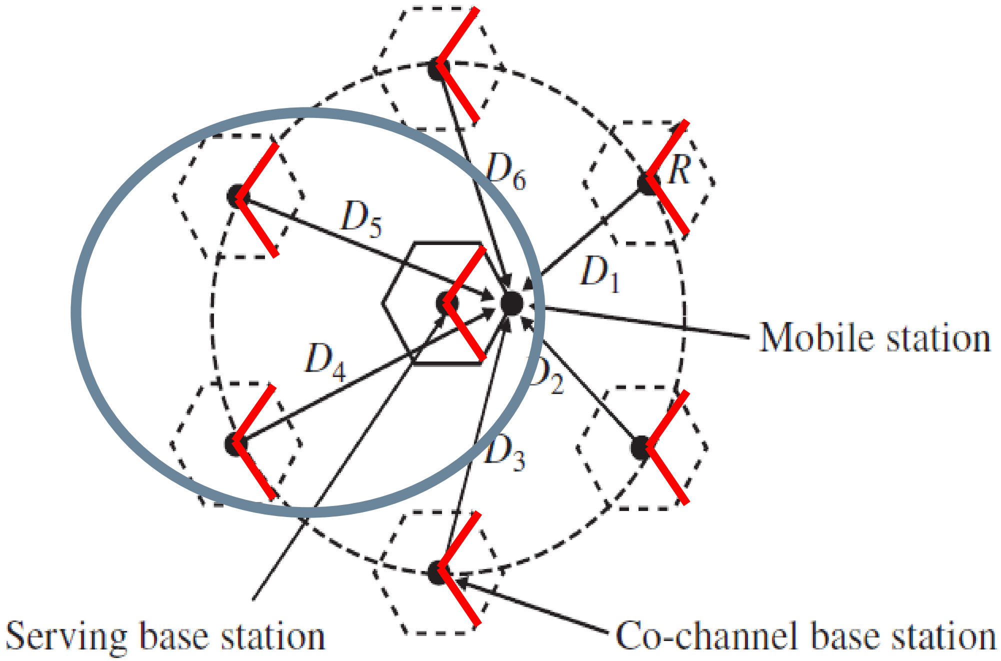
(a) Omni (b) 120° sector (c) 120° sector (alternate)

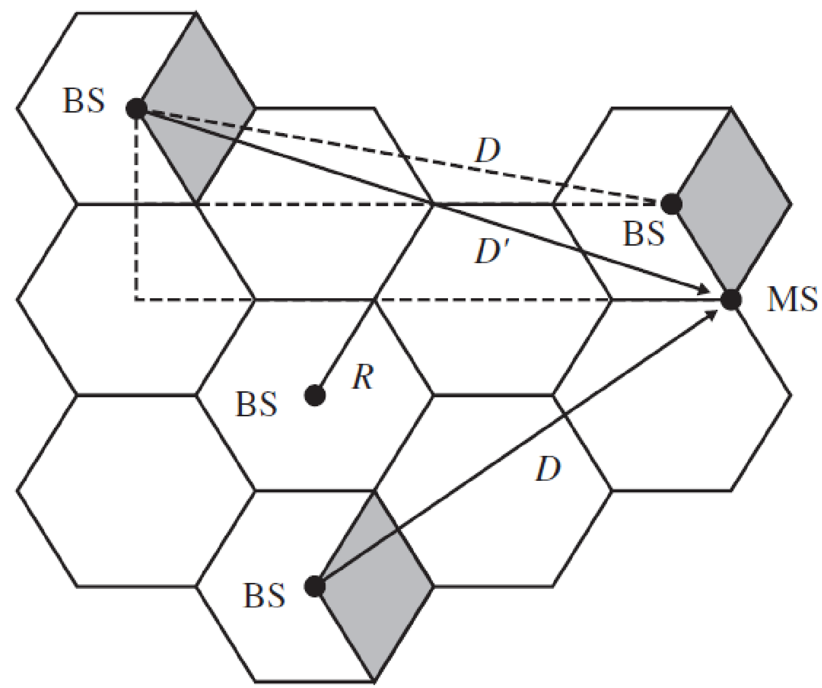
(d) 90° sector (e) 60° sector

Cell Sectoring

- The **advantages** of sectoring (besides **easy borrowing of channels** **as these are controlled by the same BS**) are that:
  - It **requires coverage of a smaller area** by **each antenna** and **hence lower power** is **required** in **transmitting radio signals** which also **helps in** **decreasing interference** **between** **co-channels cells** **(i.e., cells that uses the same range of frequencies).**
  - The **spectrum efficiency** and the **overall system capacity** **is enhanced** **(as it allows for smaller cluster sizes)**.
    - Since the **co-channel interference is decreased** this **allows to** **reuse the same frequencies in closer distances** **(i.e., allows the use of** **smaller cluster sizes** **providing for** **better capacity** **and thus** **more users can be supported**)

Cell Sectoring
CCI for 3 sector Directional Antennas



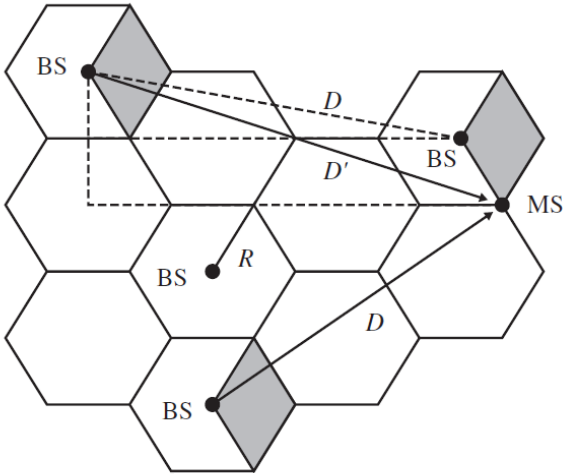


Cell Sectoring
CCI for 3 sector Directional Antennas

- Worst case for the **three-sector directional antenna is shown in the figure at the right.**
  - **No of interferers = 2 per sector (K_I = 2; instead of 6)**

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

$$\frac{C}{I}=\frac{1}{q^{-\gamma}+(q+0.7)^{-\gamma}}$$



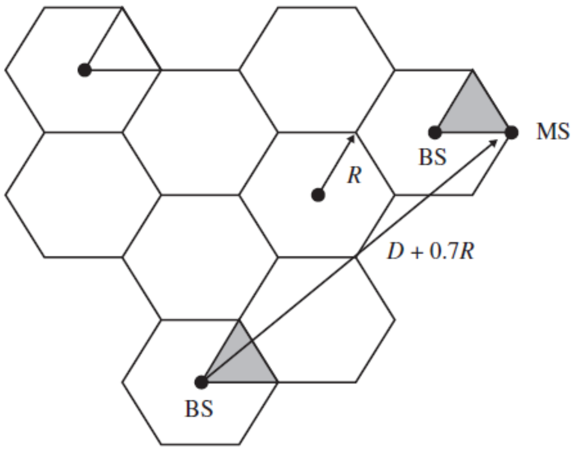
$$D=\sqrt{\left(\frac{9}{2}R\right)^2+\left(\frac{\sqrt{3}}{2}R\right)^2}$$
$$=\sqrt{21}R$$
$$\simeq 4.58R$$

$$D'=\sqrt{(5R)^2+(\sqrt{3}R)^2}$$
$$=\sqrt{28}R$$
$$\simeq 5.29R$$
$$=D+0.7R.$$

- ***Where***
  - ***q** (=$\frac{D}{R}$) is the **frequency reuse factor***
  - ***γ** is the is the **propagation path loss slope** and varies between 2 and 5 depending on the propagation environment*

Cell Sectoring
CCI for 6 sector Directional Antennas

- Worst case for the **six-sector directional antennas is shown in the figure at the right.**
  - **No of interferers = 1 per sector** (K_I = 1)



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

$$\frac{C}{I} = \frac{1}{(q+0.7)^{-\gamma}} = (q+0.7)^4$$

Thus, the use of directional antennas (Cell Sectoring) is helpful in reducing co-channel interference.

- ***Where***
  - ***q (=*** $\frac{D}{R}$ ***)*** *is the* ***frequency reuse factor***
  - *Assuming* ***γ = 4***, as the **propagation path loss slope**

Cell Sectoring

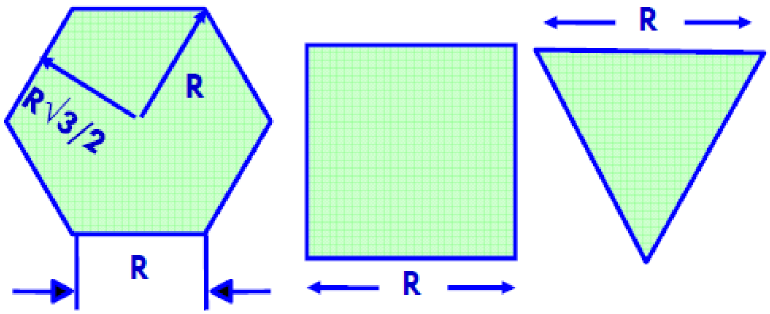
- By using **Directional Antennas** (Cell Sectoring), the **interference can be reduced** and **thus a lower frequency reuse factor (q) can be used**.
  - Thus we can reuse the same frequencies in closer distances (i.e., smaller cluster sizes) → Better Capacity → The Network can support more users.
- Using **three- or six- sector cells, the frequency reuse pattern** can be **reduced** from **7 to 4 or even 3 cells per cluster**, resulting in a **capacity increase** of **1.67** and **2.3**, **respectively**.

Ερωτήσεις;

Additional Slides

Cell Area

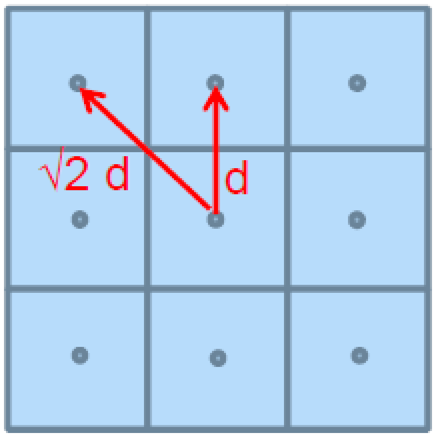
- In order for a cellular system to **be analyzed** and **evaluated**, an **appropriate cell model representing the cell's area** is needed.
- There are **many possible models** that can be used, to **represent a cell boundary** and the most popular alternatives of **hexagon**, **square**, and **equilateral triangle**.



(c) Different cell models

Cell Area

Squares

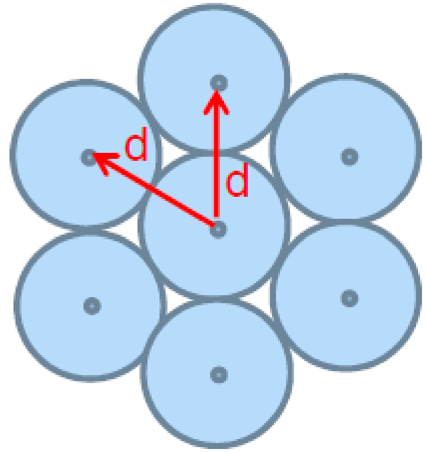


All area is covered nicely

BUT

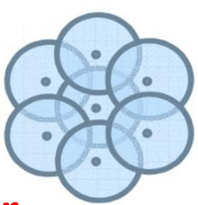
Antennas (at the centers of the squares) are **not equidistant**, variable from d to d√2.

Circles



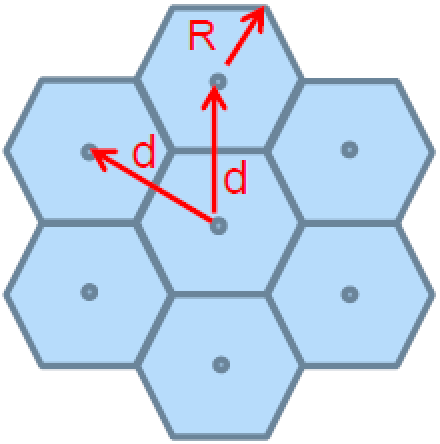
Antennas are equidistant

BUT



There are **gaps (or overlaps)** between the circles

Hexagons



Antennas are equidistant

AND

NO GAPS OR OVERLAPS (AREA IS COVERED NICELY)

Cell Area

- **Size** and **capacity** of the cell per unit area and the **impact** of the **shape of a cell** on service characteristics is shown in the figure below
  - By **increasing** the cell's **area**, the **number of channels per unit area is reduced** for the same number of channels (N).
  - A practical option is to **reduce the cell size** so that **the number of channels per unit area** (capacity) can be kept comparable to the number of subscribers in the area.

Shape of the Cell	Area	Boundary	Boundary Length/Unit Area	Channels/Unit Area with N Channels/Cells	Channels/Unit Area when Number of Channels Is Increased by a Factor K	Channels/Unit Area when Size of Cell Is Reduced by a Factor M
Square cell (side $= R$)	R^2	$4R$	$\frac{4}{R}$	$\frac{N}{R^2}$	$\frac{KN}{R^2}$	$\frac{M^2N}{R^2}$
Hexagonal cell (side $= R$)	$\frac{3\sqrt{3}}{2}R^2$	$6R$	$\frac{4}{\sqrt{3}R}$	$\frac{N}{1.5\sqrt{3}R^2}$	$\frac{KN}{1.5\sqrt{3}R^2}$	$\frac{M^2N}{1.5\sqrt{3}R^2}$
Circular cell (radius $= R$)	πR^2	$2\pi R$	$\frac{2}{R}$	$\frac{N}{\pi R^2}$	$\frac{KN}{\pi R^2}$	$\frac{M^2N}{\pi R^2}$
Triangular cell (side $= R$)	$\frac{\sqrt{3}}{4}R^2$	$3R$	$\frac{4\sqrt{3}}{R}$	$\frac{4\sqrt{3}N}{3R^2}$	$\frac{4\sqrt{3}KN}{3R^2}$	$\frac{4\sqrt{3}M^2N}{3R^2}$

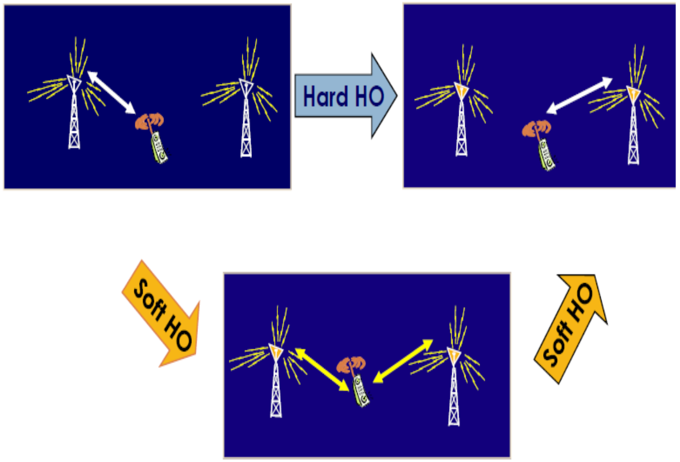
Handover Control

- **Handover Main Steps:**
  - Initiation: Either the **MS (when the signal quality received is getting worse) or sometimes the Network (when a cell is overloaded) identifies the need for handover** and **begins/triggers the handover process**
  - Resource Reservation: The required **radio resources (i.e., a new channel) necessary to support the handover** in the **new Cell, are allocated**
  - Execution: The MS is handed over to the New Cell and MS **uses the new Channel in the new cell**.
  - Completion: The **resources in the Old cell** are **Released**

Type of Handovers

- **Hard Handover (Break before Make)**
  - When the MS handovers in a new cell, **the link (channel) with the old cell have to be released before** the **new channel with the new cell is established**.
  - Used in TDMA/FDMA systems - In GSM Mobile network

- **Soft Handover (Make before Break)**
  - During the handover the MS **can use channels from two or more BSs simultaneously**
  - Used in **CDMA systems** – UMTS Mobile Networks (3G)



Handovers Vs Roaming
Cellular Vs WLANs

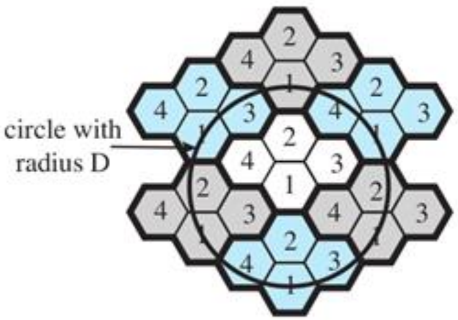
	802.11 WLANs	Cellular Telephony
Relationship	Handoff and roaming mean the same thing.	Handoff and roaming mean different things.
Handoffs (means the same in both)	Wireless host travels between access points in an organization.	Mobile phone travels between cell sites in the same cellular system.
Roaming (means different things)	Wireless host travels between access points in an organization.	Mobile phone travels to a different Cellular Network.

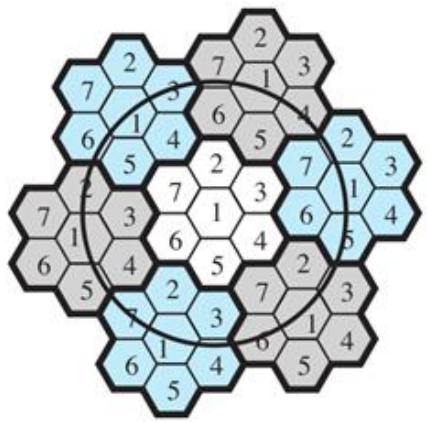
Handover (or Handoff)

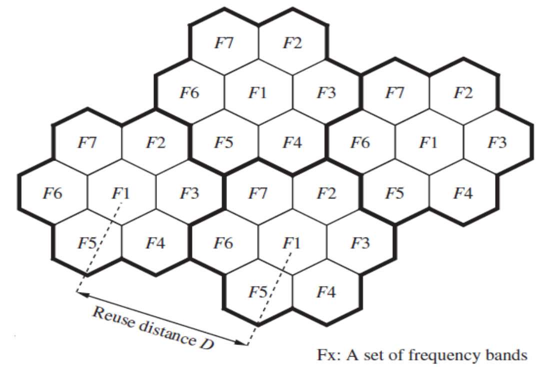
- Some important performance metrics in handover:
  - **Seamless** – User should **not know that the handover is occurring**
  - Must **avoid unnecessary handovers** due to **short time (fast) fading** (i.e., avoid ping-pong effect)
  - **Reduce the probability of blocking new calls in the new cell** (e.g., by pre-reserving resources for users that will handover in the new cell)
  - Provide **handover to a good SNR channel,** so that an admitted **call is not dropped.**

Number of cells (**N**) in Cluster – Frequency Reuse Distance (**D**) – Frequency Reuse Factor (**q**)

- **Frequency Reuse Pattern of N = Denotes the number of cells** in a **repetitious pattern – i.e., number of cells in the cluster** (**each cell in the pattern uses a unique band of frequencies**)





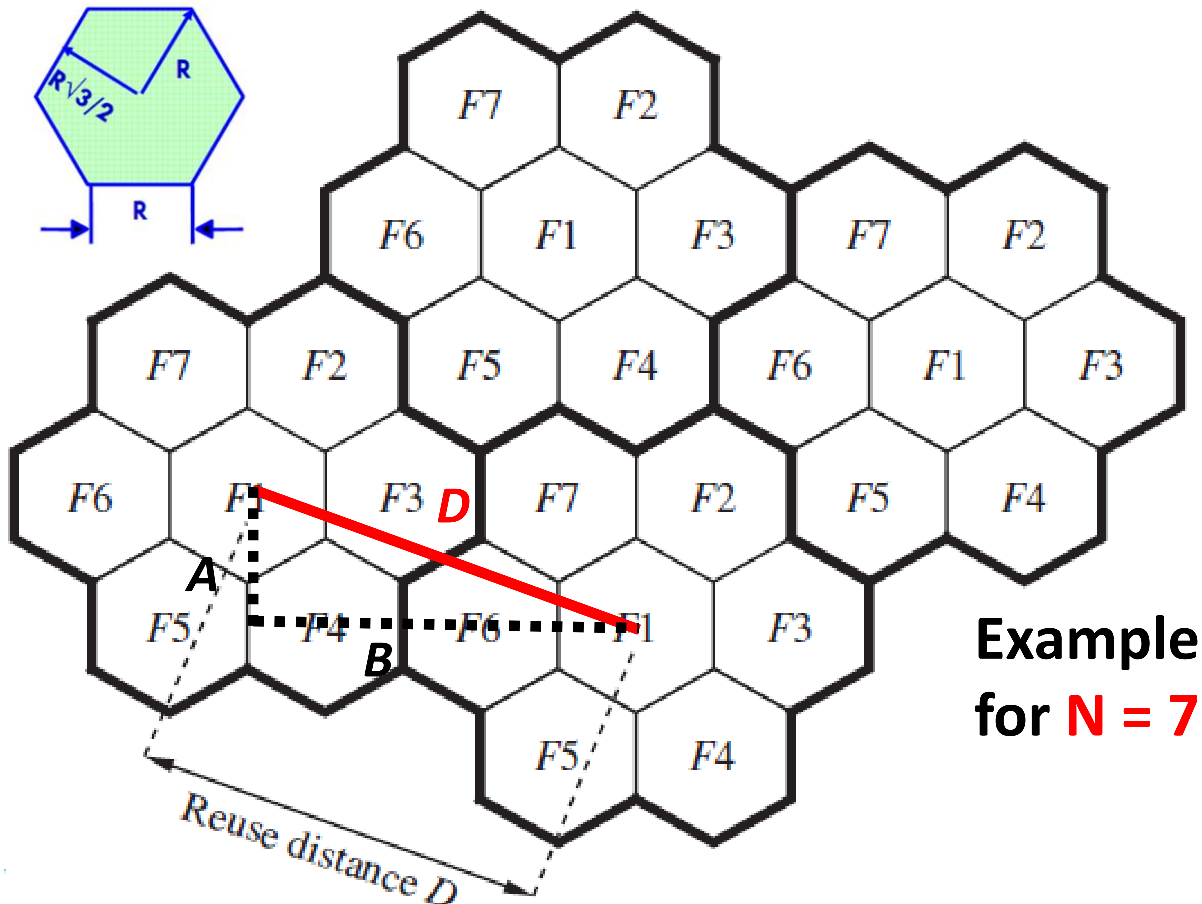


(a) Frequency reuse pattern for $N = 4$ (b) Frequency reuse pattern for $N = 7$

- **Reuse Distance D = Minimum distance between centers of cells** that use the **same band of frequencies** (called **co-channels**). These cells belong to different clusters.
- **R = Radius** of a cell

Number of cells (**N**) in Cluster – Frequency Reuse Distance (**D**) – Frequency Reuse Factor (**q**)

- For hexagonal cells, the **Reuse Distance (D)** is given by:



Fx: A set of frequency bands

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

Using "Πυθαγόρειο Θεώρημα"

$$D = \sqrt{A^2 + B^2}$$

$$B = \frac{\sqrt{3}R}{2} \times 5 \quad A = \frac{3R}{2}$$

Example for N = 7:

$$D = \sqrt{21}R = \sqrt{3N}R$$

The same formula will result for different values of N

Number of cells (**N**) in Cluster – Frequency Reuse Distance (**D**) – Frequency Reuse Factor (**q**)

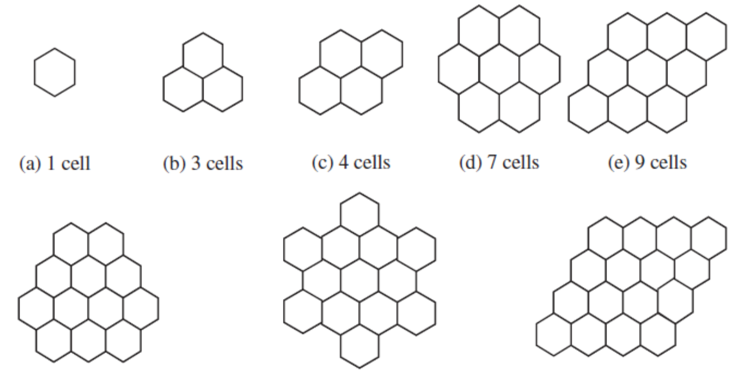
- The **co-channel reuse ratio** (i.e., the **Frequency Re-use Factor**) **q** is:

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

- A **small value** of **q provides larger capacity** since the cluster size is small and **the same frequencies (i.e., the same channels)** can be **re-used** in **more cells**.
- A **large value** of **q improves the transmission quality**, due to **smaller level of co-channel interference – the cells using the same frequencies are farther apart from each other**

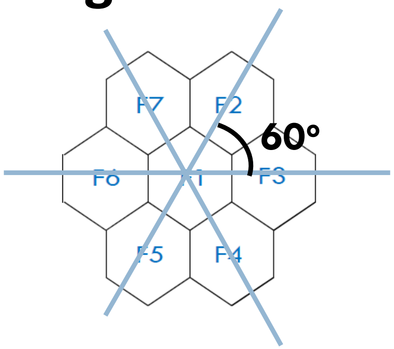
N	q
1	1.7
3	3
4	3.46
7	4.6

Frequency Reuse
Cluster Size (N)

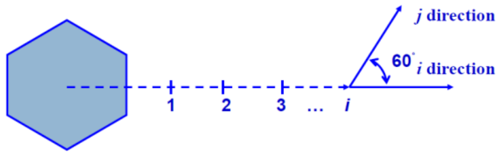


(a) 1 cell (b) 3 cells (c) 4 cells (d) 7 cells (e) 9 cells
(f) 12 cells (g) 13 cells (h) 16 cells

- **Hexagonal Geometry has**
  - Exactly **six equidistance Neighbours**
  - The **lines joining the centers of any cell** and **each of its neighbors** are **separated by multiples** of **60 degrees**

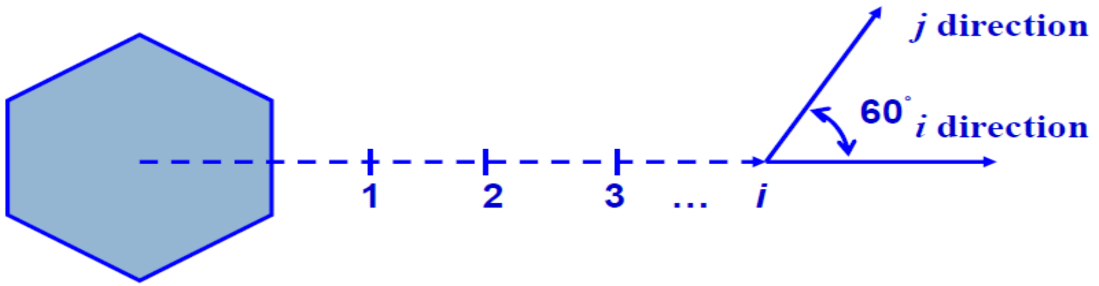


- Due this Geometry only **certain cluster sizes** and **cell layout** are **possible.**
- The **cluster size** or the **number of cells per cluster** is given by $N = i^2 + ij + j^2$
- Where ***i*** and ***j*** are integers and are **used to find the center of an adjacent cluster (or cells that uses the same frequencies)**.
- Substituting different values of ***i*** and ***j*** leads to N = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 28, . . .;
  - The most popular values are **7** and **4**.



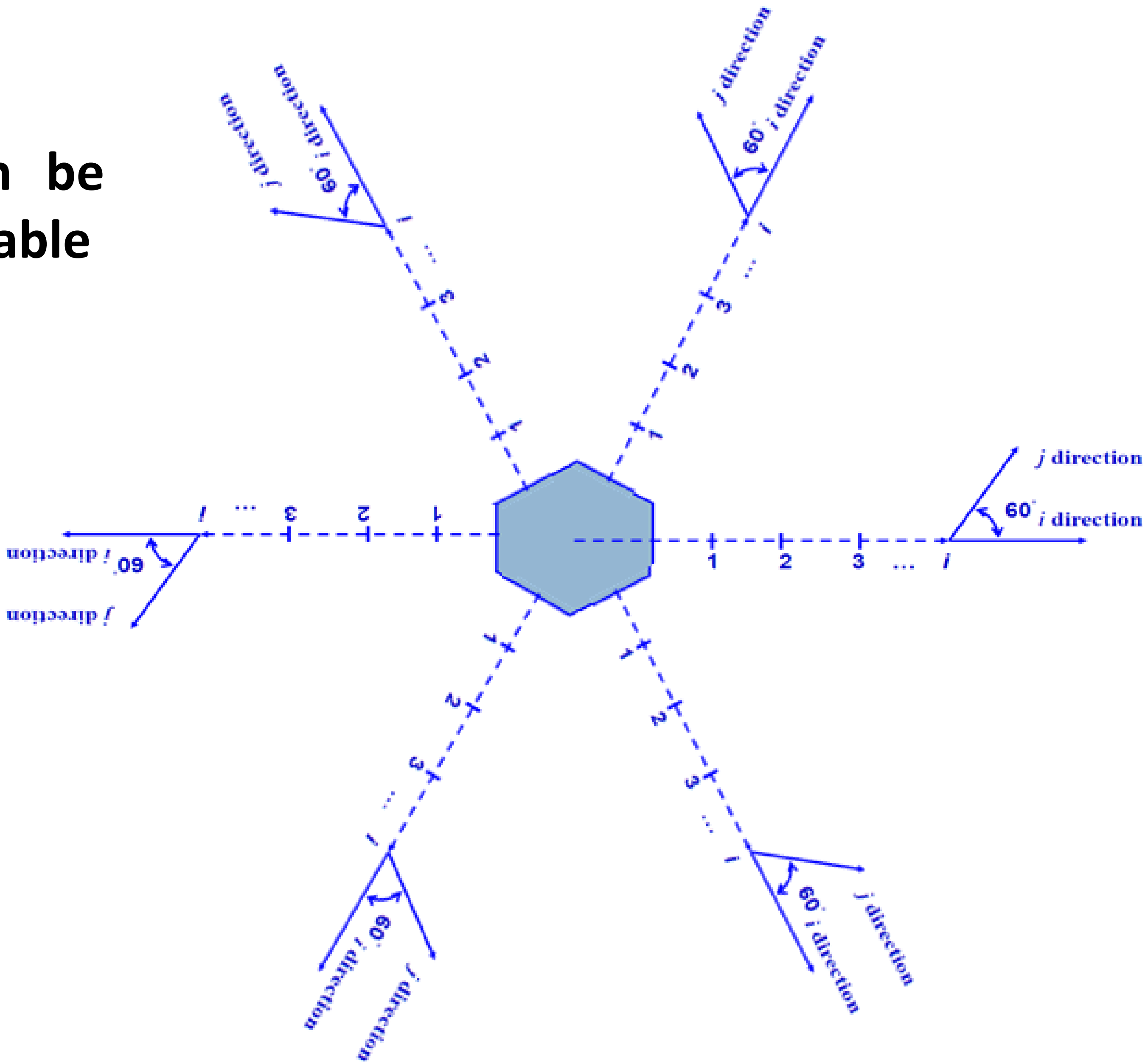
Finding the Center of an Adjacent Cluster

- **Finding the center of an adjacent cluster (or cells that uses the same frequencies; co-channel neighbours)** using integers **i** and **j**.
  - **i** represents the **number of cells to be traversed along direction i, starting from the center of a cell**, and
  - **j** represents the **number of cells to be traversed in a direction 60º** to the direction of **I**



Finding the Center of an Adjacent Cluster

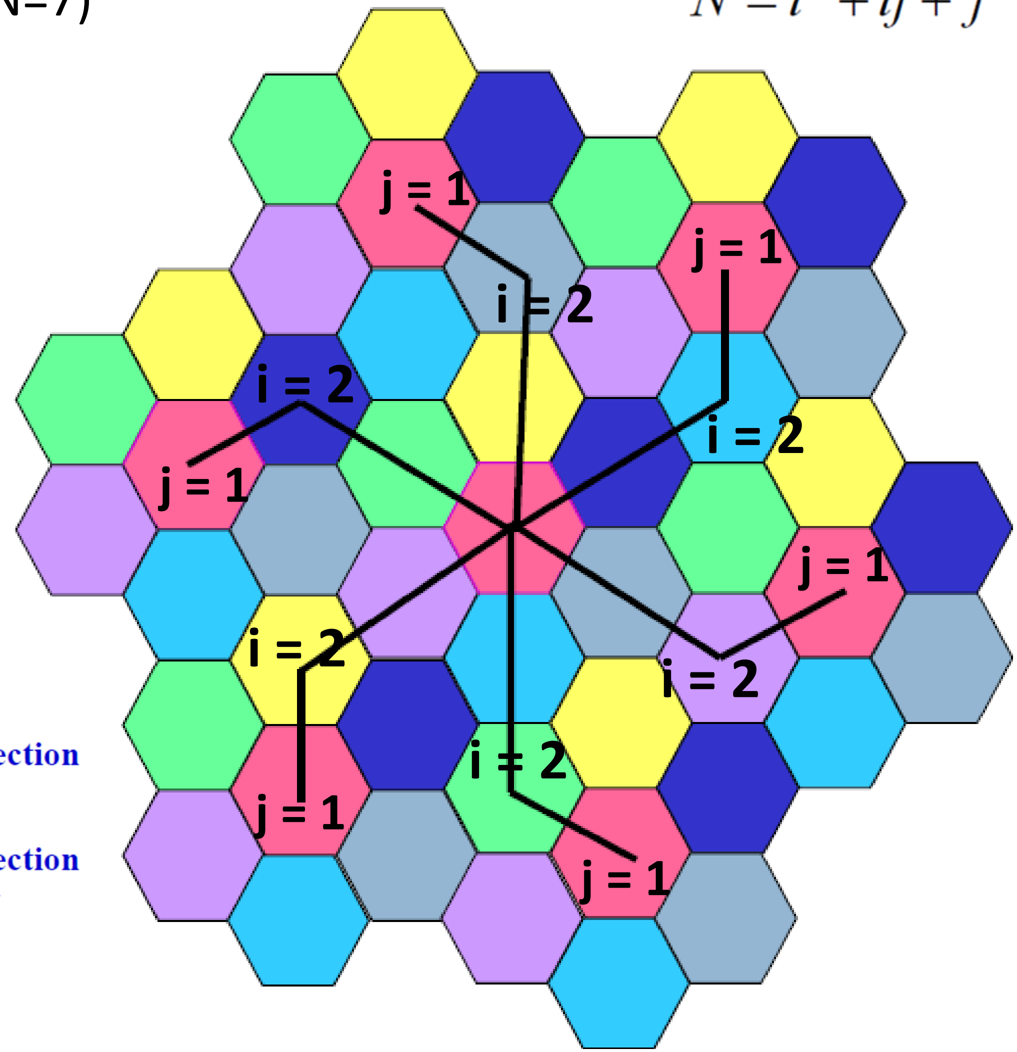
- **i and j can be interchangeable**

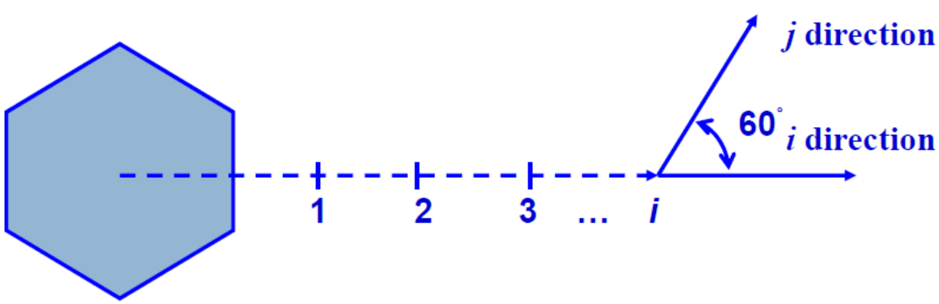


Finding the Center of an Adjacent Cluster

- **Example** for Clusters of Size 7 (N=7)
  - To find the **nearest co-channel neighbor of a particular cell**
    - 1. Move **'i'** cells (i = 2) along **any chain of hexagons**
    - 2. Then turn 60 degrees **anti-clockwise** and
    - 3. Move **'j'** cells (j = 1) .

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



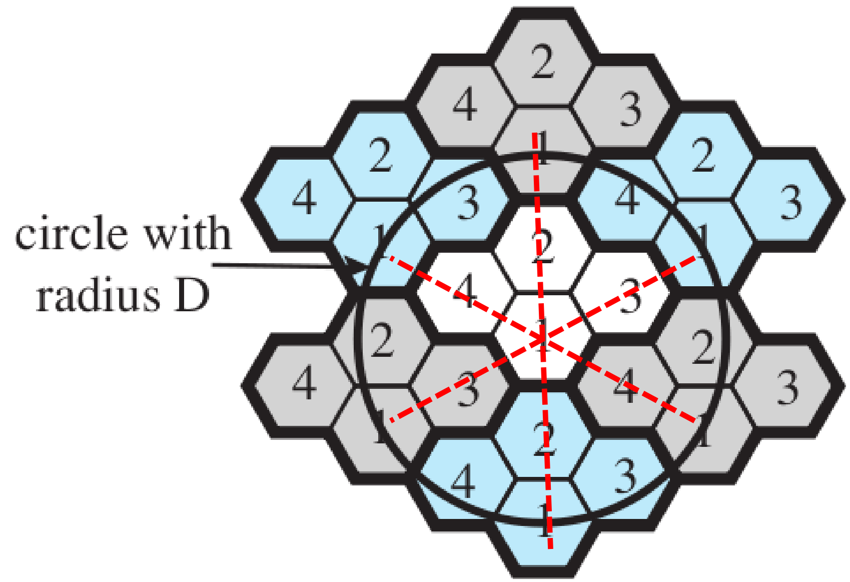


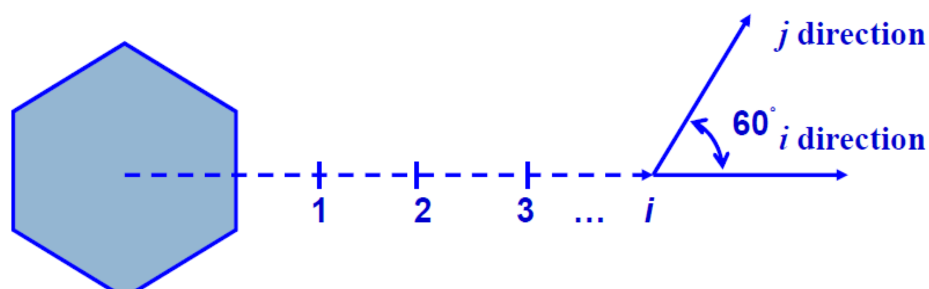
Finding the Center of an Adjacent Cluster

- Example for Clusters of Size 4 (N=4)

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

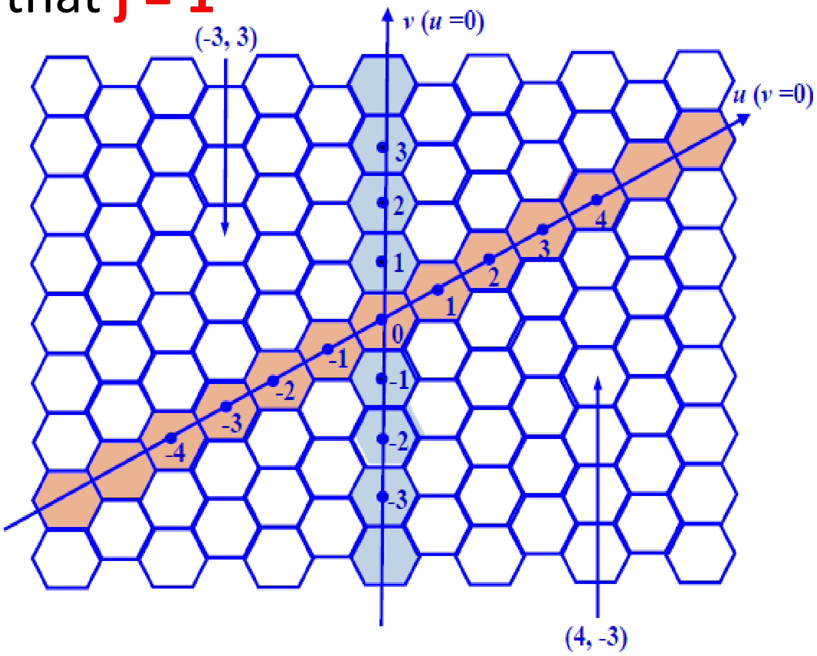
- To **find** **the nearest co-channel neighbor** of **a particular cell**
  - 1. Move **‘i’** cells (**i = 2**) along any chain of hexagons
  - 2. Then turn 60 degrees anti-clockwise and
  - 3. Move ‘j’ cells (**j = 0**) .





How to form a Cluster

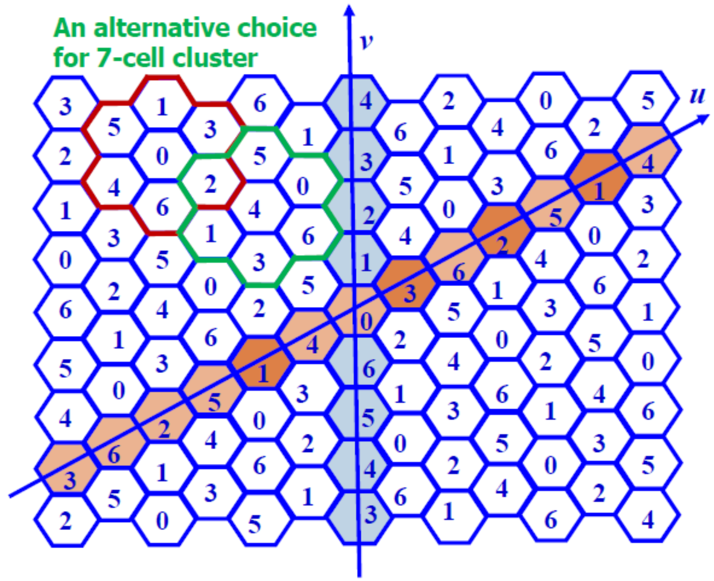
- In general, the number (N) of cells in a cluster is $N = i^2 + ij + j^2$
- The **method discussed here assumes** that **j = 1**
- **Steps used:**
  - **First, select a cell**, make the **center of the cell as the origin**, and form the **coordinate plane (u, v)** as shown in the figure.
  - The **positive half** of the **u-axis** and the positive half of the **v-axis** intersect at a **60-degree angle**.



  - Define the **unit distance (i.e., 0, 1, 2, …. of planes u and v)** as the **distance of centers of two adjacent cells**.
  - Then **for each cell center**, we can get an **ordered pair (u, v)** to mark the position.

How to form a Cluster

- Since this method is only for those cases where **j = 1, with a given N of cells, integer i is also fixed** → $N = i^2 + i + 1$.
- **Then using** $L = [(i+1)u + v] \bmod N$, we can obtain the label L for the cell whose center is at (u, v).
  - For the **origin cell** whose center is **(0, 0), u = 0, v = 0,** using the formula above, we have **L = 0** and **label this cell as 0**.
  - Then we **compute the labels of all adjacent cells**.
  - **Finally**, **the cells** with **labels** from **0 through N – 1 form a cluster** of **N cells.**
  - The **cells with the same label** can **use the same frequency bands**



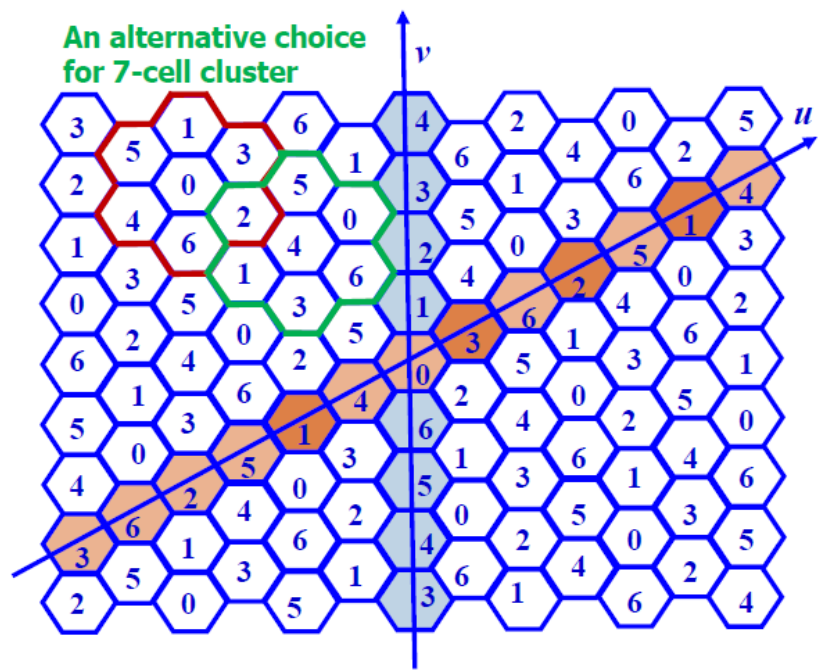
How to form a Cluster
Labeling Cells with L Values for N=7 (i.e., i= 2, j=1)

Example: For N = 7, i = 2 and j = 1

- Then using equation $L=[(i+1)u+v)] \bmod N$, we have **L = (3u + v) mod 7**.
- We can compute label **L** for any cell using its center's position **(u, v).**

Some Cell Labels for $N = 7$

u	0	1	−1	0	0	1	−1
v	0	0	0	1	−1	−1	1
L	0	3	4	1	6	2	5

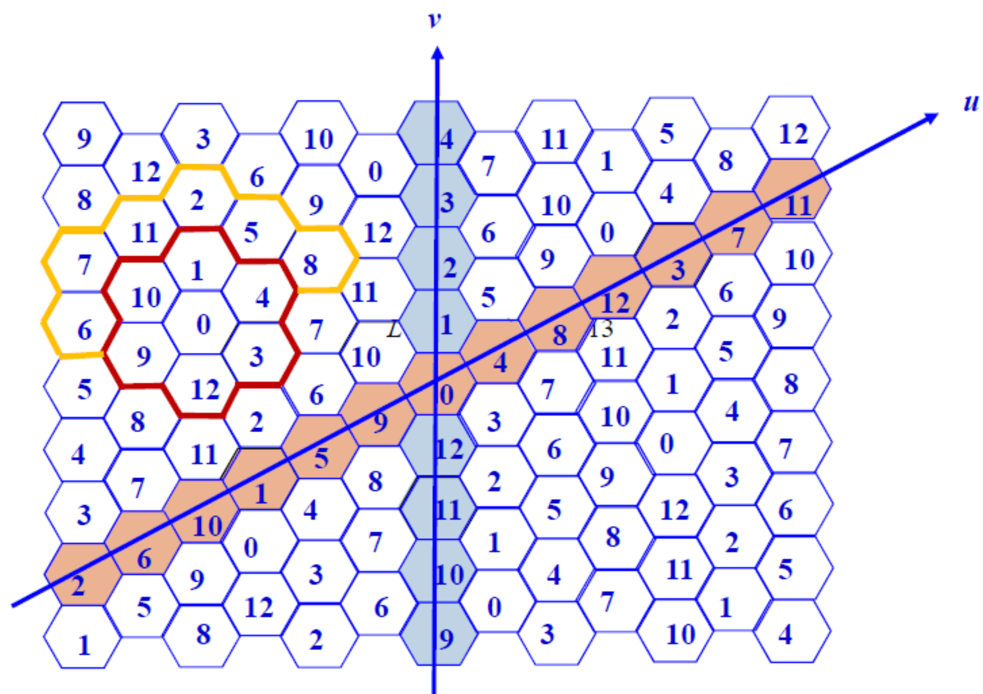


How to form a Cluster

Labeling Cells with L Values for N=13 (i.e., i= 3, j=1)

Example: For N = 13, i = 3 and j = 1

- Then using equation $L=[(i+1)u+v)] \bmod N$, we have **$L = (4u + v) \bmod 13$**.
- We can compute label **L** for any cell using its center's position **(u, v).**



Capacity Calculation — FDMA

- **n**: Capacity (number of total users)
- **m**: Number of cells to cover the area
- **N**: Number of cells per cluster
- **B**: Bandwidth per user
- **W**: Total available bandwidth (spectrum)

$$n = \frac{m}{N}\frac{W}{B}$$

Capacity Calculation — FDMA

- In the previous example,
  - m = 20,
  - N = 4, and
  - B = 30 KHz
  - W = 1 MHz,

$$n = \frac{m}{N} \times \frac{W}{B} = \frac{20}{4} \times \frac{1000}{30} = 166$$

Capacity Calculation —TDMA/FDMA

- **n**: Capacity (number of total users)
- **m**: Number of cells to cover the area
- **N**: Number of cells per cluster
- **B**: Bandwidth per user
- **W**: Total available bandwidth (spectrum)
- $\mathbf{N_u}$: Number of time slots per carrier

$$n = \frac{m}{N}\frac{W}{B}N_u$$

Capacity Calculation —TDMA/FDMA

- **Assuming again,**
  - **m =** 20**,**
  - **N =** 4**,**
  - **B =** 30 KHz**,**
  - **W =** 1 MHz**,**
  - **N_u=** 4

$$n = \frac{m}{N} \times \frac{W}{B} \times N_u = \frac{20}{4} \times \frac{1000}{30} \times 4 = 666$$

Capacity of CDMA

- In CDMA **users are separated by different codes** but **not by frequencies or time slots** as in TDMA and FDMA.
- In CDMA **many users can share the same frequency band** and **communicate at the same time**.
  - For this reason CDMA networks can use a employ a **Frequency reuse pattern** (Number of cells/Cluster) **equal to 1**.
- A channel in **TDMA** or **FDMA** is a frequency and a time slot. There is only **a limited number of channels**, which **restrict the number of simultaneous users**.
- In CDMA a **channel is a code**. There is an almost **unlimited number of codes**, **and thus channels**, **but it doesn't mean an unlimited capacity**.

Capacity of CDMA

- **Each user is a source of noise to the receivers of other users** or to the **receiver in the Base Station**. This will **limit the number of parallel users**.
- The **number of users per cell** (i.e., the capacity) is **determined by the received Signal to Noise Ratio (SNR)**.
- If there are **too many users**, the **noise (interference) will be high**, the **SNR ratio will be low** and **reception quality will be poor**.
- This is **different from TDMA and FDMA**, where the **capacity is determined by the number of available channels**.

Capacity calculation—CDMA

- **n**: Capacity (number of total users)
- **W**: Total available bandwidth (spectrum)
- **R:** Data Rate
- $\mathbf{S_r}$: Signal to Noise ratio (SNR)

$$n = \frac{W}{R \times S_r}$$

Capacity calculation—CDMA

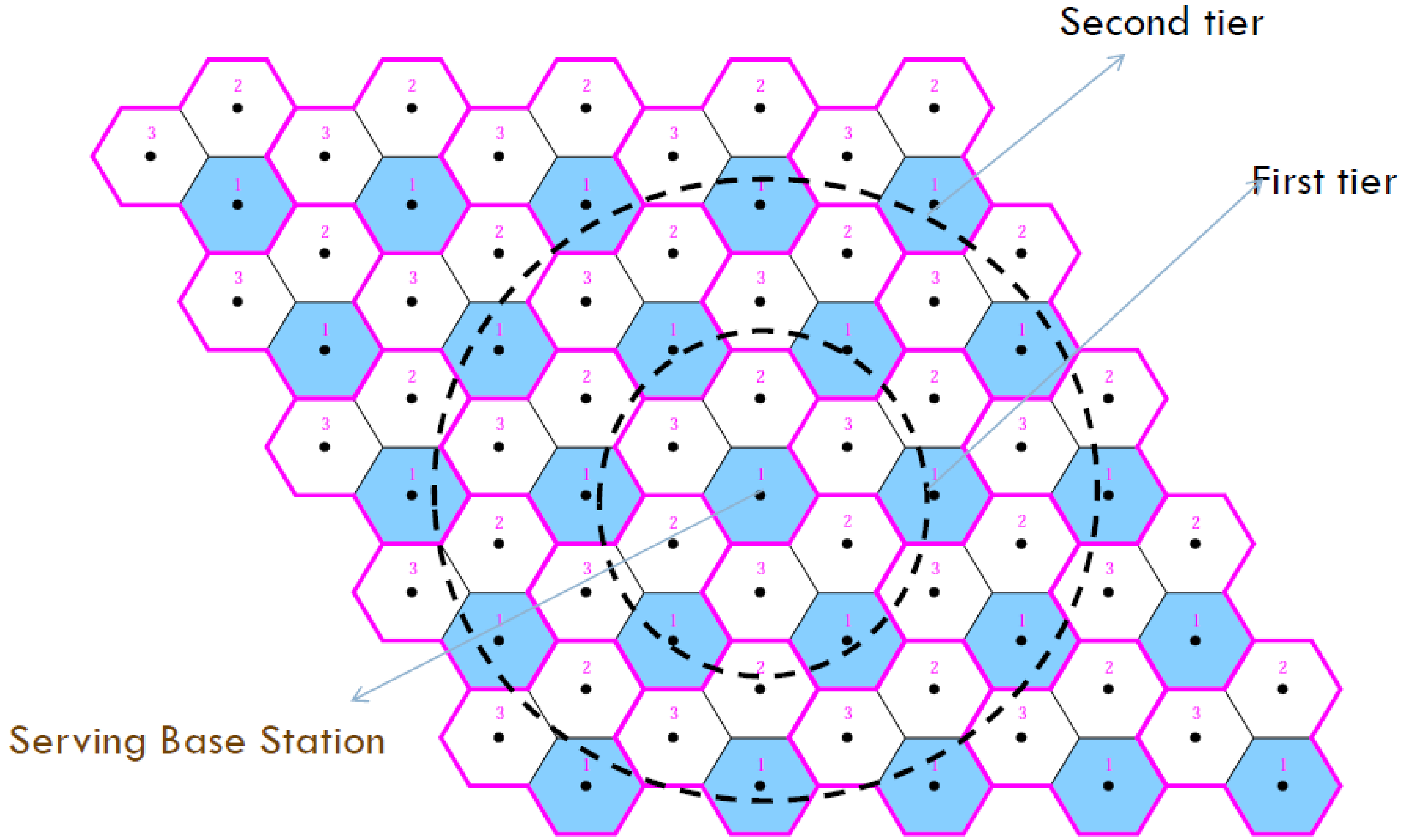
Assume

- **W** = 1.25MHz = 1,250,000 Hz
- **R** = 9600 bps
- **S_r** should be **larger than 3dB** (i.e., The signal power should be at **least 2 times** stronger than the noise power, in order for the receiver to decode the signal correctly)

$$n = \frac{W}{R \times S_r} = \frac{1250000}{9600 \times 2} = 65\, users$$

Co-Channel Interference (CCI)

- **First** and **Second Tiers Co-channels** for the case of frequency Reuse patter with **clusters of 3 cells**.



Co-Channel Interference (CCI)

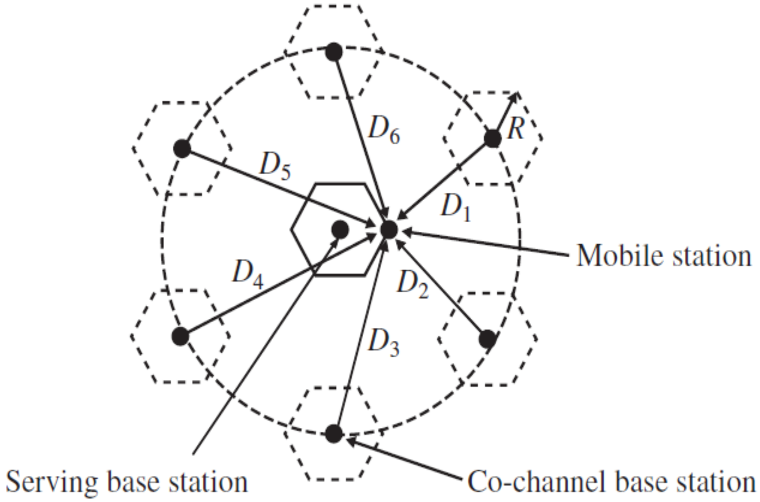
- The Co-Channel Interference ratio (CCIR) is given by

$$\frac{C}{I} = \frac{\text{Carrier}}{\text{Interference}} = \frac{C}{\sum_{k=1}^{M} I_k},$$

  - Where
    - I_k is the Co-channel interference from BS_k and
    - **M** is the **maximum number** of **Co-Channel Interfering cells**.

Co-Channel Interference (CCI)

- For cluster size of 7 (i.e., M = 6) the CCIR is given by

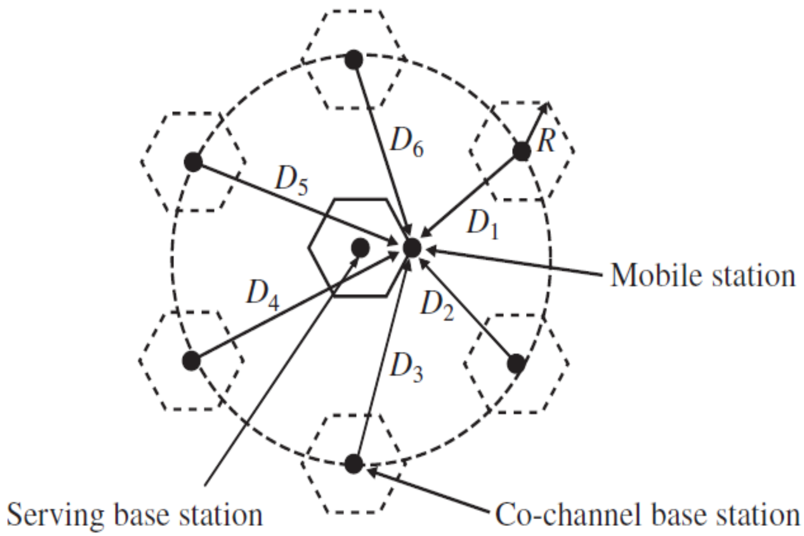


$$\frac{C}{I} = \frac{\left(\frac{D_s}{R}\right)^{-\gamma}}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-\gamma}}$$

  - γ is the **propagation path loss slope** and **varies between 2 and 5**.
  - **D_s is the distance of MS from its Serving BS**
  - D_k is the **distance of BS_k from the MS**
  - **R** is the **Radius of the cells**

Co-Channel Interference (CCI)

- **The worst case for co-channel interference,** is when the distance between the MS and its Serving BS is **R (i.e., the MS is located on cell's edge)**.



- In this case
  - D1 = D2 = **D – R**,
  - D3 = D6 = **D**, and
  - D4 = D5 = **D + R**

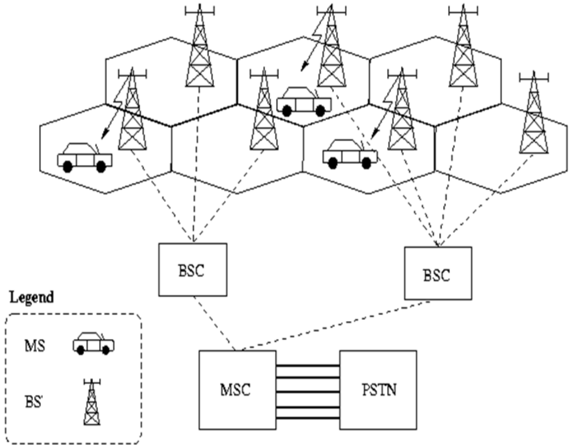
$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-\gamma}}$$

- And the CCIR in case is given as:

$$\frac{C}{I} = \frac{1}{2\,(q-1)^{-\gamma} + 2q^{-\gamma} + 2\,(q+1)^{-\gamma}},$$

- ***Where***
  - *q (=$\frac{D}{R}$) is the **frequency reuse factor** → **lower q** means **higher interference***
  - *γ is the **propagation path loss slope** and varies **between 2 to 5***

How Does Cellular System Work



- When a **Mobile Station (MS) is switched on**, it scans **for the strongest signal** received from **adjacent BSs** and connects to the **strongest BS**.
- Then a **handshaking process** takes place **between the MS** and the **MSC** to **identify the user (based on the user's IMSI)** and **register its location in the VLR/HLR (Location Management)**.
  - This procedure is **repeated Periodically as long as the MS is switched on**, so as the **MSC to monitor its location (The location of the MS is stored in the VLR)**.